Carbon footprint for drone-operated power grid smart maintenance

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Keywords: Drone, Smart maintenance, Carbon footprint, Emission reduction, Greenhouse gas

The primary objective of this thesis is to develop a model to estimate the carbon footprint of drone-operated smart power grid maintenance inspections. The secondary purposes of this thesis are to identify the emission hotspots for the maintenance inspection and find reduction scenarios to minimize the emissions caused by the maintenance inspection.

To achieve these objectives, this thesis employs methods such as life cycle assessment and calculation tools such as ISO standards for calculating carbon footprint, and data collection from actual maintenance inspections. These methods are used to generate a comprehensive model that estimates the emissions produced during each phase of the inspection activities.

The results indicate that while the baseline emissions are the lowest for currently available inspection methods for similar level of data gathering, the emission reduction scenarios offer a reduction pathway to approach carbon neutrality through improvements in efficiency, selection of more sustainable fuel sources, and tool selection such as drone systems, cameras, LiDAR, etc.

This thesis stands as an independent project aiming to provide a specific carbon footprint estimation model for drone-operated maintenance inspections. Although the models are based on measured data and may not be directly applicable to other scenarios, they can serve as useful references for rough estimates in similar contexts.

TIIVISTELMÄ

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Ympäristötekniikka

Juuso Varvemaa

Droneilla suoritettava sähköverkon älykäs kunnossapito

Diplomityö

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Tämän opinnäytetyön ensisijaisena tavoitteena on kehittää malli, jolla voidaan arvioida droneilla suoritettavien sähköverkkojen älykkään kunnossapidon hiilijalanjälki. Opinnäytetyön toissijaisina tavoitteina on tunnistaa kunnossapidon pää päästökohteet ja löytää päästövähennysmenetelmiä päästöjen minimoimiseksi.

Näiden tavoitteiden saavuttamiseksi työssä käytetään menetelmiä, kuten elinkaarianalyysiä, ja laskentatyökaluja, kuten hiilijalanjäljen laskenta ISO standardeja sekä kunnossapito toiminnasta kerättyä toiminnalista tietoa. Näitä menetelmiä käytetään kattavan mallin luomiseen, joka arvioi tarkastustoimintojen eri vaiheissa syntyviä päästöjä.

Tulokset osoittavat, että vaikka perustason päästöt ovat alhaisimmat nykyisin saatavilla olevilla tarkastusmenetelmillä vastaavanlaisen tiedonkeruun tasolla, päästöjen vähennysmenetelmät tarjoavat vähentämispolun kohti hiilineutraaliutta parantamalla tehokkuutta, valitsemalla kestävämpiä polttoainelähteitä ja työkalujen, kuten dronesysteemien, kameroiden ja LiDARin, valinnalla.

Tämä opinnäytetyö on itsenäinen projekti, jonka tavoitteena on tarjota erityinen hiilijalanjäljen arviointimalli droneilla suoritettaville huoltotoimenpiteille. Vaikka mallit perustuvat mitattuihin tietoihin ja eivät välttämättä ole suoraan sovellettavissa muihin tilanteisiin, ne voivat toimia hyödyllisinä viitteinä karkean arvion tekemisessä samanlaisissa yhteyksissä.

SYMBOLS AND ABBREVIATIONS

Abbreviations

GHG	Greenhouse gas
LiDAR	Light Detection and Ranging
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take off and Landing
EV	Electrical Vehicle
ICEV	Internal Combustion Engine Vehicle
SBTI	Science Based Target Initiative
HVO	Hydrotreated Vegetable Oil
FAME	Fatty acid methyl ester
GREET	Greenhouse gasses, Regulated emissions, and Energy use in Transportation

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1. Introduction

Growing concerns about climate change cause more and more companies and consumers to focus their attention to the effects of climate change, thus increasing the demand for awareness of greenhouse gas (GHG) emissions. The increasing awareness creates a need for internationally accepted standard of measuring GHG emissions, led to the establishment of the Greenhouse Gas Protocol (2011) reflecting a trend towards sustainability.

Public awareness of climate change has caused a lot of companies to face requirements for carbon management. A survey in 2016 for executives of international corporations indicated that the issues regarding GHG emissions cannot be ignored (Zvezdov and Hack, 2016, pp. 1267–1275). Public and political awareness has led to increases in legislation for climate control such as EU's climate law (European Commission, 2021) or European parliament's plan to increase the responsibilities of companies regarding their environmental impacts (European parliament, 2023).

In response to the demands caused by changing legal landscape, companies are increasingly evaluating their supply chains and outsourced services focusing on sustainability. This evaluation increases the need for GHG emission reporting on provided services (Zvezdov and Hack, 2016, pp. 1267–1275).

This master's thesis focuses on the carbon footprint of a drone-operated electrical grid inspection service by the company Evision. By focusing on the carbon emission implications of electrical grid inspections services, this thesis aims to create a model to improve the climate impacts of the service provider.

1.1. Evision

Evision is a small company part of Suur-Savon Sähkö concern. Evision was established to provide smart maintenance solutions to electricity distribution companies and to address growing need for smart maintenance solutions. (Evision, 2024a)

Evision provides six different main services: maintenance inspection, data analysis services, snow load locating, fault locating, mapping and modelling services, and solar farm imaging

and photography. These services can be divided into three categories smart maintenance, disruption management, and mapping and modelling services. (Evision, 2024b)

1.2. Maintenance inspection

Maintenance inspection is the main activity provided by Evision, which includes electrical grid inspection and data analysis. Electrical grid inspections conducted by Evision are done by drone as shown in figure 1. Each inspection area takes two flights, one with a LiDAR (Light Detection and Ranging) camera attached to the drone and another one with a regular camera attached.

Figure 1. Drone heading to inspect grid, operated by Evision pilot.

1.2.1. LiDAR imaging

LiDAR (Light Detection and Ranging) is an imaging method using light waves to measure distances. LiDAR systems can be used to generate 2D or 3D images of the imaged area (McManamon, 2019). In electrical grid inspection LiDAR is used to generate a 3D model of the power line and the surrounding area as presented in figure 2.

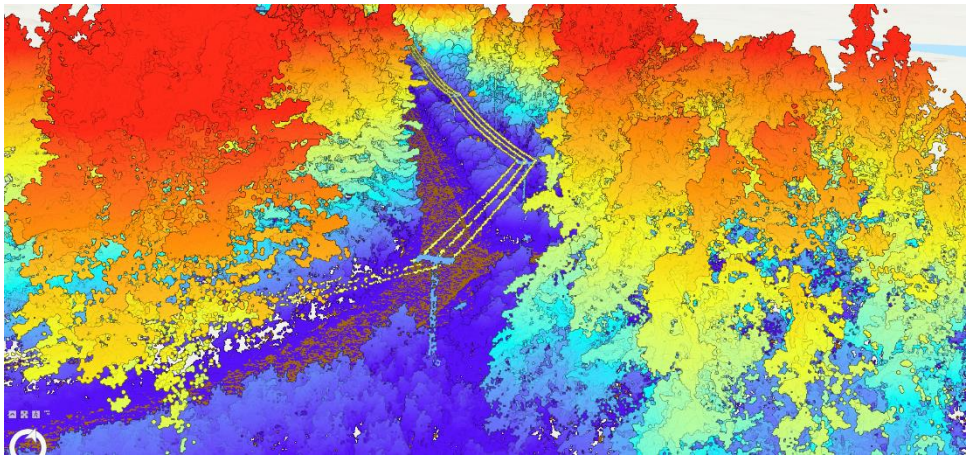

Figure 2. 3D LiDAR model generated of power line and surrounding area

LiDAR model is used for identifying need for clearance in the vicinity of the power line from trees. Identifying clearance needs allows for anticipating future disruptions such as falling trees or branches that can cause faults to power lines leaving people with disturbances in electricity distribution. Predictive maintenance is allowing for maintenance before anything causes faults in the power line, rather than reactive maintenance after a failure or a fault. (Mobley, 2002)

1.2.2. Aerial imaging

The second flight, equipped with standard camera attachment is carried out for inspection of condition of the lines and poles and visual confirmation to the results from the LiDAR scan. LiDAR scan flags potential clearance needs, and the aerial image can then be used to verify or refute the clearance notice, if there are discrepancies noticed between data flagged by LiDAR scan and visual observation from the aerial images.

1.3. Goal and scope

The objectives of this thesis are to create a detailed overview of operational greenhouse gas (GHG) emissions or electrical grid inspection services provided by Evision Oy. It aims to identify strategies for minimizing the operational greenhouse gas emissions. Additionally seeking the to answer the question whether there are alternative strategies to enhance either the efficiency, to reduce GHG emissions, or both for the inspection process. The focus is

placed on the inspection service due to its predictable and scalable nature, which suggests that the model generated has the greatest likelihood to be adaptable to the other services provided by Evision.

Scope of the thesis is limited to the direct GHG emissions of the inspection service data gathering, and the lifecycle assessment of the products utilized for the inspection service. Inclusion of the lifecycle assessment stems from the necessity to understand the true greenhouse gas emission performance of different scenarios, rather than concentrating purely on direct GHG emissions. This allows for more comprehensive approach for understanding the greenhouse gas emissions of each scenario.

1.4. Thesis structure

The thesis is divided in two primary parts: theoretical framework and a practical case study. Theoretical part focuses on the methods of calculating carbon footprint and conducting lifecycle assessment. The case study applies the methods from theoretical part for calculating carbon footprint for maintenance inspection and optimizing maintenance inspection carbon footprint. The values for calculating carbon footprint are based on values reported by the company and literature sources. The data for lifecycle assessment is combination of values provided by producers of the vehicles and materials used for the inspection service and literature sources. In addition to this some assumptions are made.

The primary objective for carbon footprint calculations is to create a model to evaluate potential GHG emissions for future projects. Secondary objective is to identify GHG emission hotspots in maintenance inspection and to find potential opportunities for GHG emission reduction during the lifecycle of the service.

2. Power grid

The power grid of Finland consists of main grid, High-voltage distribution grid, and local distribution grid. High-voltage distribution grids are responsible for regional electricity distribution. The local distribution grid has the option to access the main grid by either using the high-voltage distribution grid or connecting directly to the main grid. (Energiateollisuus, 2024)

2.1. Structure of the power grid

The backbone of the power grid is the main grid, consisting of 400 kV, 220 kV, and 110 kV transmission lines. The purpose of the main grid is to connect major power plants, factories, and distribution networks to allow for effective operation of the power grid. The main grid also connects the Finnish power grid as a part of a Nordic synchronous area. The main grid, which is owned and operated by Fingrid Oyj, consists of around 14 000 km of transmission line and over 120 substations. The responsibilities of Fingrid include grid monitoring, construction, and development of the grid, and reliability of electricity delivery to distribution networks. (Fingrid, 2024a)

Distribution grid includes both high-voltage distribution grid and local distribution grid. Local distribution grid is defined as grid with nominal voltage below 110 kV. Distribution grid is divided between several companies responsible for regional electricity transmission. Currently, there are 77 distribution grid operators and nine high voltage distribution grid operators. (Energiavirasto, 2024)

Becoming a distribution grid operator requires a permit that allows for operation in both local distribution grid and high-voltage distribution grid. The permit describes geographic responsibility area. Because a distribution grid is a natural monopoly, there is strong regulation imposed on the obligations and responsibilities of the operator. (Energiavirasto, 2024)

2.2. Regulation of distribution grid

Regulation for distribution grids is required due to them being naturally monopolies. This is because of the economic unviability to build competing grids alongside an already operational network in the area. Alongside the economic issues regarding viability the Energy authority of Finland gives permits based on the area of operation that enhance the natural monopoly for the distribution grid but allow for stronger regulation. (Energiavirasto, 2024)

Finnish power grid is highly regulated by two laws, firstly the electricity market act 588/2013 (Sähkömarkkinalaki 588/2013, 2013) and secondly the electrical safety act 1135/2016. (Sähköturvallisuuslaki 1135/2016, 2016). The laws relating to distribution grid are enforced by Finnish safety and Chemicals Agency (Tukes).

2.2.1. Electricity market act

The purpose for electricity market act is to ensure the conditions for efficient, reliable, and sustainably functioning energy markets. Providing security of supply, competitive prices, and reasonable service principles for the end-users. (Sähkömarkkinalaki 588/2013, 2013)

Companies operating in the electricity field, both in production and distribution are obligated by the electricity market act to take care of their customers and network users' electricity related services. According to the electricity market act § 18, Network operators are required to offer their services to all electricity market participants equally and without discrimination, without unjustified condition that restrict competition in electricity trade. (Sähkömarkkinalaki 588/2013, 2013)

According to electricity market act § 51, the distribution network needs to be designed, constructed, and maintained in such a way that the network meets following requirements for reliability set by the operator of the main grid. Requirements laid down in electricity market act § 51 are about electricity distribution disturbances caused as a result of a storm or snow load. For urban planned areas the maximum time for disturbances allowed in electricity market act § 51 is 6 hours and in non-urban areas the maximum is 36 hours. (Sähkömarkkinalaki 588/2013, 2013)

Ministry of economic affairs proposed an amendment to the electricity market act. The proposed amendment seeks to move the national law towards EU electricity market directive, with focus on adapting electricity trading regulations especially on decentralised renewable energy production. The proposal aims to enhance the consumer rights relating to energy markets, by introducing measures against unfair practices in retail markets, and promoting smart grid ideals. Key takeaway from the proposal is the separation of network operations and competitive business, such as energy storage and EV charging. The proposal is effective from 1.6.2024, and electricity dispute board is established to be in effect from 1.9.2024 onwards. (työ- ja elinkeinoministeriö, 2022)

2.2.2. Electricity safety act

The purpose of electrical safety act 1135/2016 is to provide legal regulation to ensure the safety of electrical equipment and installations, and to prevent harmful effects caused by said equipment and installations. Additionally, the electrical safety act 1135/2016 aims to protect the rights of those harmed by electrical equipment or installations, and to ensure conformity and free movement of electrical equipment. (Sähköturvallisuuslaki 1135/2016, 2016)

Electrical safety act § 44 creates a classification for electrical installations and inspection requirements as well as maintenance requirements for the types of electrical installations. This classification system does not apply to communication networks, elevators, aircraft, or electrical installations in vehicles (Sähköturvallisuuslaki 1135/2016, 2016)The electrical safety act § 44 defines class 1 electrical installations as either residential buildings with two or more residential units, or electrical installations in other than residential buildings with the main fuse having nominal current of more than 35 amperes and does not belong to class 2 or 3 (Sähköturvallisuuslaki 1135/2016, 2016)The electrical safety act § 44 defines class 2 electrical installations as either installations with nominal voltage of over 1 000 volts, excluding installations with only devices or systems fed with nominal voltage up to 1 000 volts, or low voltage connections with a power of over 1600 kVA (Sähköturvallisuuslaki 1135/2016, 2016). Electrical safety act § 44 defines class 3 electrical installations as systems part of power grid operated by grid operators, such as distribution grids, transmission grids, or substations. (Sähköturvallisuuslaki 1135/2016, 2016)

The electrical safety act § 49 legislates the inspection and maintenance of classified electrical installations. Class 1 and 2 installations have to be inspected every 10 years excluding

residential buildings. Class 3 installations have to be inspected every 5 years. The owner of the installation is responsible for inspection and maintenance of the installation. (Sähköturvallisuuslaki 1135/2016, 2016)

The supervisory control of electrical safety act is defined to be controlled by Tukes in electric safety act §87, and the enforcement of the electrical safety act is defined in §88 as the electrical safety official and acting as electrical safety official is Tukes. (Sähköturvallisuuslaki 1135/2016, 2016). Electrical safety act §89, §91, and §93 legislate the means of inspecting electrical equipment and installations (Sähköturvallisuuslaki 1135/2016, 2016).

3. Maintenance

Maintenance is defined as all technical, administrative, and managerial actions intended to retain the performance of an item to allow it to perform its functions. The goal of maintenance is to extend the life cycle of the maintained item (Smith and Mobley, 2008, pp. 3–25). Inspection and maintenance are required in the electrical safety act (1135/2016, 2016) for all electrical installations, and are stricter for class 3 installations such as distribution grids (Sähköturvallisuuslaki 1135/2016, 2016).

3.1. Types of maintenance

Maintenance can generally be separated into preventative and corrective maintenance. The separation is based on whether the maintenance is focused on preventing an issue or if a fault is already causing disturbance. Both main categories have subcategories presented in figure 3. (SFS-EN 13306, 2017)

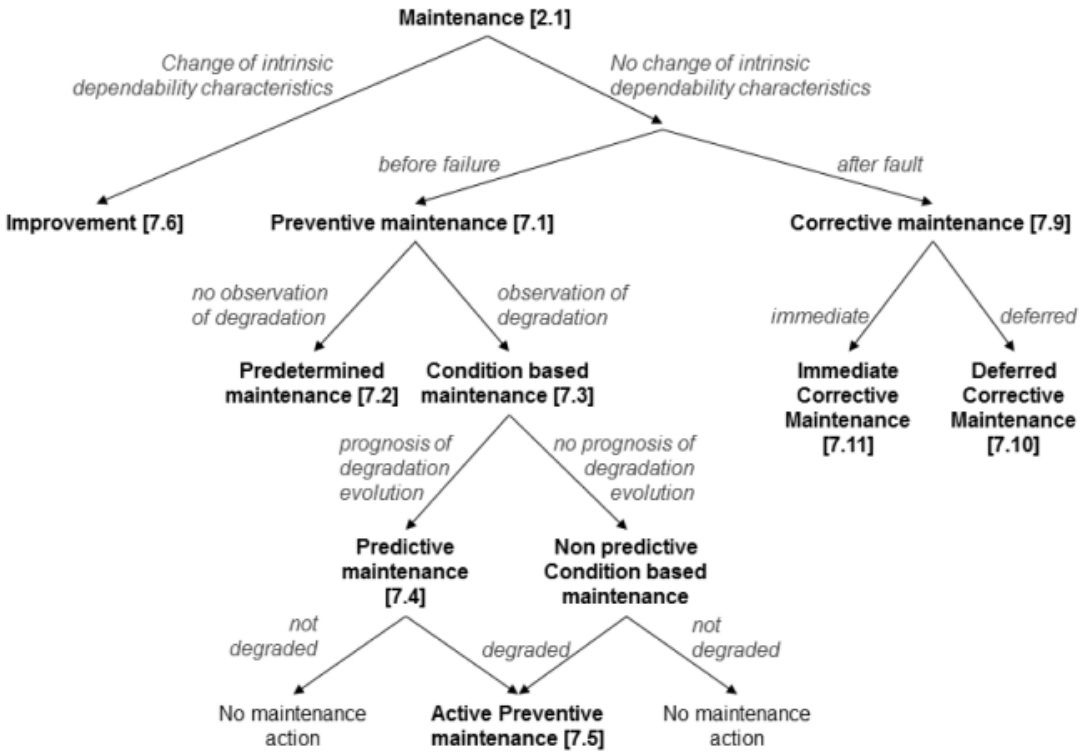

Figure 3. Maintenance types as presented in SFS-EN 13306 standard. (SFS-EN 13306, 2017)

3.1.1. Corrective maintenance

Corrective maintenance is defined as maintenance that occurs after recognition of a fault, aiming to restore the intended function of the item in question. Corrective maintenance has 2 subcategories deferred- and immediate corrective maintenance. (SFS-EN 13306, 2017)

Deferred corrective maintenance is corrective maintenance that is not immediately carried out after fault recognition. Deferred corrective maintenance is used in situations where the fault is not causing major disruption for the use of the item and the maintenance can be scheduled for later in accordance with rules. (SFS-EN 13306, 2017)

Immediate corrective maintenance is done without delay after fault recognition. immediate corrective maintenance is used when the fault is either serious enough or causing major disruption for the usage of the item not allowing for scheduled maintenance. (SFS-EN 13306, 2017)

3.1.2. Preventative maintenance

Preventative maintenance is the other main category of maintenance. The main role of preventative maintenance is to mitigate the degradation and probability of a failure in an item. (SFS-EN 13306, 2017)

Preventative maintenance is an umbrella for many different subcategories of maintenance. The subcategories under preventative maintenance all focus on prevention of a fault or degradation rather than repairing issues causing disruption. (SFS-EN 13306, 2017)

3.1.3. Predetermined maintenance

Predetermined maintenance is maintenance that follows preset intervals often time intervals or number of unit use intervals, without prior investigation about the conditions of the item (SFS-EN 13306, 2017).

An example of predetermined maintenance is an oil change for a vehicle. Done on either time interval or unit of use interval based on the distance driven with said vehicle.

3.1.4. Condition based maintenance

Condition based maintenance is done based on the actual conditions of the equipment determined based on monitoring or a diagnostic system. Condition based maintenance allows for resolving issues before they cause major disruption to the process (Yang, 2004).

Condition based maintenance has two subcategories predictive- and non-predictive condition based maintenance. The subcategories can be differentiated based on whether a forecast generated by inspection or data analysis was used to determine the need for the maintenance. (SFS-EN 13306, 2017)

3.1.5. Non predictive condition based maintenance

Non predictive condition based maintenance is maintenance based on inspected physical conditions such as condition based maintenance, but it is conducted without using predictions made based on the physical conditions such as future deterioration, or possibility of fault in the future. (SFS-EN 13306, 2017)

3.1.6. Predictive maintenance

Predictive maintenance on the other hand is condition based maintenance following a prediction based on data analysis of degradation. (SFS-EN 13306, 2017)

The largest benefit of predictive maintenance is its ability to significantly reduce operational outages and improve the efficiency of the system (Mobley, 2002). The core of predictive maintenance is the use of analytics and machine learning algorithms to predict possible causes for failures before they materialize in a fault. Pre-emptive strategies are very different to traditional reactive maintenance methods, which address issues post failure. (Levitt, 2011, vol. 1)

3.1.7. Smart maintenance

Maintenance inspection done by Evision falls under the smart maintenance. Smart maintenance is often used interchangeably with predictive maintenance, but they refer to different concepts within the preventative maintenance strategies. Main difference between smart and preventive maintenance is usage of a broad variety of different technologies such as AI tools, machine learning, and data analysis to allow for predictive maintenance. (Salonen, 2023, pp. 366–374). In case of Evision the data gathered with LiDAR is fed through machine learning algorithms to identify potential issues for power lines. Smart maintenance allows for active preventative maintenance, as predictive maintenance.

According to Salonen (2023) “These techniques are vital in order to prevent critical failures and disturbances to occur” when referring to smart- and preventative maintenance methods. (Salonen, 2023, pp. 366–374)

4. Unmanned aerial vehicles

Unmanned aerial vehicle (UAV) also known as a drone is a powered flying system that does not carry a pilot inside the system and can be either remotely piloted or operated autonomously using on-board systems to navigate (Harvard, 2024). Drones have multiple different uses depending on the type and size of the drone. Drones can be categorized into four main categories based on the build of the drone multi-rotor drones, fixed-wing drones, single-rotor drones, and fixed-wing hybrid vertical take-off and landing (VTOL) (Rennie, 2016).

4.1. Multi-rotor drone

Multi-rotor drones (see figure 4) are the most used category of drone for civilian use, both professional and recreational. Multi-rotor drones are relatively small drones with great controllability, making them a versatile type of drone for multitude of uses. The main advantages of multi-rotor drones are the ease of use, cost effectiveness, and easy installation of different types of attachments such as cameras. The main disadvantages for multi-rotor drones are related to their low flight time and high energy consumption. (JOUAV, 2024)

Multi-rotor drones come in different styles with quadcopter being the most common type of multi-rotor drone. Higher payloads for multi-rotor drones requires larger drones which usually means upgrading the number of rotors in the drone from 4 in quadcopter to six in hexacopter or eight in octocopter. (Rennie, 2016). Adding rotors makes the drone harder to control and causes the drone to consume more energy due to added weight. Multi-rotor drones have short flight time, often sub one hour, this leads to tasks that take more time than the flight time of a single battery requiring several batteries to complete (JOUAV, 2024).

Figure 4. DJI Matrice 300 RTK (DJI, 2024a)

4.2. Fixed-wing Drones

Fixed-wing drones (see figure 5) are built from a rigid chassis that works more like an airplane rather than the traditional drone which works more like a helicopter. Fixed-wing drone provides vertical lift using aerodynamic wings rather than rotors (Rennie, 2016). Fixed-wing drones only require rotors for moving forward, this enhances the flight speed and flight time of the drone (JOUAV, 2024).

Main advantages for fixed wing drones are in the form of ability to cover a larger area due to the longer flight time of couple of hours. Fixed wing drones can also be combustion engine powered providing up to 16 hours of flight time. (Rennie, 2016)

Disadvantages of fixed-wing drones include cost, limited manoeuvrability, and space-, equipment requirements. Fixed wing drones are usually more expensive than multi-rotor drones and lack the manoeuvrability due to them only having a rotor to generate thrust, limiting the ability to stay still in the air. The take-off and landing also requires more space than other drone types and might require specialized equipment. (JOUAV, 2024)

Figure 5. Fixed-wing drone on the ground (JOUAV, 2024)

4.3. Single-rotor drone

Single-rotor drones (see figure 6) or helicopter drones are generally durable and have design similar to that of a helicopter. Single-rotor drones are powered by a single rotor generating lift and thrust, with a tail rotor to provide controllability and stability. (Rennie, 2016)

The main advantages for single-rotor drones are vertical take-off and landing (VTOL), long flight times with fuel powered combustion engine, and greater capability with payloads. Main advantage is with the flight time provided by combustion engine that removes the need for batteries allowing for smoother operation. (JOUAV, 2024)

Downsides for single-rotor drones relate to the cost and difficulty to operate. Single-rotor drones tend to be larger than other categories of drones making them generally more expensive. The similarity to helicopters increases the operational difficulty making them require more training to operate. The common large size combined with being difficult to operate makes single-rotor drones more dangerous. (JOUAV, 2024).

Figure 6. PDH-GS120 Fuel powered single-rotor drone (Prodrone, 2024).

4.4. Fixed-wing hybrid VTOL drones

Fixed-wing hybrid VTOL drones as the name suggests are a hybrid between multi-rotor drone and a fixed-wing drone. Fixed-wing hybrid VTOL drones offer the manoeuvrability of multi-rotor drone. Another perk from multi-rotor drones is the capability for VTOL. Benefits from fixed-wing designs include better flight time due to the aerobics of the drone. (Rennie, 2016)

Main advantages of the hybrid drones are the increased manoeuvrability compared to fixed-wing drones. The improved flight time compared to multi-rotor drones offering the best of both worlds. (JOUAV, 2024)

The downside for hybrid drones is their advanced design and technology making them harder to operate and increases the cost of the drone. (JOUAV, 2024) Figure 7 shows LHTechUAV 25kg Electric Vertical lift Fixed wing (VTOL) drone.

Figure 7. LHTechUAV 25kg Electric Vertical lift Fixed wing (VTOL) drone (LHTechUAV, 2024)

Table 1. Advantages and disadvantages for drone types

Drone type	Advantage	Disadvantage
Multi-rotor drone	• Good manoeuvrability • Vertical take-off and landing • Ability to hover	• Short flight time • High energy consumption
Fixed-wing drone	• Longer flight time • Lower energy consumption • Aerodynamic flying	• Harder to operate • No vertical take-off and landing • Requires space and/or equipment to take-off and land
Single-rotor drone	• Vertical take-off and landing • Long flight time	• Harder to operate • price
Fixed-wing hybrid VTOL drone	• Vertical take-off and landing • Ability to hover • Long flight time	• Harder to operate • Price

5. Methodology

This chapter will go over the methodology and principles used in order to calculate the carbon footprint for drone-based maintenance inspection. This thesis mainly uses carbon footprint which is a climate based subcategory of Life-cycle Assessment for parts of the analysis. Lifecycle Assessment and calculating carbon footprint are based on international ISO standards.

Theoretical framework goes through the aforementioned methods from Lifecycle Assessment (LCA) and the ISO standards for LCA followed by carbon footprint calculations and the ISO standard related to carbon footprint. The order is due to the ISO standard for carbon footprint superseding the ISO standards 14040 and 14044 for LCA. (ISO 14067, 2018)

5.1. Lifecycle assessment

Lifecycle assessment (LCA) is a method used to evaluate the environmental impacts of a product, service, or process within limited scope. A common scope is cradle to cradle (prev. cradle to grave). This scope serves as a good example to provide the basic knowledge on what is often included in LCA. Cradle to grave means that environmental impacts are considered from raw material extraction through processing, manufacturing, distribution, use, maintenance, to end of life. (ISO 14040, 2006)

LCA was created due to growing concern for the environment and a need for scientific approach to assess the environmental impacts of products and services. The primary purpose behind LCA is to identify opportunities to improve the environmental performance of a product or a service in different points withing their lifecycle. LCA does not reduce the environmental impacts, but it generates a tool to help in policy making, policy and process design, and planning. LCA serves as a tool to understand environmental impacts, following the insights provided by LCA can lead to more sustainable products, services, or processes. (Jeroen,B. et al., 2011, pp. 90–96)

LCA follows set of international ISO standards. Key standards being EN ISO 14040:2006 and EN ISO 14044:2006. Standards ensure consistency and credibility for the LCA process. (ISO 14040, 2006)

5.1.1. ISO 14040

The ISO 14040 standard provides standard framework and principles for conducting LCA studies. The standard is essential for generating a reliable, consistent, and credible evaluation of environmental impacts for entirety of the process, product, or services life cycle. The standard outlines that LCA study should include four phases (ISO 14040, 2006).

The four phases are,

1) Goal and scope definition consists of definition of system boundaries, goal of the study, and the main assumptions made for the study.
2) Life cycle inventory (LCI): consists of data collection within system boundaries.
3) Life cycle impact assessment (LCIA): consists of assessing the environmental impacts based on the data collected in LCI phase.
4) Interpretation consists of analysing the results of LCIA phase and making recommendations based on the findings.

LCA studies need to be comparable for them to be reliable. For comparability the assumptions made in each step of the study have to be made clear and only studies that make similar assumptions are comparable with each other. This leads to requirements from both ISO 14040 and ISO 14044 to make requirements to the assumptions that can be made to make the studies reliable and transparent. (ISO 14040, 2006)

5.1.2. ISO 14044

Following the framework for conducting LCA study provided in the ISO 14040 standard, ISO 14044 provides guidelines for practical implementation of LCA studies. ISO 14044 offers guidance for each phase of the LCA study facilitating implementation of LCA study. A significant difference between the standards is that ISO 14044 includes provisions for reviewing and reporting requirements to ensure quality of the study. (ISO 14044, 2006)

ISO 14044 builds on top of the four-phase structure from ISO 14040: Goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. This is achieved through detailed explanations and requirements for each phase. ISO 14044 emphasizes the need for reliable documentation and transparency in assumptions made and the data collection practices ensuring reproducibility of the LCA study. (ISO 14044, 2006)

A key focus of ISO 14044 is the emphasis on methodological consistency. Following the requirements set out in the standard ensure consistency in conducting LCI and LCIA phases, which in turn guarantees that the LCA study follows a consistent approach that leads to better reliability and repeatability of the study. (ISO 14044, 2006)

Another aspect highlighted in ISO 14044 is transparency in reporting. The standard requires that all assumptions, methodologies, and data sources used in the study are clearly documented. This is necessary for the reliability, repeatability, and critical review process. Additionally, transparency increases the relevance of the study. (ISO 14044, 2006)

5.2. Carbon footprint

Carbon footprint quantifies the total GHG emissions generated during a products, services, or processes lifecycle including energy consumption, transportation, fuel consumption, direct emissions, and indirect emissions from generating a product or service delivery. Carbon footprint is measured in CO_2e or carbon dioxide equivalent emissions. (Klöpffer and Grahl, 2014)

Carbon footprint is often presented as carbon dioxide equivalent or CO_2eq or as mass $t\,CO_2eq$. CO_2eq is a measurement used to normalize different greenhouse gasses (GHGs) based on their global warming potential (GWP) to the GWP of carbon dioxide (CO_2) allowing for calculation using multiple GHG emissions gasses. Other notable greenhouse gasses include methane (CH_4) and nitrous oxide (N_2O). Most common use of GWP is GWP_{100} which translates to the impact of each GHG to equivalent amount of CO_2 that would have the same effect over 100-year period. (Lynch et al., 2020, p. 44023)

There are three common ways for calculating carbon footprint: GHG protocol standards, EN ISO 14064 part 1, and EN ISO 14067. GHG protocol is a global standardized framework developed by World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) (Greenhouse Gas Protocol, 2011). Part one of EN ISO

14064 outlines specifications for designing, developing, managing, and reporting GHG inventories. It also includes requirements for GHG emission removal, inventory quality management, inventory reporting, internal auditing, and organizations responsibilities in verifying the GHG emissions and emission removals (ISO 14064, 2019). EN ISO 14067 provides principles, requirements, and guidelines for carbon footprint assessment, based on LCA. ISO 14067 covers entire life cycle of a product or a service aiming to standardize the way that carbon footprint is calculated and reported. The goal of the standardization is to generate a reliable system to support claims related to carbon footprint (ISO 14067, 2018).

6. Case Evision

Evision case works as the basis for understanding the environmental impacts related to smart maintenance inspection of power grids. This thesis provides the baseline and evaluation to reduce the emissions of the smart maintenance operations.

The drone-based maintenance inspection is the current baseline for the maintenance inspection. The maintenance inspection allows for condition-based maintenance to occur instead of predetermined maintenance. Inspection for maintenance needs is required by law in the electrical safety act (Sähköturvallisuuslaki 1135/2016, 2016). Without drone-based smart systems the maintenance inspection is done by driving to the area and walking the same route as the drone would fly inspecting the need for maintenance of the power line. The issue regarding this is the effectiveness of walking under the line and the skill required to determine the need for maintenance. The other options beside walking the power line or using a drone for inspection are helicopters or snowmobiles.

First the GHG emissions for drone-based inspection have to be assessed to produce a baseline comparison point that has the potential to find emission hotspots and provide insight for potential emission reduction. Maintenance inspection has three stages operation planning, data collection, and data processing and storage. All three stages contain emission causing activity with a large majority of emissions caused by data collection, due to data collection being the only stage which causes emissions outside of computer electricity consumption. The emissions from other stages data storage and data processing revolve around electricity consumption for computers and are a small fraction of all the emissions and cannot be defined within a functional unit thus they are not considered for this thesis.

Emissions caused by data collection are categorized into 2 categories direct and indirect. Direct emissions are caused by electricity consumption from the drones, fuel consumption by the vehicles used, and fuel consumption by a power generator used to charge the drone batteries. Power generator is used because the drones do not have enough battery pairs to conduct an entire day worth of flights with just grid electricity.

Indirect emissions are lifecycle emissions such as emissions from producing the materials used for maintenance inspection, emissions from maintaining and using materials for example replacing tyres for the vehicles in use, and end of life emissions for materials used.

Figure 9 presents the system boundaries for the carbon footprint calculations. The maintenance inspection operation consists of three stages operation planning. Which includes flight planning. The second step is the data collection stage which includes collecting drones from the storage driving to the inspection area, setting up the take-off location, flying the planned flights, packing up the take-off location, driving between different take-off location repeating for the length of the workday, and after the last take-off location driving back to the drone storage. The final phase of the maintenance inspection is data processing and storage, which consists of uploading the flight data, LiDAR data and taken photographs to be processed, processing the data collected, and storing the collected data in cloud. The system boundary is set to only focus on the carbon footprint of the data collection phase, due to the carbon emissions from the other two phases being purely from data storage and computer use.

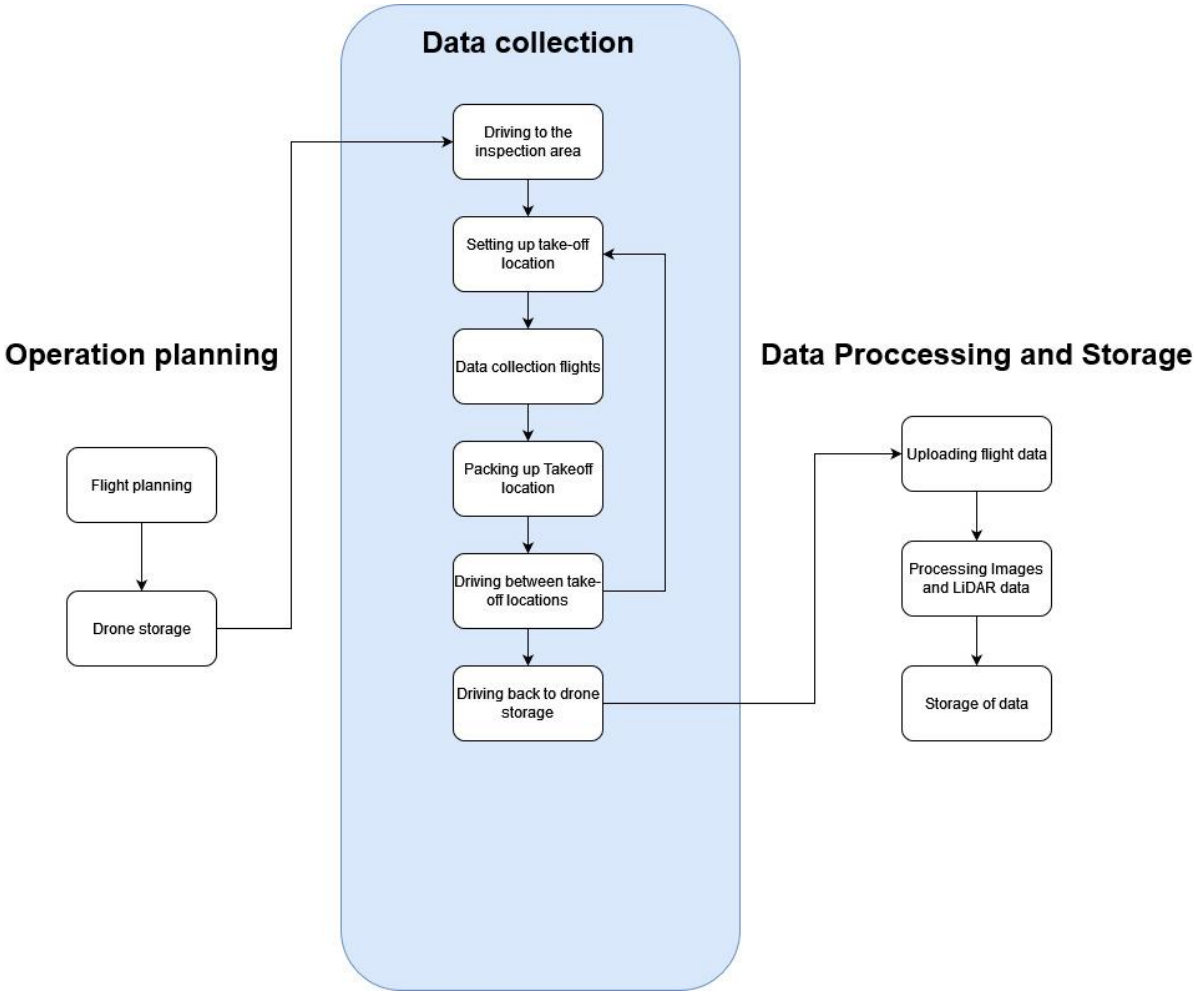

Figure 9. system boundaries for operational footprint.

6.1. Data collection and management

The data used for this thesis is based on data measured from the maintenance inspection activities by Evision during the year 2023. Flight data was collected from flight logs for the drones and vehicle fuel consumption data was gathered from vehicle use invoicing by contractors and company vehicles. A model was generated based on the real life data gathered for the maintenance inspection activity. The model was generated based on the entire flight data split into averages for 100km inspection chunks or functional units. Average values were used instead of median values, because there were no major outliers that would have affected the average value in the data set, thus median value was not necessary.

The models presented in chapter 7. Reduction options are generated based on the real life model created for baseline calculation and adjusted to fit the emission reduction scenario under calculation based on best available data, or best estimation. The models generated are not based on any previous research and instead are generated for the isolated specific scenarios present for the operational area of Evision.

6.2. Functional unit

Functional unit (fu) is a quantified description of service that serves as a reference base for calculations relating to the subject allowing for scalability in impact assessment (Traverso et al., 2019, pp. 1–10). Functional unit in this thesis is defined as the emissions caused by inspecting 100 km of electrical grid. The value of 100 km was selected to ensure that fluctuations that may appear in smaller sample sizes would be negated. Fluctuations in the data appear due to differences between distances to the areas needing inspection, road layouts of the areas, and grid topology.

6.3. Assumptions

Assumptions made in order to produce the baseline emissions are applied to every suggestion to enhance the comparability of the carbon footprint models provided.

In terms of normalizing the differences of inspection operations daily averages through entire projects are used for each step. This assumption was made to normalize the dataset. In reality there is variance in data caused by multitude of reasons that are not repeatable. This non repeatable variance is caused by factors such as weather, human efficiency, area layout, flight restrictions, thus the variance is acknowledged but the dataset is normalized to daily averages.

The drone battery usage per flight is assumed to always be 70% of the total charge of a new battery, according to manufacturer reported specifications for the batteries. Batteries lose their charge potential during their lifecycle. This reduction of operational capacity for the batteries is not considered for the sake of the calculation, due to the uncertainty of the health for each individual battery set creating variance to the data, thus it is assumed that each battery is brand new and has not gone through charge cycles reducing the health of the batteries.

Power generators are used to charge drone batteries on the field since a drone patrol on the field does not have enough battery capacity to fly for the entire day without charging batteries during the workday. Power generators and vehicle inverter systems are considered to be in accordance with 2-kW diesel power generators presented in a 2012 study by Jakhrani

et al. (2012, pp. 78–81). The rationale for focusing on fuel consumption per kWh 2-kW power generators use small engine gasoline and vehicles with inverters use diesel. This provides the opportunity to separate the emissions caused by inverter use and power generator use. The fuel consumption used from the study is 0.42 l/kWh (Jakhrani et al., 2012, pp. 78–81).

The distances to inspection areas and the distances between take-off locations were normalized based on an estimate of the road distance compared to the flight distance. The road distance was estimated to be 1.5 times the aerial distance by Niko Räsänen (2024, personal communication). Niko Räsänen is the head of business, smart maintenance for Evision Oy. The estimation was created based on the take-off location map data overlaid with road map for the inspection areas, leading to the estimation for the dataset used for this thesis.

6.1. Baseline scenario

Baseline scenario is generated based on the operational footprint of the maintenance inspection activity and the lifecycle emissions of the materials used to provide maintenance inspection. This includes operational emissions, drone indirect emissions, battery system indirect emissions, and vehicle indirect emissions.

6.1.1. Operational fuel and electricity consumption

Data for calculating direct emissions from maintenance inspection is based on fuel and electricity consumption of the maintenance inspection operation. Fuel and electricity consumption are measured from major completed projects during 2023.

Fuel consumption data is derived from fuel usage of the vehicles used to transport the drones from storage facilities to take-off locations and back to storage facilities. This dataset is compiled from driving logs from the vehicles, fuel invoices, and service invoices. Average distance driven for each functional unit was recorded at 805.90 km, with daily average distance per drone unit being 153.5 km/day.

Driving between take-off locations requires more distance to be covered than just the distance between take off locations due to road layout in the area of operations. The distance was estimated to be around 1.5 times the distance between take off locations by Niko

Räsänen (2024, personal communication) and by comparing take-off location maps overlaid with road maps, the estimation matches the reality of distances for the dataset used for this thesis. The estimation is based on the data gathered from the area. For different regions the estimation might be a poor estimate due to the differences in grid- and road layouts.

Daily average inspection by drone was 19 km per day. Using the estimation for driving in the inspection area the average distance travelled by car within the inspection area was 28.6 km per day, with average distance to the inspection area being 62.5 km.

Data for calculating electricity consumption for operational activities is derived from the drone flight logs. The flight logs show the take-off locations and distance flown from each take-off location. The drones are powered DJI TB 60 batteries, that have capacity of 5.935 mAh and voltage of 52.8 V reported by the producer (DJI, 2024b). By using this information, the energy consumption per battery is calculated using equation 1.

$$E(kWh) = \frac{Q(mAh) * U(V)}{1\ 000\ 000} \quad (1)$$

E The energy content of the battery

Q The electric charge of the battery

U The voltage of the battery

The full charge for a battery is calculated to be 0.3134 kWh. Drones use two batteries per flight and fly two flights per inspection route, meaning that there are four battery charges used per inspection route. Each inspection route is flown twice, once with LiDAR attachment and once with a camera attachment. Most take off locations have multiple inspection routes attached, and each route is flown twice. For each flight the drone battery is fully charged to 100% charge before the flight and flown until 30% charge remains, leading the electricity usage of 0.439 kWh per flight. The average distance per take-off location is 3.304 km. with a daily average 5.76 inspection areas per day, it takes 5.25 flight days to complete 100 km of area inspected. By combining the average flight distance and electricity consumption during flights, the total electricity consumption needed to complete a functional unit is calculated at 26.628 kWh. When accounting for the total energy efficiency of a lithium-ion battery the energy efficiency ranges from 77% to 90% (Lin et al., 2023, p. 109386). Based on this a total energy efficiency of 85% is used for this thesis. When energy efficiency is accounted for the total energy consumption for a functional unit is 31.33 kWh/fu

Current operational capacity for drone operations is three sets of batteries per drone patrol are currently in use limiting the flights per day without use of external support. The external support is power generator, or the transport vehicle engine equipped with inverter, which allows for charging the battery sets in the field. On daily basis the three first flight sets can be completed with batteries charged using grid electricity. Any flights after the first three flight sets are done with batteries charged using electricity generated by the portable power generator or transport vehicle equipped with inverter.

The total fuel consumption for vehicle use was 8.54 litres/100km based on the fuel invoicing data included in the dataset. The data is based on the fuel invoicing since there is no measured data for fuel consumption from the field conditions, thus data based on capita spent is used.

In a study in 2012 (Jakhrani et al., 2012, pp- 78-81) estimations for portable diesel generators was considered. The fuel consumption for a 2-kW power generator was recorded at 0.42 l/kWh, and the efficiency was calculated to be 52% for a 2-kW diesel generator. The power generator used to charge drone batteries is a 2-kW generator, leading to the findings from the study to be used for the purpose of understanding the fuel consumption of portable generators. In addition, for the portable generators the vehicle inverter system is evaluated based on the findings of this study to report the fuel consumption during charging the batteries. The inverter system works with the vehicle engine running while the vehicle is stationary so, it is assumed that the vehicle acts as a 2-kW diesel powered generator while charging.

In the dataset, 52.08% of the electricity consumption was charged with grid electricity and 47.92% of electricity consumption was generated with power generators. Thus, the dataset has grid electricity consumption of 16.32 kWh/fu, and power generator use of 15.01 kWh/fu.

From the 15.01 kWh/fu electricity generated using power generators the fuel consumption for charging can be calculated according to the study by Jakhrani et al. (2012). Giving the fuel consumption for charging per functional unit to be 6.30 litres.

6.1.2. Drones

The Lifecycle data for drones is based on a study focusing on GHG emissions of drone deliveries by Figliozzi (2017, pp. 251–261). In the study vehicle phase emissions are calculated using raw material acquisition, raw material processing, drone manufacturing,

distribution, and end of life using the GREET (the Greenhouse gasses, Regulated emissions, and Energy use in Transportation) model. The GREET model is a model created to estimate full fuel cycle emissions for transport fuels (Subramanyan et al., 2008, pp. 278–285). Emissions caused by creating a drone body are 56 $kg\ CO2_e$. As drone lifetime is set at three years, the indirect lifecycle emissions of the drone is dependent on the number of days the drone is flown during the year. Due to the uncertainty of the drone use, the indirect emissions caused by drone production are set according to a study conducted by Thiago Rodrigues, et al. (2021) at 1.8 $g\ CO2_e/km$. Based on this data the emissions per 100 km functional unit are 72 $g\ CO2_e/fu$. The emissions per functional unit are calculated by first dividing the total indirect emissions caused by drones with the lifecycle of the drone. That value is 1.8 $g\ CO2_e/km$ After that the value is multiplied by the distance required for a functional unit which is 400 km of flight. 100 km of inspection flight 100 km of return flight with camera attachment, 100 km of inspection flight 100 km of return flight with LiDAR attachment.

6.1.3. Batteries

A charge cycle is defined as charging a battery system by the manufacturer. The cycles are calculated within the control software of the drone as per the manufacturer maintenance guide (DJI, n.d.). Charge cycles are used due to battery degradation, each charge cycle causes batteries to lose their capacity retention potential. The batteries are considered to be at the end-of-life stage when the charge capacity reaches 80% of the original capacity (Paw and Ang, 2023, p. 107493). Batteries used by the drones are rated at 200 cycles by the producer (DJI, 2024b). For the purposes of this thesis, the producer rating of 200 cycles is used to calculate battery lifecycle emissions. The total drone battery vehicle phase, or life cycle emissions are at 435 $kg\ CO2_e$ (Figliozzi, 2017, pp. 251–261) or at 504 $kg\ CO2_e$ (Çalışır et al., 2023, p. 125543). Similar batteries as are in use were used to calculate the values for study by Rodrigues et al (2021) with the per kilometre value being 1.3 $g\ CO2_e/km$, based on this the value used for this thesis is the estimated value is used at 52 $g\ CO2_e/fu$.

6.1.4. Vehicles

Vehicles currently in use are small to medium diesel-powered internal combustion engine vehicles (ICEV), with average fuel consumption of 8.54 litres/ 100 km. A diesel-powered

light duty vehicle is estimated to have indirect GHG emissions of 38.1 $g\ CO2_e/\ km$ with 15-year lifetime and assumed 12 000 km/year (Ma et al., 2012, pp. 160–173). These values make the per functional unit emissions for vehicles excluding fuel 31.20 $kg\ CO2_e/fu$. The indirect emissions per functional unit are calculated from the aforementioned value of 38.1 $g\ CO2_e/\ km$ and multiplied by the distance driven per 100 km of electrical grid inspected which is 805.9 km

Vehicle life cycle covers the entire life cycle of the vehicle and all emissions attributed to the vehicle besides the emissions from the fuel consumption of the vehicle. Emissions included in this phase count things such as Raw materials, manufacturing, maintenance, etc. (Ma et al., 2012, pp. 160–173)

6.1.5. Emission factors

Emission factor is a representative value provided for an activity or product that relates the amount of pollutants released to the atmosphere during the activity, such as kilograms of carbon dioxide emitted from driving 100 kilometres (United States Environmental protection agency, 2023).

Emission factor value for fuel usage is the value from 2023 Greenhouse gas reporting: conversion factors by the United Kingdom government report. The emission factor for fuel is 2510 $g\ CO2_e/l$, as per the value for common diesel biofuel blend. (GOV.UK, 2023)

Emission factor used for emissions caused by electricity production is based on the 2022 residual mix of electricity production in Finland reported by the ministry of energy. The emission factor for electricity production is 40 $g\ CO2_e/kWh$, this accounts for direct emissions for electricity production in Finland for 2023 (Fingrid, 2024b).

6.1.6. Baseline footprint

The baseline footprint is calculated based on the operational consumption during the maintenance inspection, and the indirect emissions caused by the non-use phases of the vehicles and drones used in the maintenance inspection operation.

Operational consumption per functional unit consists of emissions from vehicles, emissions from energy consumption, and emissions from energy production with power generator.

Per functional unit inspected by drone an extra distance is required to be covered a vehicle which is 805.90 km, consuming 8.54 litres/100 kilometres. The total fuel consumption for a functional unit is 81.13 litres, with the emission factor for diesel biofuel blend being 2.51 $kg\ CO2_e/l$, the total emissions caused by vehicle fuel consumption are 203.64 $kg\ CO2_e/fu$. The vehicles travel to and back from the inspection area and within the inspection area, pre functional unit the distance covered during maintenance inspection is 150.01 km, and the distance covered by a vehicle to transport materials to the inspection area is 655.73 km per functional unit. This gives the fuel consumption for distance covered during inspection to be 12.82 litres, and fuel consumed for distance covered to and back from the inspection area to be 56.00 litres. Based on these numbers, the emissions for inspection area activities caused by vehicles are 32.19 $kg\ CO2_e/fu$, and the emissions caused by traveling to and from the inspection area to be 140.56 $kg\ CO2_e/fu$. Table 2 presents the values for vehicle fuel consumption and emissions caused by vehicle use during maintenance inspection per functional unit.

Table 2. Emissions and fuel consumption from vehicle use during maintenance inspection.

Total distance traveled	805.88	***km***
distance driven in inspection area	150.01	km
Distance traveled to target	655.73	km
Fuel economy	8.54	$l/100km$
Fuel consumption	68.82	l
Fuel consumption Inspection area	12.82	l
Fuel consumption travel	56.00	l
Emission Factor, fuel	2.51	$kg\ CO2_e/l$
Emissions Fuel, Inspection	32.19	$kg\ CO2_e/fu$
Emissions Fuel, Travel	140.56	$kg\ CO2_e/fu$
Emissions from vehicle fuel consumption	172.74	$kg\ CO2_e/fu$

The total electricity consumption for inspecting a functional unit is 31.32 kWh/fu, with 16.32 kWh/fu from grid electricity, and 15.01 kWh/fu from 2-kW power generator. The total emissions caused by maintenance inspections electricity consumption are 16.47 $kg\ CO2_e/fu$. The emissions caused by grid electricity are 0.65 $kg\ CO2_e/fu$, and from power generator use are 15.82 $kg\ CO2_e/fu$. Table 3 presents the values for electricity consumption, and emissions caused by electricity consumption. The total emissions caused

by baseline maintenance operation are presented in table 4 including direct and indirect emissions. Figure 9 presents the share of different direct emissions and figure 10 presents the share of total emissions.

Table 3. Emissions and electricity consumption values for maintenance inspection

Energy consumed	26.63	$\boldsymbol{kWh}$
battery efficiency	85.00	%
Total energy consumed	31.33	kWh
Generator use %	47.90	%
Generator use	15.01	kWh
Grid electricity	16.32	kWh
Generator fuel use	6.30	l
Emission factor, grid electricity	0.04	$kg\ CO2_e/kWh$
Emission factor fuel	2.51	$kg\ CO2_e/l$
Emissions from grid electricity	0.65	$kg\ CO2_e/fu$
Emissions by generator	15.82	$kg\ CO2_e/fu$
Emissions	16.47	$kg\ CO2_e/fu$

Table 4. both direct and indirect baseline emissions

Emissions electricity, grid	0.65	$\boldsymbol{kg\ CO2_e/fu}$
Emissions electricity, generator	15.82	$kg\ CO2_e/fu$
Emissions vehicle Inspection	32.19	$kg\ CO2_e/fu$
Emissions vehicle, transport	140.56	$kg\ CO2_e/fu$
Indirect emissions, Drones	0.07	$kg\ CO2_e/fu$
Indirect emissions, Batteries	0.05	$kg\ CO2_e/fu$
Indirect emissions, Vehicles	30.70	$kg\ CO2_e/fu$
Emissions total	**220.04**	$\boldsymbol{kg\ CO2_e/fu}$
Direct emissions	189.22	$kg\ CO2_e/fu$
Indirect emissions	30.83	$kg\ CO2_e/fu$

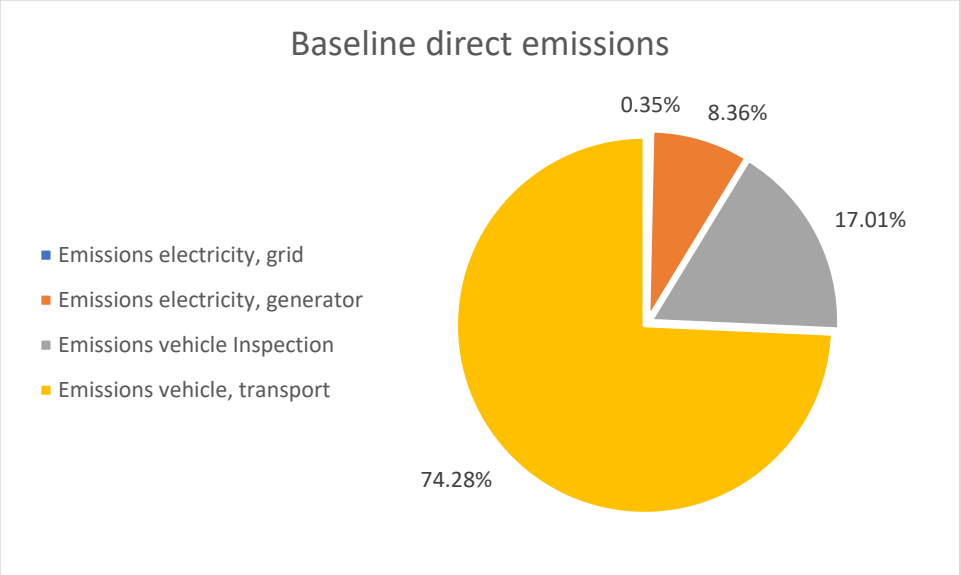

Figure 9. Breakdown of emission shares for baseline direct emissions.

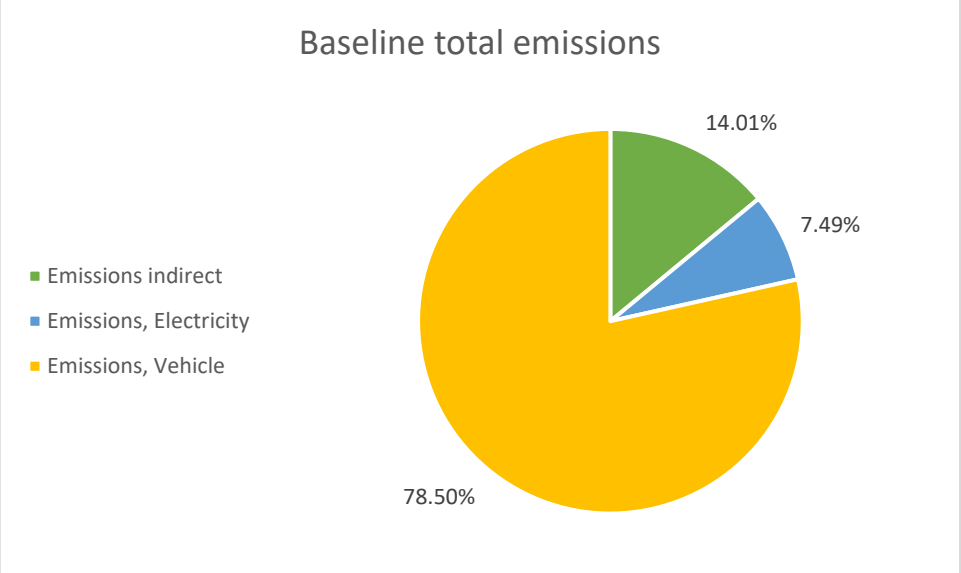

Figure 10. Breakdown of emission shares for total baseline emissions.

The emission profiles indicate that majority of the emissions caused are due to vehicle use. This is due to the high volume of travel by vehicle that happens during the maintenance inspections. The differences in the shares of emissions by electricity can be attributed due to the total emissions power generator is included in the emissions from electricity. Indirect emissions include vehicle indirect emissions, drone body indirect emissions, and battery indirect emissions.

A comparison to validate the values calculated in this thesis are values reported by Airpelago a Swedish drone maintenance inspection company. The values from Airpelago represent the

direct emissions caused by maintenance inspection and are 277.2 $kg\ CO2_e/fu$ (Hjalmarsson, 2024). The values calculated for Evision are slightly lower than the values for Airpelago. This can be accounted to the differences in estimations, and road layouts in the area that the data was collected from. Airpelago estimation of the distance within the inspection area as 2 times the distance of grid inspected, as per Evision estimation is 1.5 times the distance.

6.2. Hotspot recognition

Based on the emission profile the hotspot for emissions in baseline scenario is the vehicle use causing 78.50% of the total emissions. Within the vehicle use the hotspot for emissions are emissions caused by transport to the inspection area accounting for 74.28% of the total direct emissions for baseline scenario. The hotspot for drone electricity use is the power generator accounting for both power generator and inverter use for battery charging accounting for 96.05% of the emissions caused by drone use. Main emphasis when determining emission reduction scenarios should be placed on the vehicle fuel consumption and power generator use.

7. Reduction scenarios

This chapter aims to recognize ways to reduce the overall carbon footprint for maintenance inspection by focusing on possible avenues for optimizing the process to achieve reductions in greenhouse gas emissions. This chapter estimates the emissions for currently available scenarios for power grid inspections, that do not use a drone for the inspection, options that can be achieved by optimizing the current scenario, and options achieved by upgrading current equipment with different scenarios.

Based on the hotspot observations reducing the vehicle use emissions is the most efficient way to reduce the overall carbon footprint of the maintenance inspection activity. The emissions caused by maintenance inspection can be reduced in multitude of ways including but not limited to optimizing drone operations, reducing fuel consumption, switching to electric vehicles.

7.1. Currently available alternative methods

Current alternative scenarios for maintenance inspection are mainly either the data gathering done with a helicopter or by inspection on foot. Inspection by foot happens both as basic inspection and as non-condition based maintenance, where the power line is walked under to inspect if anything needs maintaining, but this type of maintenance does not account for the condition of the line infrastructure.

7.1.1. Helicopter inspection

Helicopter based maintenance inspection works in a similar manner to drone based maintenance inspection, where helicopter flies overthe line and uses LiDAR technology and visual images to collect data for analysis to estimate the conditions and maintenance needs of the grid. (Yan et al., 2021, pp. 3147–3159)

Helicopter based inspection is the first iteration of aerial smart maintenance for power line inspection and is a common scenario for power line inspections all over the globe. (Yang et al., 2020, pp. 9350–9365) The benefits of fast and manoeuvrable airborne vehicle for inspecting large areas of power line are undeniable, but the major downsides for helicopter

inspection are costs, and environmental aspects of the helicopter use. (Yang et al., 2020, pp. 9350–9365)

The model of helicopter used for maintenance inspection for the region is McDonnel Douglas 500 D/E. The fuel consumption of MD 500 D/E is 28 Gallons or 106 litres per hour (USDA, 2019). The power grid is a web of interconnected lines and branches with dead ends. Due to the web like layout of the power grid the helicopter is assumed to need to cover one and a quarter the distance of the power grid inspected, in addition to reaching the inspection area. This assumption is based on the flight time of MD 500D/E of 2.5 hours according to manufacturer specifications (MD Helicopters, 2023). Helicopters use aviation fuel, and the emission factor for aviation fuel is 2.51 $kg\ CO2_e/l$ (GOV.UK, 2023). The helicopter inspection does two 2.5-hour sessions a day with the assumption that the helicopter is able to inspect 250 km of power grid per day leading to each 2.5-hour session conducting a full functional unit. This means that the emissions per functional unit consist of flight from helicopter hangar to the inspection area, inspection flight and flight back from the inspection area to the hangar.

For helicopter inspection scenario calculations, it is assumed that the distance between helicopters storage and the inspection area is the same as for drone storage and inspection area. Additionally, the helicopter speed is assumed to be 240 km/h between the storage facility and inspection area based on manufacturer specifications and 60 km/h while inspecting the power grid. Based on these assumptions for inspecting a functional unit, calculations are presented in table 5. The fuel consumption per functional unit would be 276.04 litres of aviation fuel causing 692.86 $kg\ CO2_e/fu$, or 3.7 times the emissions caused by the baseline scenario without taking indirect emissions into account. In addition to the helicopter flying over the powerline the refuelling is accomplished by a fuel tank towed to the area using a diesel ICEV. It is assumed that the ICEV has the same fuel consumption as the vehicles used for the drone scenario. The Vehicle has to cover the distance to the inspection area and back increasing the emissions from the inspection by 26.79 $kg\ CO2_e/fu$.

The values for helicopter-based inspections are presented under the most favourable conditions, with the intention of displaying the data in its most advantageous context for the helicopter inspection. This methodological approach is designed to minimize the potential variability between drone and helicopter inspection scenarios. By providing helicopter

inspection with the most optimized conditions, it aims to dispel any doubts regarding performance differences between the scenarios. Figure 11 presents the differences between drone and helicopter-based inspection. Additionally, the lifecycle emissions for helicopter inspection are not calculated since the operational emission even in the optimal situation are already way above the emissions of baseline scenario.

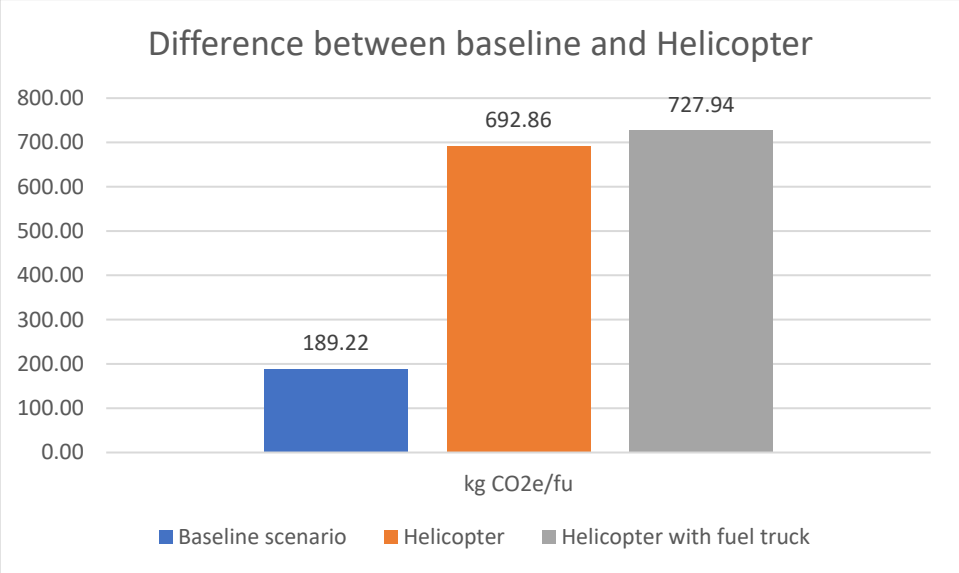

Figure 11. Difference between baseline and helicopter inspection scenarios.

The differences between helicopter and helicopter with fuel truck is as small because the use of a fuel truck and refuelling the helicopter on the field allows for higher efficiency for the helicopter team increasing the daily inspection from 200 km to 250 km, this higher efficiency results in part of the emissions caused by the fuel truck to be offset.

Table 5. Direct emission values for helicopter maintenance inspection

Helicopter	MD 500 D/E	
Distance flown	250.00	km
Distance flown in inspection area	125.00	km
Distance flown to target	125.00	km
Fuel consumption per hour	106.00	l/h
Emission Factor fuel	2.51	$kg\ CO2_e/l$
Emissions per hour	266.06	$kg\ CO2_e/h$
Speed in inspection area	60.00	km/h
Speed to inspection area	240.00	km/h
Time in inspection area	2.08	h
Time to travel	0.52	h
total time spent	2.60	h
Fuel consumption	276.04	l
Inspection area	220.83	l
Travelling	55.21	l
Distance driven	554.29	km
Fuel economy	138.57	$l/100km$
Fuel consumption	692.86	l
Emission Factor	250.00	$kg\ CO2_e/l$
Emissions	125.00	$kg\ CO2_e/fu$
Emissions, Inspection	125.00	$kg\ CO2_e/fu$
Emissions, other	106.00	$kg\ CO2_e/fu$
Emissions total	2.51	$kg\ CO2_e/fu$

7.1.2. Foot patrol

Foot patrol inspection works by inspectors walking under the power line, which does not provide the LiDAR data or the aerial images that helicopters or drones provide.

For the foot patrol scenario calculating the actual carbon footprint is incredibly difficult due to the variables affecting the inspection speed and thus emissions caused by foot patrol inspections. To compare the drone-based maintenance inspection a break-even analysis was conducted based on the daily inspection distance for foot patrol inspections. Figure 12 presents the GHG emission curve for foot patrol inspections in the most optimized situation for carbon footprint.

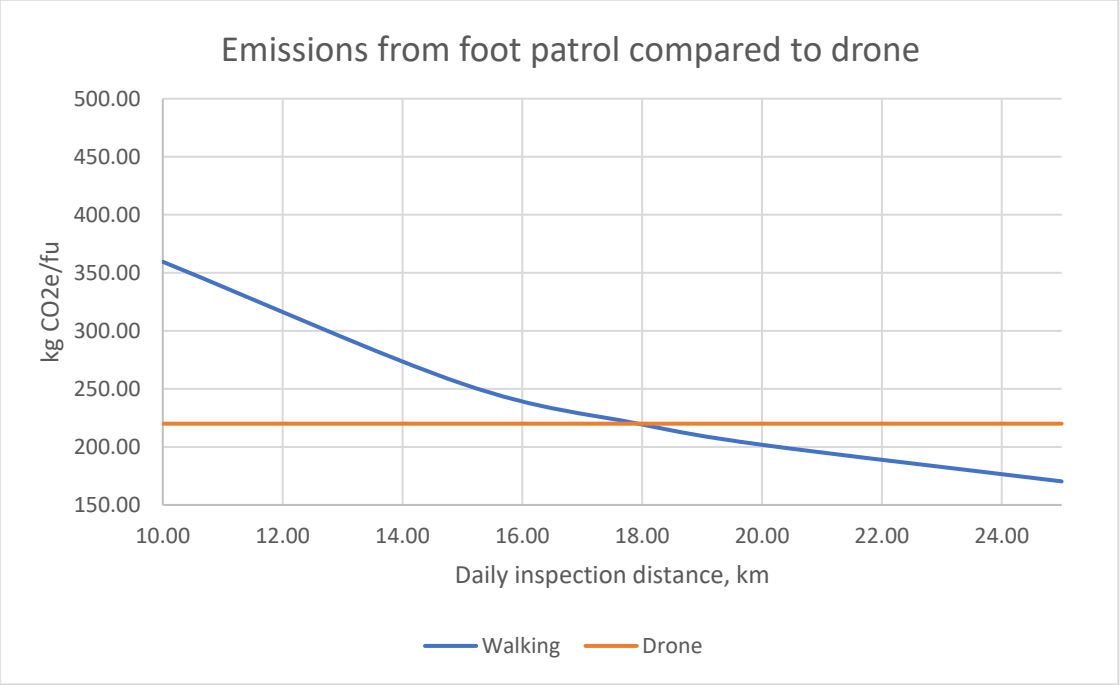

Figure 12. Emission curve for walking compared to drone

The curve is calculated based on the emissions caused by traveling to the inspection area assumed to be the same as the distance from the drone storage. The break-even scenario for the carbon footprint between drone and foot patrol was calculated based on the emissions caused by baseline scenario and calculating the breakeven daily inspection distance to achieve the same emissions as baseline scenario.

To calculate the breakeven speed, excel solver was used to adjust the daily inspection distance to match the emissions caused by foot patrol inspection to baseline scenario. Table 6 presents the breakeven scenario for foot patrol inspection compared to drone inspection.

The emission curve for walking is decreasing due to the distance between the power line and the office or start point is around 62.5 km. Reducing the times that the distance between the office and power line has to be driven reduces the total emissions caused by maintenance inspection.

Table 6. Breakeven scenario for drone and foot patrol inspection

Breakeven scenario		
Distance inspected	100.00	km
Inspected distance/day	17.93	km
Days to inspect	5.58	day
Distance driven	871.60	km
Distance traveled to target	124.90	km
Distance in area	175.00	km
Fuel economy	8.54	$l/100km$
Fuel consumption	74.44	l
Emission Factor	2.51	$kg\ CO2_e/l$
Emissions vehicle, travel	186.83	$kg\ CO2_e/fu$
Emissions indirect	33.21	$kg\ CO2_e/fu$
Emissions total	220.04	$kg\ CO2_e/fu$

The data shows that the daily inspection distance to achieve breakeven value is at 17.93 km per day, which is not the same as the distance walked as the distance inspected does not account for any need for walking any leg of the inspection more than once due to the branched nature of the grid. When assessing the actual walking speed required to achieve the daily inspection distance the actual walked distance is up to two times the distance inspected due to the branched nature of the power grid. Average working age human walking speed is around 4.4 kilometres per hour (Alves et al., 2020, p. 7360), which would render the breakeven scenario achievable, but the walking speed is measured on even land without having to inspect a powerline above. The walking speed for inspection is impossible to measure due to the changing conditions on the trail, and the requirement to inspect powerlines above.

7.2. Relative low cost emission reduction options

Relative low cost emission reduction options include options that do not require major upgrades for the materials used for inspection services, such as drones, vehicles, or systems. Small investments are considered for this scenario such as a mount allowing for both sensors to be attached to the drone at the same time. In the baseline scenario, each flight is done twice. Once for each sensor attached to the drone

For this chapter the recognized ways of lowering the carbon footprint of the maintenance inspection without major investments three solutions have been recognized thus far which are mounting both sensors at the same time to the drone, optimizing field operations and flight planning, replacing power generator with a battery system.

7.2.1. Dual sensor

Dual sensor option focuses on the GHG emissions if both sensors could be mounted on the drone at the same time resulting in a situation which would increase the inspection performance, reducing the time it takes to inspect a full functional unit reducing the carbon footprint by reducing the emission hotspot of travel between storage and inspection area. A recent optimization calculation conducted by the company showed that dual sensor could increase the daily inspection rate by 50% higher distance inspected daily resulting in major emission reduction due to reducing the daily transport from storage to the inspection area and improving the performance by reducing the time required to complete a functional unit.

The calculation of 50% increased performance for maintenance inspection did not account for the plausible reduction in single flight length due to the weight difference of the drone payload, which could reduce the distance that the drone is capable of flying per battery charge. For the purposes of this thesis the reduction in single flight distance caused by the increased payload weight is considered being insignificant due to the variation being smaller than the daily variables in the data such as temperature, humidity, wind speed, etc.

Mounting both sensors at the same time requires a special mounting solution which is contributing to dual sensor not being implemented as of writing, but a solution that allows for dual sensor mounting does exist.

The emissions for dual sensors were calculated using the same method as baseline scenario, with the difference of required flights being half the amount due to the removal of the need for conduct two flights to gather the necessary data. Table 7. presents the vehicle fuel use for dual sensor inspection per functional unit.

Table 7. Vehicle emissions for dual sensor inspection

Distance traveled	**511.67**	***km***
Inspection area distance	150.00	km
Distance traveled to target	361.67	km
Fuel economy	8.54	$l/100km$
Fuel consumption	43.70	l
Inspection area	12.81	l
Other	30.89	l
Emission Factor	2.51	$kg\ CO2_e/l$
Emissions vehicle Inspection	32.15	$kg\ CO2_e/fu$
Emissions vehicle, travel	77.52	$kg\ CO2_e/fu$
Emissions from vehicles	109.68	$kg\ CO2_e/fu$

The difference between baseline and dual sensor inspection in total emissions is 36% or 79.20 $kg\ CO2_e/fu$. The differences in direct and indirect emissions are both between 35% and 37%. Figure 13 presents the difference between baseline and dual sensor inspection in a visual way. Figure 14 presents the breakdown of the emission allocation for Dual sensor scenario.

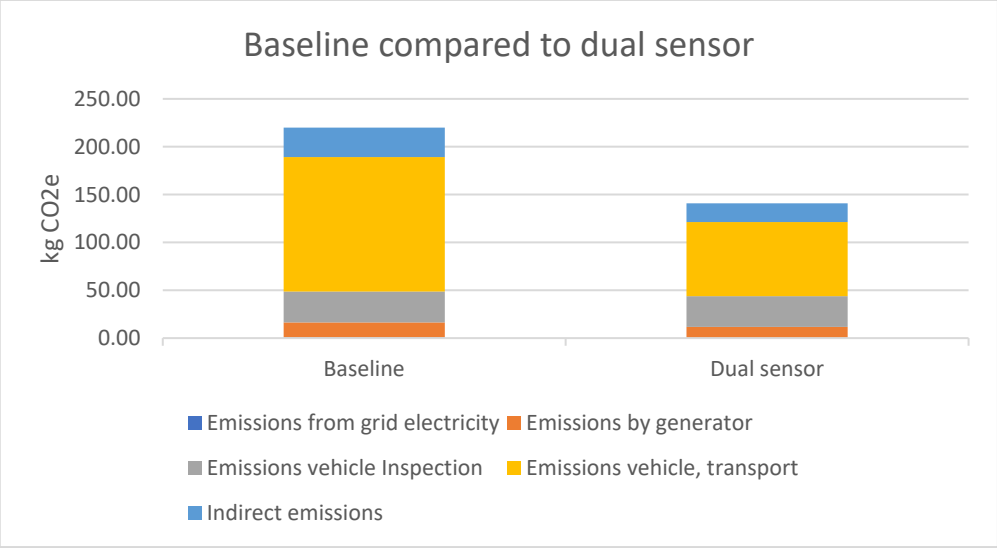

Figure 13. Baseline emissions compared to emissions from dual sensor scenario

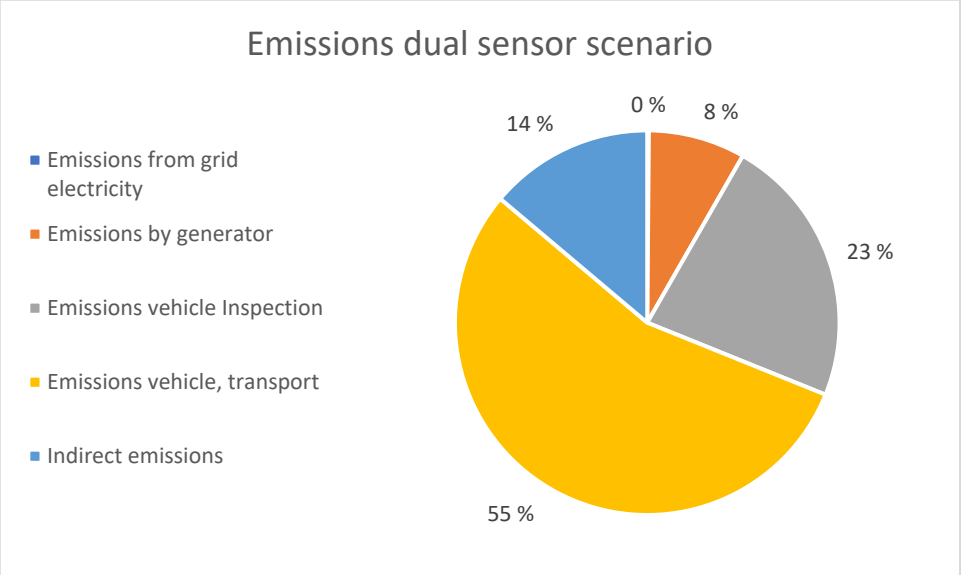

Figure 14. Breakdown of dual sensor scenario emissions

The emission reduction by dual sensor scenario mostly comes from increased efficiency in inspection activities increasing the speed of inspection activities. Increasing efficiency reduces the days it takes to complete a functional unit, which reduces the distance that is required to travel to and from the inspection area daily. The emission reduction can be noted due to the overall reduction in driven distance per functional unit from 805.88 km/fu to 511.67 km/fu as seen from table 7. The values presented for the increased efficiency are based on a theoretical estimation of increased efficiency and have a chance of not directly translating into reality as they are estimated to perform.

7.2.2. Fuel source

Considering the that the vehicle fuel consumption being the largest emission hotspot leads to considering a renewable fuel source to reduce the GHG emissions of the maintenance inspection activity. Renewable fuel sources could have other positive attributes as well such as reducing the reliability on fossil fuels, but these other positive attributes fall outside of the scope of this thesis.

Biofuels are alternative fuels to diesel fuel produced using vegetable oils or animal fats. There are different kinds of biofuels depending on the method and ingredients used. Fatty acid methyl ester (FAME) biofuels are called biodiesel. FAME biodiesel is created by processing vegetable oils or animal fats with methanol to form methyl esters and glycerol

(Gerpen, 2005, pp. 1097–1107). FAME biodiesel has poor performance in colder conditions due to its higher density (Pechout et al., 2019, p. 133748). Because of this FAME biodiesel is rarely used in Finland.

Hydrotreated vegetable oil (HVO) is a method of creating renewable fuel from oils from vegetables and trees. HVO fuels are produced by hydrotreating renewable oil by reacting the oil with hydrogen under high pressure and temperature to force oxygen and water out resulting in paraffinic hydrocarbon similar to petroleum-based diesel (Aatola et al., 2009, pp. 1251–1262). HVO is not considered biodiesel but renewable diesel. HVO renewable diesel has similar physical and chemical properties as regular diesel. HVO renewable diesel has good cold flow properties and storage stability which makes it ideal to use in colder climates such as Finland (Serrano et al., 2021, p. 470).

There are multiple different values for HVO renewable diesel emission factors ranging from 0.03558 $kg\ CO2_e/l$ (GOV.UK, 2023) to 1.0742 $kg\ CO2_e/l$ (Xu et al., 2022, pp. 7512–7521). These values represent emission reduction from 98.58% reduction to 57.21% reduction. These represent limit values from literature allowing for the ideal that

These represent limits for the value of the emission factor. It is known that the value of the emission factor should fall between 98.58% to 57.21% lower than the emission factor for petroleum based diesel. A field to wheels emission factor for biodiesel would be 0.6922 $kg\ CO2_e/l$ (Garraín et al., 2010, vol. 01). A field to wheels factor represents the true emissions far better for this scenario. The emission factor for HVO renewable diesel is 72.42% lower per GJ of gross energy when compared to petroleum-based diesel, which falls into middle of the range previously given, thus the value is used since it represents an average value for HVO renewable diesel emission reduction. Calculations follow the same route as baseline scenario calculations with fuel emission factor replaced for the emission factor for HVO renewable diesel. The value used for this thesis is 0.6922 $kg\ CO2_e/l$ (Garraín et al., 2010, vol. 01).

Alternative fuels scenario GHG emissions for both baseline and dual sensor scenarios were calculated using HVO biofuels. Figure 15 presents the emissions for baseline scenario, dual sensor scenario, baseline scenario using renewable diesel, and dual sensor scenario using renewable diesel. Values the baseline scenario using HVO renewable diesel and the dual sensor scenario using HVO renewable diesel are presented in appendices 1 and 2.

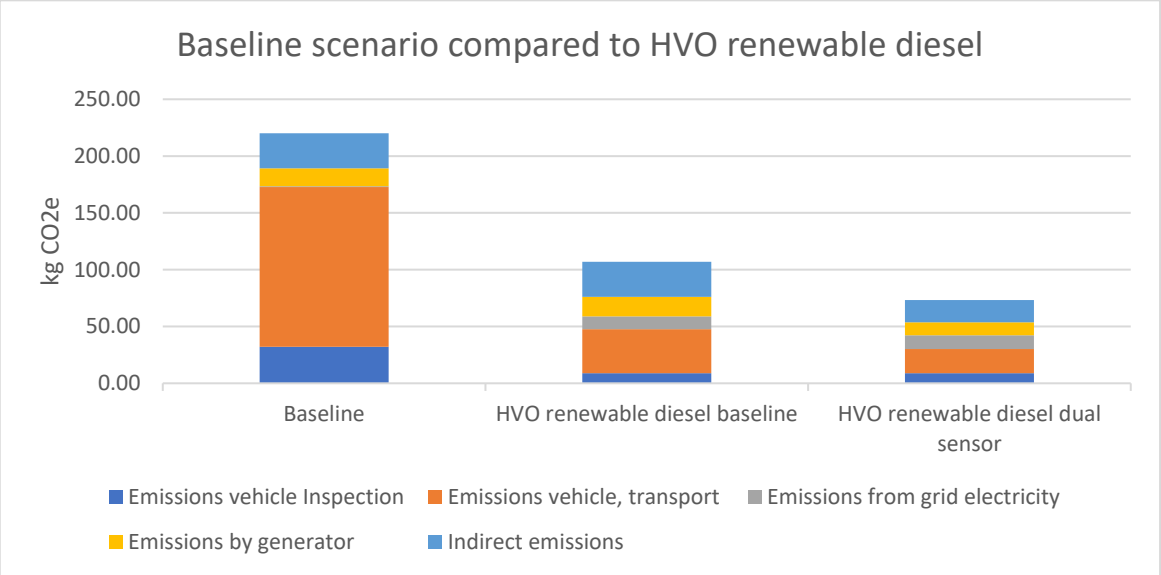

Figure 15. Emissions from baseline scenario compared to HVO renewable diesel

Switching to alternative fuel would result in GHG emission reduction 42.57% emission reduction when compared to the baseline scenario of using petroleum-based diesel. Calculations did not account for lower energy concentration in biofuels, because the difference in volume-based emission factor and energy content based emission factor is 1.54% which is insignificant with the scale of the difference when compared to the baseline. The largest cause for emission reduction for renewable fuels is the lower emission factor for renewable fuels when compared to the petroleum based fuels.

7.2.3. Battery pack

Replacing power generators with battery packs akin to power banks is considered to reduce the emissions caused by charging the batteries on the field. Larger battery packs are commonly found around 5kWh range which would allow for the entire daily inspection operation be conducted with grid electricity reducing the fuel consumption caused by power generators. 96% of the emissions caused by drone use are from the power generator fuel consumption.

A 5kWh battery pack could sustain the energy demand for daily maintenance inspection operation. A battery pack is also assumed to have round trip efficiency of 80% (Schimpe et al., 2018, pp. 211–229). Figure 16 presents the baseline scenario compared with battery pack

scenario. Figure 17 presents the HVO dual sensor scenario with battery pack scenario. Values for the battery pack scenario with baseline calculations and the battery pack scenario with HVO dual sensor calculations are presented in appendix 3 and 4.

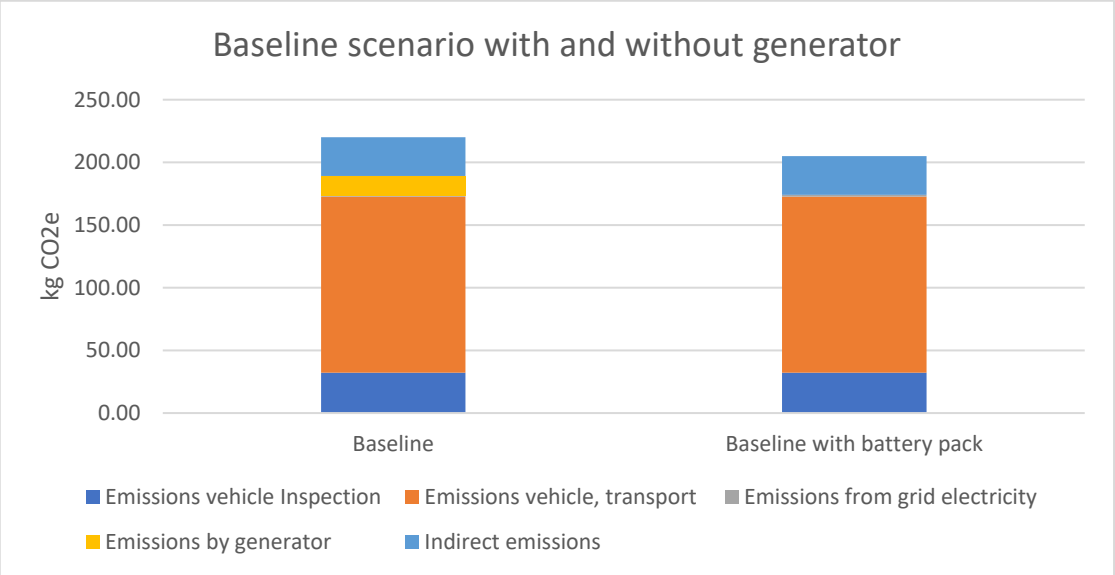

Figure 16. Baseline scenario with and without generator

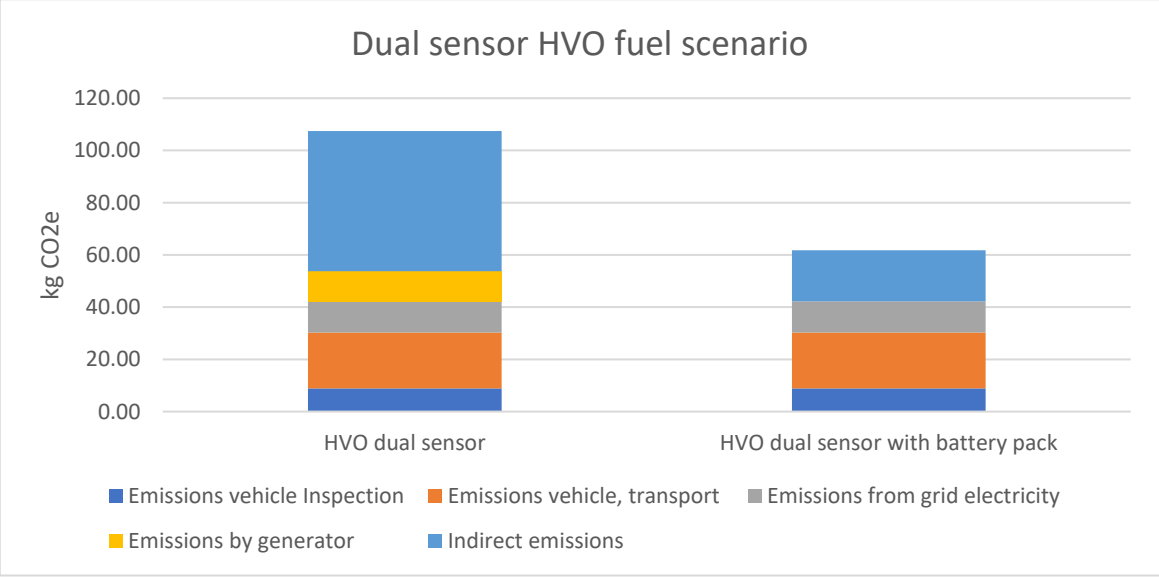

Figure 17. Dual sensor HVO fuel with and without generator

The emission reduction achieved with a battery pack system is 6.86% for baseline scenario and 42.52% for dual sensor HVO fuel scenario when accounting for indirect emissions. The calculations do not account for indirect emissions caused by the generators or battery packs. The emission reduction seen in figures 16 and 17 can be attributed to the removal of the fuel use for power generators used in charging the drone flight batteries on the field.

7.3. Higher cost emission reduction options

This chapter focuses on the emission reduction options which would major investments or redesigns of the maintenance inspection operations. The emission reduction options presented in this chapter are more theoretical in practice due to them being less achievable without major investments or redesigns of the process. such as upgrading to electric vehicles or drones with higher operating ranges. The emission reduction options presented in this chapter are a longer term ideals or more theoretical, due to the lack of available data and technological advancements.

7.3.1. Electric vehicle

Switching to electric vehicles (EVs) was found as a plausible scenario for emission reduction for maintenance inspection. EVs are generally considered to cause less emissions when compared to internal combustion engine vehicles (ICEVs) (Qiao et al., 2019, pp. 222–233). The electric vehicle scenario is assumed to use a generic electric vehicle. The energy consumption is model for which is based on UDDS model, which is based on urban areas in the United States (Wang et al., 2015, pp. 710–719). The electricity consumption for UDDS model average for generic electric vehicle allows for electricity consumption of 16.43 kWh/100km (Wang et al., 2015, pp. 710–719). The roundtrip efficiency for an EV is 83.7% (Qiao et al., 2019, pp. 222–233), but the roundtrip efficiency is already accounted for in the electricity consumption value.

The lifecycle emissions for EVs are 14052 $kg\ CO2_e$ compared to ICEVs 11230 $kg\ CO2_e$. This value is based on cradle to gate during production when accounting for all materials, and gate to cradle for end of life not accounting for recycling benefits (Qiao et al., 2019, pp. 222–233). Based on these values the indirect emissions for EVs are 25.13% higher than the indirect emissions for ICEVs allowing for comparison between baseline indirect emissions and EVs Scenario indirect emissions.

Figure 18 presents the comparisons of baseline emissions to EV scenario emissions and previous most optimized emission scenario to including an EV to the scenario. Figure 19

presents the emission breakdown for baseline EV scenario. Figure 20 presents the emission breakdown for dual sensor battery pack EV scenario.

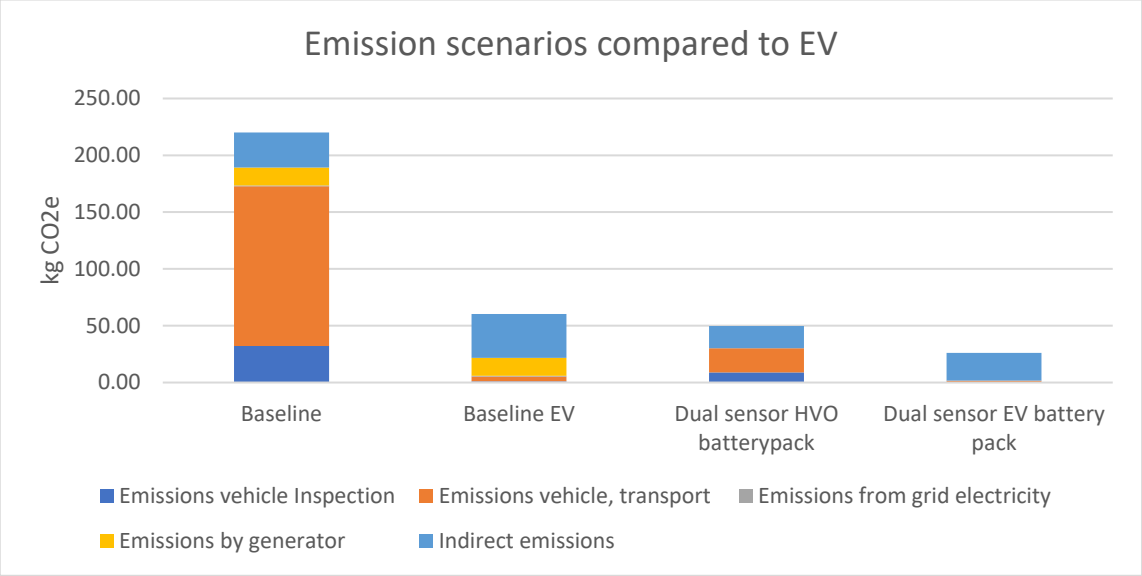

Figure 18. EV emission reduction scenarios compared to the baseline and optimized

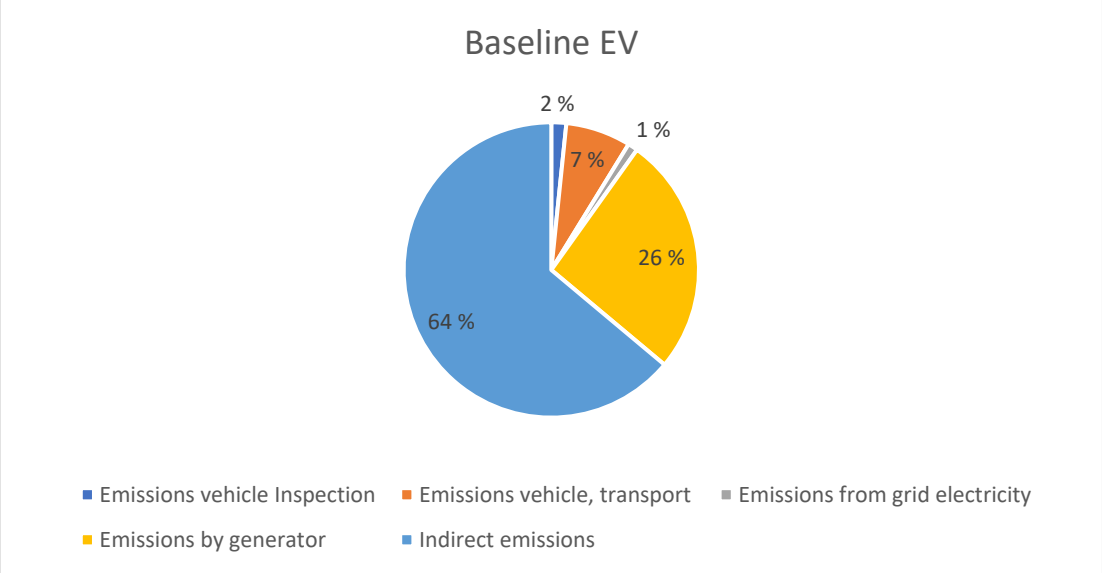

Figure 19. Emission breakdown for baseline EV

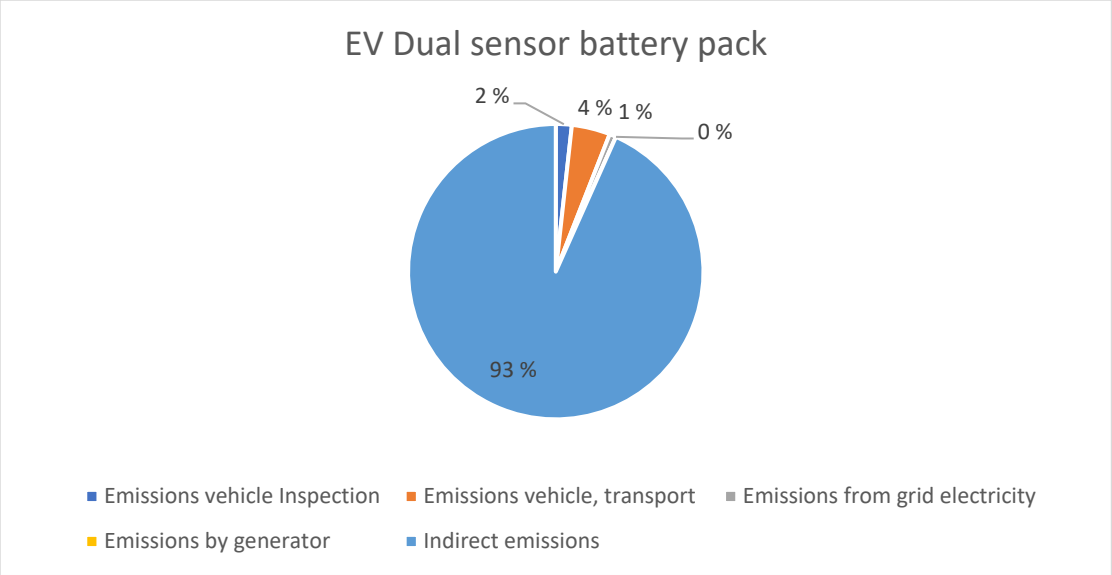

Figure 20. Emission breakdown for EV Dual sensor battery pack

The emission reduction for the optimized scenario exceeds 95% direct emission reduction. The remaining direct emissions are 4.1 $kg\ CO2_e$ further reduction would require complete overhaul of the maintenance inspection operation and would result in just slight improvement in carbon footprint. Situations where the entire operation would require to be overhauled might arise due to operational efficiency, but the carbon footprint reduction would be marginal and thus does not require complete overhaul due to the emission reduction requirements.

7.3.2. Long range drone

For this chapter few different types of drones are considered for long range operation. Starting with a hybrid drone Avartek boxer. Avartek boxer operates with electric motors but has an internal 4 kW generator built into the drone allowing for flight time up to two hours at the time (Avartek, n.d.). other drones considered include a truly long range military surveillance drone providing a comparable platform to the helicopter, and lastly theoretical situation with a long range glider drone. Last scenario does not have calculations included due to the limitations of pre-existing research and public data provided for said drones.

First the energy content of the batteries used by Avartek boxer is estimated. Although the energy content of the batteries is not published the indication of 30 minutes of flight time per battery set (Avartek, n.d.). The provided flight time would indicate that the energy

content of the batteries should be similar to the energy content of the TB60 used in the baseline scenario. Thus, the energy content of the batteries is assumed to be 0.3 kWh. The Flight time using 5 litres of fuel is 2 hours (Avartek, n.d.). Assuming that the inspection flight is conducted at 7 m/s, or 25.2 km/h. Based on the inspection speed and flight time of 2 hours a take-off location could manage 50 km of inspection and a workday could include 2 flight locations, if two drones were used per take-off location. Giving daily inspection distance of 100km or a functional unit. Using the emission factors previously used, the fuel emission factor is at 2.51 $kg\ CO2_e/l$ (GOV.UK, 2023) And emission factor for electricity consumption is 0.04 $kg\ CO2_e/kWh$ (Fingrid, 2024b). It is assumed that the Hybrid drone due to its higher payload capability of 25 kg is always carrying dual sensor (Avartek, n.d.). Using these values the emissions for using Avartek boxer in baseline scenario would cause emissions of 105.25 $kg\ CO2_e/fu$, and using Avartek boxer in the Dual sensor electric vehicle scenario emissions would be 42.18 $kg\ CO2_e/fu$. Figure 21 compares the hybrid drone baseline scenario to the baseline scenario, and figure 22. Compares dual sensor EV battery pack scenario to hybrid drone dual sensor EV scenario.

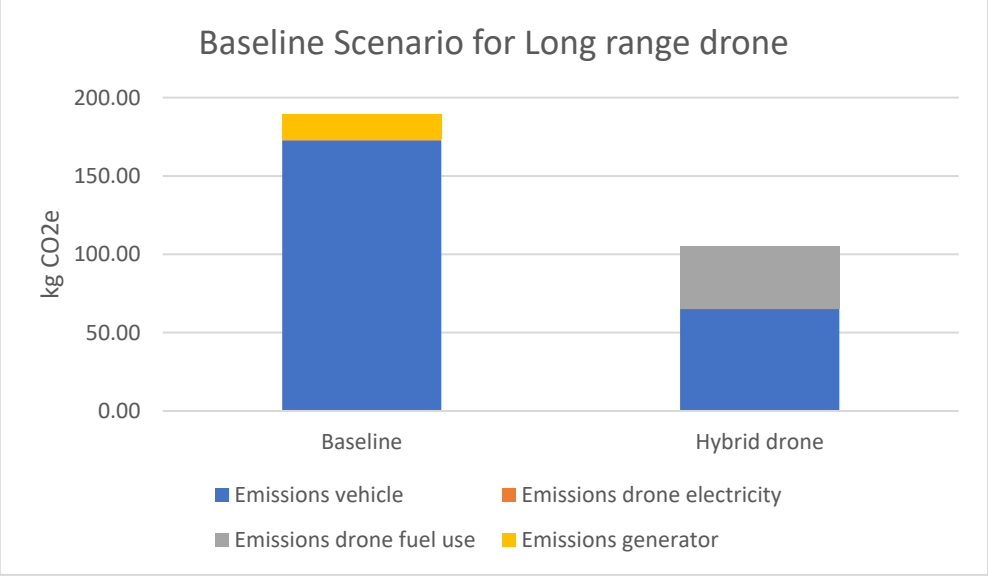

Figure 21. Baseline scenario with hybrid drone

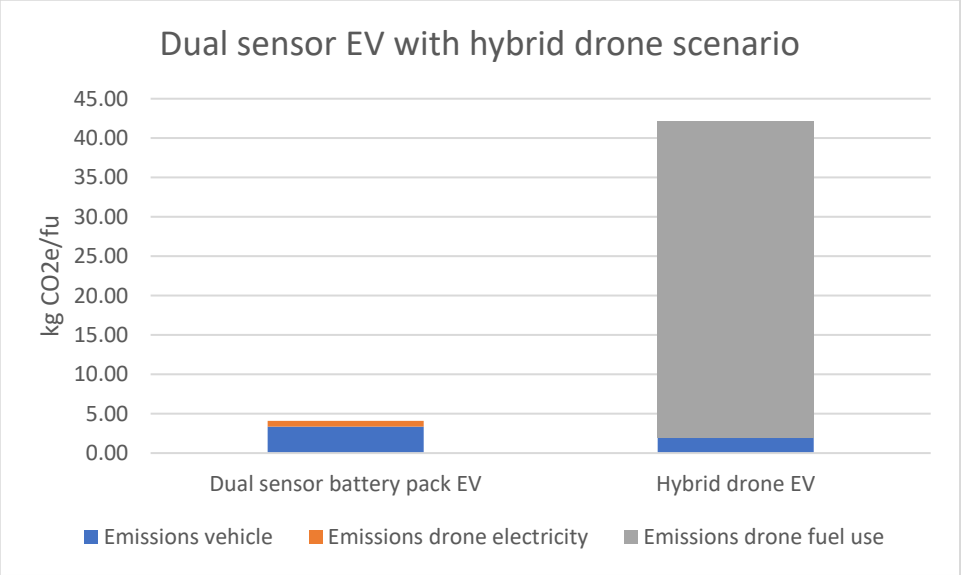

Figure 22. Dual sensor EV with hybrid drone

The hybrid drone has better operational performance compared to other scenarios and outperforms the baseline scenario in emission aspects but is outperformed by the EV scenarios in emission aspects. A long range drone would need to operate using electricity or future renewable fuels to outperform the current optimized scenario.

Second option for long range drone selected is the US Airforce MQ-1B Predator. This option is selected to be comparable option to the helicopter scenario to provide inside how poorly the helicopter performs in terms of GHG emissions. The MQ-1B Predator drone is a large military armed intelligence drone that requires similar capabilities from an airfield as to a fighter jet (USAF, 2015). The reported fuel capacity for the MQ-1B is 100 gallons or 378.54 litres, the reported operational range is 770 miles or 1239.2 km, and the reported deployed mission time is 24 hours (USAF, 2015). From this the fuel consumption can be calculated at 15.77 litres per hour of operation. Using the emission factor for Aviation fuel at 2.54 $kg\ CO2_e/l$ (GOV.UK, 2023) the emissions caused by MQ-1B predator per functional unit would be 77.59 $kg\ CO2_e/fu$ compared to the 701.15 $kg\ CO2_e/fu$ of the helicopter or the 189.22 $kg\ CO2_e/fu$ of the baseline scenario. When comparing to other scenarios the MQ-1B predator drone would be a fairly good option for emission reduction, with the major downside of the cost of the drone system at 20 million USD in 2009 (USAF, 2015). Figure 23 presents the comparison of the estimated direct emissions from MQ-1B predator drone compared to helicopter scenario and baseline scenario.

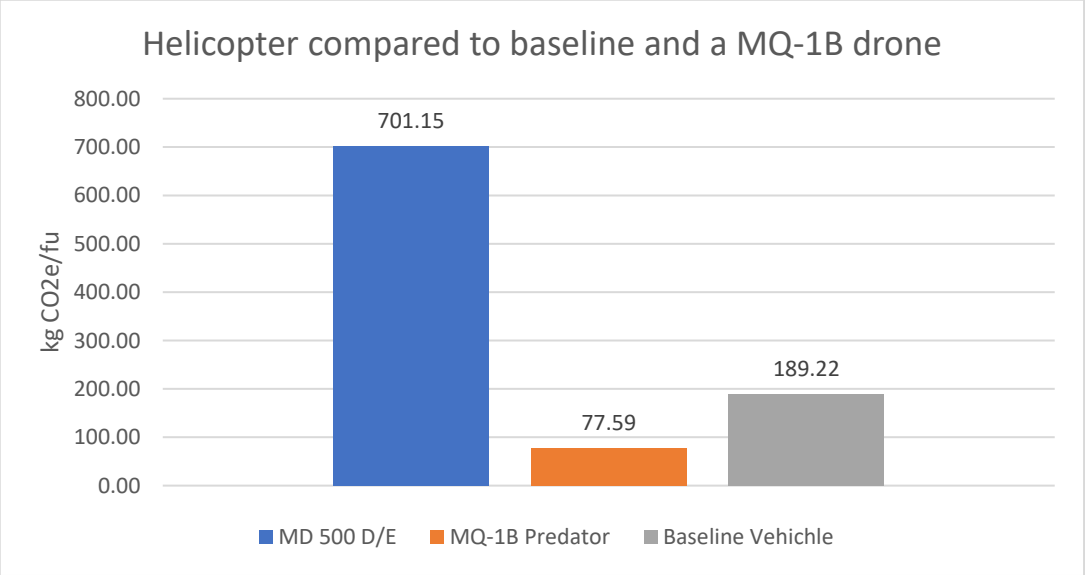

Figure 23. MQ-1B predator drone compared to baseline scenario and helicopter

The MQ-1B scenario provides insight into the possibility of a true long range drone being a feasible alternative to the current operational system but a proven solution is yet to be found in the long range drone category. Technically a long range drone working with electric engines with good enough aerodynamics or other systems such as a zeppelin design to sustain a range of over 100km would be optimal for maintenance inspection.

7.4. Limitations of the research

There are multitude of limitations for the cases presented. Different circumstances would yield different results for scenarios such as EV selection would change the energy consumption model based on the EV model selected or indirect emissions based on the production circumstances or the model of the vehicle or the type of the renewable diesel selected changes the emissions based on the calculation method and scope of the calculation. This variance in scenarios makes all of the reduction scenarios estimations made based on generalized assumptions.

The baseline scenario that is based on the data collected for this thesis has generalisations and most calculations are done based on average values provided by data collection. The variance in the datasets causes difference in the inspection areas with some areas being more favourable and some less favourable for the calculation.

The indirect emission calculation is purely based on a study and does not necessarily reflect the real life indirect emissions for each scenario, due to variability in the indirect emissions caused by different scenarios.

8. Discussion

This chapter focuses on analysing the data presented in the emission reduction scenarios. The emission reduction scenarios are evaluated based on three terms effectiveness, feasibility, and assumed cost level. In addition, a plan to reduce the emissions as much as possible is generated.

Baseline emission scenario is an improvement over the pre-existing ways of inspecting the power grid, as foot patrol inspections do not gather the overhead data used for analysis. When compared to the other pre-existing scenario that provides data able to be analysed helicopter inspection the baseline scenario outperforms the helicopter inspection in terms of emissions by 73%. This short analysis provides the insight that the drone-based maintenance even when done in the baseline scenario still outperforms other forms of pre-existing scenarios and should be optimized to provide the best performing scenario.

Without dismantling the entire baseline operations by introducing a long-range drone and automation the best performing scenario is dual sensor attached to the drone with using battery pack on the field to charge the extra batteries and the transportation is conducted using an electric vehicle. With these optimizations the total emissions are reduced by 88.12% and the direct emissions are reduced by 97.84%. This combination scenario is the most effective option for all quad copter-based operations. The downside of this scenario is the large investment requirement for EVs which at this stage is not a feasible option due to the cost of upgrading the vehicle fleet in use to EVs. Upgrading to EV scenario is a long term option that should be considered, when possible but so far, the scenario is unlikely to happen in the near future.

The second best performing scenario that does not involve EVs is the same scenario, but with the use of HVO renewable diesel. By switching to renewable diesel, the total emissions are reduced by 77.40% and the direct emissions are reduced by 84.01%. The Renewable diesel battery pack dual sensor is a feasible scenario due to it requiring minimal investment and allowing for major emission reduction. The assumed cost increase can be attributed to the higher cost from renewable diesel.

The other scenarios dual sensor and battery pack are assumed for both the previous optimizations due to them being incredibly efficient and easily achievable with fairly low cost or technological improvements. Dual sensor where both LiDAR and camera are attached to the drone at the same time directly improves the performance by 35.87% in direct emissions and 35.99% in total emissions. With the battery pack, the difference in emissions is less noticeable when only considering baseline emissions, but the emissions caused by generator account for 96.03% the emissions for drone usage.

The emission reduction options paint a general plan to reduce the operational emissions from the baseline and allow for a clear path towards carbon neutrality for maintenance inspection. The plan to achieve emission reduction is a four step system. The first step is to add the dual sensor mount to the drones allowing for optimized operations in the field. The second step is instantly achievable by switching to renewable diesel for ICEV transport for the maintenance operations. The third step would be to invest in battery pack solution that would reduce the emissions from drone usage, and the fourth and last step to reduce the emissions from maintenance inspection would be to upgrade the vehicle fleet in use to electric vehicles. Figure 24 presents the emission reduction options and suggested steps in a visual way and collects all of the data generated for this thesis.

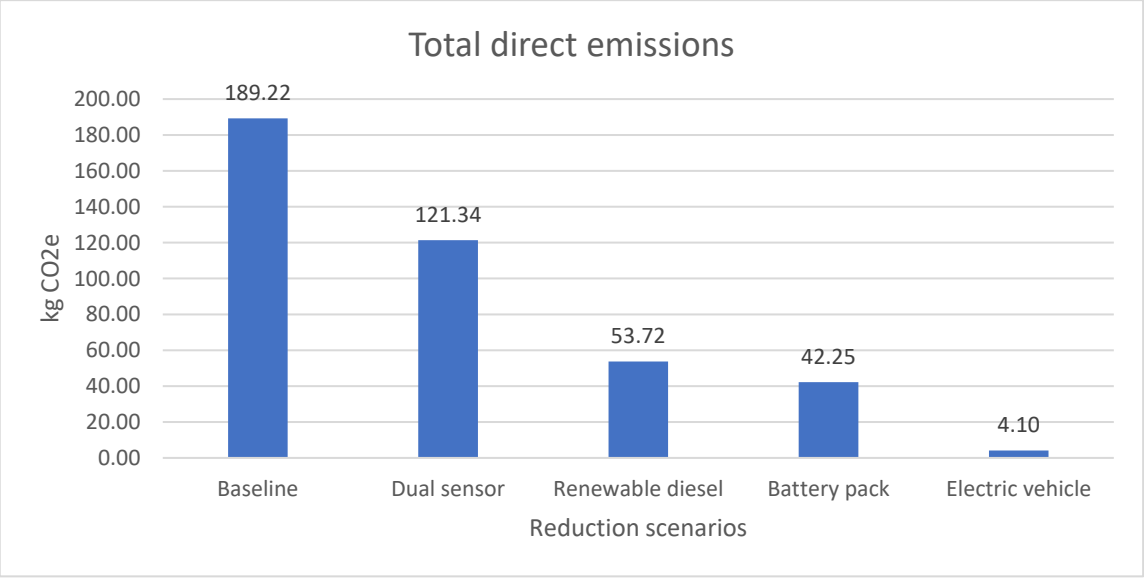

Figure 24. Total direct emissions per reduction option

8.1. Suggestions for future

For future research a system involving true long range drone scenarios could be considered to improve the estimation generated in this thesis, that an electric or zeppelin style drone able to achieve ranges above 100 km would provide an excellent option for maintenance inspection.

In addition, future research could be conducted with data collection regarding scenarios calculated for this thesis to prove or disprove the calculations presented. Future research could also be conducted to aim for carbon neutrality for maintenance inspection either through emission reduction scenarios such as presented in this thesis or through carbon sinks.

9. Conclusions

This thesis provides a framework for achieving a substantial GHG emission reduction model for drone-operated electrical grid maintenance inspection. The reduction is achieved by enhancing the baseline operational model by improving efficiency with dual sensor payloads, significant GHG emission reductions through renewable fuels, and removing petroleum-based fuels from each step of the maintenance inspection process. While transitioning to electric vehicles remains a long-term objective due to initial investment costs, but renewable fuels provide a viable option for emission reduction in the short-term. The phased progressive plan ensures that each step towards carbon neutrality is more approachable while maintaining maintenance inspection operations.

In conclusion the proposed emission reduction pathway demonstrates an effective and balanced path towards carbon neutrality but also balanced regarding feasibility and costs. Implementation of these optimizations will result in more sustainable and lower GHG emissions operating model to electrical grid maintenance inspection contributing positively to GHG emission reduction initiatives.

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Appendix

Appendix 1. HVO renewable diesel for baseline scenario

HVO biofuel		
Fuel use		
Distance driven	805.88	$\boldsymbol{km}$
Inspection area distance	150.15	km
Distance to target	655.73	km
Fuel economy	8.54	$l/100km$
Fuel consumption	68.82	l
Inspection area	12.82	l
Other	56.00	l
Emission Factor	0.69	$kg\ CO2_e/l$
Emissions vehicle Inspection	8.88	$kg\ CO2_e/fu$
Emissions vehicle, transport	38.76	$kg\ CO2_e/fu$
Emissions	47.64	$kg\ CO2_e/fu$
Electricity		
Energy consumed	26.63	$\boldsymbol{kWh}$
battery efficiency	85.00 %	%
Total energy consumed	31.32705882	kWh
Generator use %	47.90 %	
Generator use	15.01	kWh
Non generator power	16.32	kWh
Generator fuel use	6.85	l
Emission factor	0.69	$kg\ CO2_e/kWh$
Emission factor fuel	2.51	$kg\ CO2_e/l$
Emissions from grid electricity	11.30	$kg\ CO2_e/fu$
Emissions by generator	17.20	$kg\ CO2_e/fu$
Emissions	28.50	$kg\ CO2_e/fu$
Emissions vehicle Inspection	8.88	$kg\ CO2_e/fu$
Emissions vehicle, transport	38.76	$kg\ CO2_e/fu$
Emissions from grid electricity	11.30	$kg\ CO2_e/fu$
Emissions by generator	17.20	$kg\ CO2_e/fu$
Emissions	76.14	$kg\ CO2_e/fu$

Appendix 2. HVO renewable diesel in dual sensor scenario

HVO With dual sensor		
Fuel use		
Distance driven	511.67	$\boldsymbol{k}m$
Inspection area distance	150.00	km
Distance to target	361.67	km
Fuel economy	8.54	$l/100km$
Fuel consumption	43.70	l
Inspection area	12.81	l
Other	30.89	l
Emission Factor	0.69	$kg\ CO2_e/l$
Emissions vehicle Inspection	8.87	$kg\ CO2_e/fu$
Emissions vehicle, transport	21.38	$kg\ CO2_e/fu$
Emissions	30.25	$kg\ CO2_e/fu$
Electricity		
Energy consumed	13.31	kWh
battery efficiency	85.00	%
Total energy consumed	15.67	kWh
Generator use %	69.47 %	
Generator use	10.88	kWh
η _generator	0.42	kWh
Non generator power	4.78	l
Generator fuel use	4.57	l
Emission factor	0.04	$kg\ CO2_e/l$
Emission factor fuel	2.51	$kg\ CO2_e/kWh$
Emissions from grid electricity	0.19	$kg\ CO2_e/fu$
Emissions by generator	11.47	$kg\ CO2_e/fu$
Emissions	11.66	$kg\ CO2_e/fu$
Emissions vehicle Inspection	13.76	$kg\ CO2_e/fu$
Emissions vehicle, transport	33.18	$kg\ CO2_e/fu$
Emissions from grid electricity	0.19	$kg\ CO2_e/fu$
Emissions by generator	11.47	$kg\ CO2_e/fu$
Emissions	58.60	$kg\ CO2_e/fu$

Appendix 3. Baseline scenario with battery pack

Baseline scenario with battery pack		
Fuel use		
Distance driven	805.88	$\boldsymbol{km}$
Inspection area distance	150.15	km
Distance to target	655.73	km
Fuel economy	8.54	$l/100km$
Fuel consumption	68.82	l
Inspection area	12.82	l
Other	56.00	l
Emission Factor	2.51	$kg\ CO2_e/l$
Emissions vehicle Inspection	32.19	$kg\ CO2_e/fu$
Emissions vehicle, transport	140.56	$kg\ CO2_e/fu$
Emissions	172.74	$kg\ CO2_e/fu$
Electricity		
Energy consumed	26.63	kWh
battery efficiency	85	%
Battery pack efficiency	80	%
Battery pack use	42	%
Total energy consumed	34.62	kWh
Emission factor	0.04	$kg\ CO2_e/kWh$
Emissions from grid electricity	1.38	$kg\ CO2_e/kWh$
Emissions	1.38	$kg\ CO2_e/fu$
Emissions from grid electricity	1.38	$kg\ CO2_e/fu$
Emissions by generator	0.00	$kg\ CO2_e/fu$
Emissions vehicle Inspection	32.19	$kg\ CO2_e/fu$
Emissions vehicle, transport	140.56	$kg\ CO2_e/fu$
Emissions total	174.13	$kg\ CO2_e/fu$

Appendix 4. HVO Dual sensor with Battery pack

HVO With dual sensor		
Fuel use		
Distance driven	511.67	$\boldsymbol{k}m$
Inspection area distance	150.00	km
Distance to target	361.67	km
Fuel economy	8.54	$l/100km$
Fuel consumption	43.70	l
Inspection area	12.81	l
Other	30.89	l
Emission Factor	0.69	$kg\ CO2_e/l$
Emissions vehicle Inspection	8.87	$kg\ CO2_e/fu$
Emissions vehicle, transport	21.38	$kg\ CO2_e/fu$
Emissions	30.25	$kg\ CO2_e/fu$
Electricity		
Energy consumed	13.31	kWh
battery efficiency	85.00 %	%
Battery pack efficiency	0.8	%
Battery pack use	0.6947	%
Total energy consumed	18.38	kWh
Emission factor	0.04	$kg\ CO2_e/l$
Emissions from grid electricity	0.74	$kg\ CO2_e/kWh$
Emissions	0.74	$kg\ CO2_e/fu$
Emissions vehicle Inspection	13.76	$kg\ CO2_e/fu$
Emissions vehicle, transport	33.18	$kg\ CO2_e/fu$
Emissions from grid electricity	0.19	$kg\ CO2_e/fu$
Emissions by generator	0.00	$kg\ CO2_e/fu$
Emissions	47.13	$kg\ CO2_e/fu$

Appendix 5. Baseline EV scenario

Vehicle electricity		
Distance driven	805.88	$\boldsymbol{k}m$
Inspection area distance	150.15	km
Distance to target	655.73	km
Energy consumption	16.42	$kWh/100km$
Fuel consumption	132.32	kWh
Inspection area	24.65	kWh
Other	107.67	kWh
Emission Factor	0.04	$kg\ CO2_e/kWh$
Emissions vehicle Inspection	0.99	$kg\ CO2_e/fu$
Emissions vehicle, transport	4.31	$kg\ CO2_e/fu$
Emissions, vehicle	5.29	$kg\ CO2_e/fu$
Electricity		
Energy consumed	26.63	kWh
battery efficiency	0.85	%
Total energy consumed	31.33	%
Generator use %	0.48	%
Generator use	15.01	kWh
Non generator power	16.32	kWh
Generator fuel use	6.30	l
Emission factor	0.04	$kg\ CO2_e/fu$
Emission factor fuel	2.51	$kg\ CO2_e/l$
Emissions from grid electricity	0.65	$kg\ CO2_e/fu$
Emissions by generator	15.82	$kg\ CO2_e/fu$
Emissions	16.47	$kg\ CO2_e/fu$

Appendix 6. Dual sensor EV battery pack scenario

Distance driven	**511.67**	$\boldsymbol{km}$
Inspection area distance	150.00	km
Distance to target	361.67	km
Energy consumption	16.42	$kWh/100km$
Fuel consumption	84.02	kWh
Inspection area	24.63	kWh
Other	59.39	kWh
Emission Factor	0.04	$kg\ CO2_e/kWh$
Emissions vehicle Inspection	0.99	$kg\ CO2_e/fu$
Emissions vehicle, transport	2.38	$kg\ CO2_e/fu$
Emissions, vehicle	3.36	$kg\ CO2_e/fu$
Electricity		
Energy consumed	13.31	kWh
battery efficiency	85	%
Battery pack efficiency	80	%
Battery pack use	69	%
Total energy consumed	18.38	kWh
Emission factor	0.04	$kg\ CO2_e/kWh$
Emissions from grid electricity	0.74	$kg\ CO2_e/fu$
Emissions	0.74	$kg\ CO2_e/fu$

Appendix 7. Hybrid drone baseline

Distance driven	**303.50**	$\boldsymbol{km}$
Inspection area distance	150.00	km
Distance to target	153.50	km
Fuel economy	8.54	$l/100km$
Fuel consumption	25.92	l
Inspection area	12.81	l
Other	13.11	l
Emission Factor	2.51	$kg\ CO2_e/l$
Emissions vehicle Inspection	32.15	$kg\ CO2_e/fu$
Emissions vehicle, transport	32.90	$kg\ CO2_e/fu$
Emissions	65.06	$kg\ CO2_e/fu$
Energy consumed	0.60	kWh
battery efficiency	0.80	%
Total energy consumed	0.75	%
Drone fuel use	16.00	l
Emission factor	0.04	$kg\ CO2_e/kWh$
Emission factor fuel	2.51	$kg\ CO2_e/l$
Emissions from grid electricity	0.03	$kg\ CO2_e/fu$
Emissions from fuel	40.16	$kg\ CO2_e/fu$
Emissions	40.19	$kg\ CO2_e/fu$

Appendix 8. Hybrid drone EV scenario

Distance driven	**303.50**	$\boldsymbol{km}$
Inspection area distance	150.00	km
Distance to target	153.50	km
Energy consumption	16.42	$kWh/100km$
Fuel consumption	49.83	kWh
Inspection area	24.63	kWh
Other	25.20	kWh
Emission Factor	0.04	$kg\ CO2_e/kWh$
Emissions vehicle Inspection	0.99	$kg\ CO2_e/fu$
Emissions vehicle, transport	1.01	$kg\ CO2_e/fu$
Emissions, vehicle	1.99	$kg\ CO2_e/fu$
Energy consumed	0.60	kWh
battery efficiency	0.80	%
Total energy consumed	0.75	%
Drone fuel use	16.00	l
Emission factor	0.04	$kg\ CO2_e/kWh$
Emission factor fuel	2.51	$kg\ CO2_e/l$
Emissions from grid electricity	0.03	$kg\ CO2_e/fu$
Emissions from fuel	40.16	$kg\ CO2_e/fu$
Emissions	40.19	$kg\ CO2_e/fu$