LIFE-CYCLE AND SITE-SPECIFIC CLIMATE IMPACTS OF A TYPICAL FINNISH ON-SHORE WIND FARM

Jyväskylä University
School of Business and Economics

Master's Thesis

2023

Author: Jan Lehtomaja
Subject: Master's Degree Programme in
Corporate Environmental Management
Supervisors: Stefan Baumeister and Sami El Geneidy

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ABSTRACT

Author
Jan Lehtomaja

Title
Life-cycle and site-specific climate impacts of the typical Finnish on-shore wind farm

Subject Master's Degree Programme in Corporate Environmental Management	Type of work Master's Thesis
Date 1.6.2023	Number of pages 117

Abstract

The aim of this study was to evaluate climate impacts of a typical Finnish wind farm. Three research questions were: 1) What is the typical Finnish wind farm's carbon footprint? 2) what is the energy payback time of the typical Finnish wind farm? and 3) does the typical Finnish wind farm have a better net-negative impact on climate than the commercial forest area on which it was built?

Data for the study were collected via academic literature, wind turbine life cycle assessment reports, geographic information system (GIS) analysis and through the Natural Resources Institute Finland's Statistics database. The GIS analysis was conducted to retrieve the volume of roundwood on the wind farm's site.

The carbon footprint of the typical Finnish wind farm was found to be 7,18 g CO_2e/kWh and the wind farm's energy payback time 7,06 months. This study found that during 22 years (consisting of the wind farm's construction and operation phases) the typical Finnish wind farm had a net-negative impact on climate change of at least 169 767,72 t CO_2. In the absence of the typical Finnish wind farm, producing the equivalent amount of electricity by Finnish electricity mix was considered in calculating the net impact of the commercial forest area. This resulted in a net-positive impact on climate change of 192 393,42 t CO_2. However, the typical Finnish wind farm did not represent a carbon sink. Climate impacts represent only a part of environmental impacts caused by wind power.

The results of this study might have implications for the acceptability of wind power by general society as well as used for calculating climate impact assessment.

Key words
Wind power, carbon footprint, life cycle assessment, energy payback time, carbon sequestration, carbon storage

Place of storage
Jyväskylä University Library

TIIVISTELMÄ

Tekijä Jan Lehtomaja	
Työn nimi Life-cycle and site-specific climate impacts of the typical Finnish on-shore wind farm	
Oppiaine Master's Degree Programme in Corporate Environmental Management	Työn laji Maisterintutkielma
Päivämäärä 1.6.2023	Sivumäärä 117
Tiivistelmä Tutkimuksen tavoitteena oli arvioida tyypillisen suomalaisen tuulivoimapuiston ilmastovaikutuksia. Aihetta lähestyttiin kolmella tutkimuskysymyksellä selvittäen tuulivoimapuiston 1) hiilijalanjälki ja 2) energiantakaisinmaksuaika sekä 3) onko puistolla parempi nettonegatiivinen ilmastovaikutus kuin talousmetsällä, johon se on rakennettu. Tutkimuksen aineisto kerättiin akateemisen kirjallisuuden, elinkaariarviointiraporttien, paikkatieto-analyysin (GIS) ja Luonnonvarakeskuksen tietokannan avulla. GIS-analyysillä selvitettiin runkopuun määrä tuulivoimapuistoalueella. Tyypillisen suomalaisen tuulivoimapuiston hiilijalanjälki on tulosten perusteella 7,18 g CO_2e/kWh ja tuulivoimapuiston energiantakaisinmaksuaika 7,06 kuukautta. Tutkimuksessa havaittiin, että 22 vuoden aikana (puiston rakentaminen ja tuotantovaihe) tyypillisellä suomalaisella tuulivoimapuistolla on nettonegatiivinen ilmastovaikutus, joka on vähintään 169 767,72 t CO_2. Skenaariossa, että tuulivoimapuistoa ei rakennettaisi, talousmetsän ilmastovaikutusten laskennassa on huomioitu vastaava sähkömäärän tuotto suomalaisella energialähteiden yhdistelmällä. Tässä tapauksessa nettopositiivinen vaikutus on tulosten perusteella 192 393,42 t CO_2. Tuloksia ei voi kuitenkaan tulkita niin, että tuulivoimapuisto olisi hiilinielu. Ilmastovaikutukset ovat yksi osa tuulivoiman aiheuttamista ympäristövaikutuksista. Tämän tutkielman tuloksilla voidaan hyödyntää ilmastovaikutusten arvioinnin laskennassa ja niillä olla osaltaan vaikutuksia siihen, kuinka tuulivoima nähdään yhteiskunnassa.	
Asiasanat Tuulivoima, hiilijalanjälki, elinkaariarviointi, energian takaisinmaksu, hiilen sidonta, hiilen varastointi	
Säilytyspaikka Jyväskylän yliopiston kirjasto	

CONTENTS

LIST OF FIGURES AND TABLES

FIGURES

TABLES

LIST OF ABBREVIATIONS

BEF – biomass expansion factor
CO_2 – carbon dioxide
C - carbon
CF – carbon footprint
CS – carbon sequestration
EPBT - energy payback time
FWPA – Finnish Wind Power Association (STY - Suomen Tuulivoimayhdistys [in Finnish])
GIS - geographic information system
GCC – global carbon cycle
GHG(s) – greenhouse gas(es)
HWP(s) – harvested wood product(s)
ISO – International Organisation for Standardization
kWh – kilowatt hour
LCA – life-cycle assessment
MWh – megawatt hour
OSF – Official Statistics Finland
RES(s) – Renewable Energy Source(s)
SOC – soil organic carbon
SOCS – soil organic carbon sequestration
SOM – soil organic matter
WMS – web map service

1 INTRODUCTION

Wind power is recognized as a sustainable and renewable energy source (RES) (see for example Gareiou, Drimili & Zervas, 2021). In the academic literature, wind power has been presented as a mature and environmentally friendly technology, which has the ability to reduce humanity's dependency on conventional sources of energy, such as natural gas, coal, and oil (Bhandari, Kumar & Mayer 2020, p. 1). According to Schreiber, Marx and Zapp (2019, p. 561), wind power is considered as one of the most promising RESs. Such statement is further emphasized by Mendecka and Lombardi (2019, p. 462), who stated that wind power is put at the forefront of renewable energy planning.

Wind power represents a *circular way* of thinking through the use of already existing energy source – wind – in energy production. This way of thinking signifies an effort to reduce greenhouse gas (GHG) emissions to the atmosphere by using a renewable energy source that can be, as stated in the word "renewable", renewed, hence, to be used over and over again. Contrary to *circular way* of thinking, *straight line way* of thinking consists of the "industrial approach", that is of burning fossil fuels such as coal and oil, which only adds carbon dioxide (CO_2) to the atmosphere and is therefore not part of the more sustainable "cyclical model" of thinking. (Wheeler, 2011.)

Thus, the straight line of thinking disbalances the Earth's (global) carbon cycle (GCC), meaning that more CO_2 is "pumped" into the atmosphere than oceans, terrestrial biosphere, and land (lithosphere) can sequester and store. The greater amount of CO_2 in the atmosphere causes the greenhouse effect, where GHGs are trapping heat and consequently warming the Earth. According to Hannah (2011), human-induced fossil fuel burning, which involves primarily the emissions of CO_2, has caused the greatest disruption to the GCC.

As a result of this, the importance of wind power is increasing not only because of climate change and energy security (Wang & Wang 2015, p. 437) but also because of global increase in energy demand (Vargas, Zenón, Oswald, Islas, Güereca & Manzini, 2014). As wind turbines do not emit GHGs during their electricity production phase, wind power is often cited as an effective tool in mitigating or alleviating climate change (see for example Kaldellis and Apostolou 2017, p. 82). Hence, if optimal conditions for wind turbine operation are met, wind power has the potential to (i) decrease country's dependency on energy imports; (ii) tackle air and water pollution as well as alleviate climate change by decreasing the energy production share of fossil-fueled powerplants (and as such benefit human health); (iii) eliminate environmental and health issues linked to the extraction of non-renewable fuels. Based on data provided by Official Statistics of Finland (OSF) (2021a, 2021b), it could be concluded that alongside of hydropower, wind power's increase in the share of Finnish electricity production has caused a decrease in Finland's dependency on energy imports. In other words, as the share of domestic RESs (including wind power) has steadily been increasing, the amount of imported electricity has been on the decline.

In consequence, Finnish wind power represents a real-life example of the wind power's ability to contribute to state's energy sufficiency. Nevertheless, important to add is that factors such as domestic electricity consumption or the increasing share of hydro power and lastly, decrease in Finland's total electricity consumption have also most likely impacted the decrease of energy imports to Finland.

Despite the fact that many studies assessed life-cycle environmental impacts of wind turbines and farms in various global environments – in Germany (Schreiber et al., 2019) or Brazil (Oebels & Pacca, 2013). Thus, no study to this date focused on evaluating life-cycle environmental impacts of wind turbines and farms in the Finnish context. In addition, no study concentrated on Finnish wind farm's energy-payback time or compared forest environments and wind farm ability to alleviate climate change.

When we examine wind power from an environmental perspective, despite wind power's absence of direct CO_2 emissions and of other GHGs, such as methane (CH_4) or nitrous oxide (N_2O), there are climate as well as other environmental impacts associated with each of the wind turbines' life cycle phases. However, when compared to more conventional energy production sources, such as (black) coal, natural gas or lignite, wind power represents a more efficient tool in decreasing society's impact on climate from energy production (Šerešová et al. 2020, p. 8).

It is usually the manufacture of the wind turbine, which brings about the highest GHG emissions of all turbine's life-cycle phases (see for example Vestas 2017, p. 59, Garrett & Rønde, 2013 or Oebels & Pacca 2013, p. 65). In a study of Bonou, Laurent and Olsen (2016, p. 332), manufacturing phase covered about 80 % of turbine's total GHG emissions and the study of Guezuraga, Zauner and Pölz (2012) specified it was the tower construction that accounted for 55 % of the entire turbine production phase. Other life-cycle phases, such as transportation or maintenance of the turbine come with significantly lower GHG emissions. Depending on the applied life-cycle assessment (LCA) methodology for decommissioning of wind turbines, among other studies, recycling of wind turbine parts was considered in Martínez, Sanz, Pellegrini, Jiménez and Blanco (2009, p. 671) and Tremeac and Meunier (2009). In these studies, at the end-of-life phase, wind turbine part recycling was awarded with significant environmental credits, meaning that it lowered the turbine's total life-cycle GHG emissions. Ghenai (2012, pp. 28-29) compared the climate impacts of turbine recycling and landfilling and found that recycling of the wind turbine parts reduced GHG emissions by 55 %, specifically by 49 5917, 28 kg of CO_2.

Existing LCA studies have documented the "global warming potential" (GWP) (100 years) and energy payback time (EPBT) of on-shore wind farms in Brazil (Oebels & Pacca, 2013), Germany (off-shore wind farm *alpha ventus* in the North Sea) (Wagner et al., 2011), and of onshore wind farm in Turkey (Demir & Taşkın, 2013) and Sweden (Russ & Reid-McConnell, 2020). As a basis for their LCA study, some authors conducted LCA of a "typical 'virtual'" power plant (Vestas, 2019). These studies were conducted not only by people working in the academia but also by the wind turbine industry players themselves. However, no study to this date has documented the GWP and EPBT of a typical Finnish wind farm.

This study has three aims. The first aim is to calculate the typical Finnish wind farm's whole life-cycle carbon footprint (CF). The second aim is to find out the time period required to recover the equivalent amount of energy consumed by the typical Finnish wind farm throughout the same wind farm's entire life-cycle. The third aim is to observe whether the typical Finnish wind farm has a better net-negative impact on climate than the commercial forest, which used to grow on the wind farm's site before the wind farm's construction. On the basis of the abovementioned aims, the following three research questions were created and discussed in the thesis:

1) What is the typical Finnish wind farm's carbon footprint?
2) What is the energy payback time of the typical Finnish wind farm?
3) Does the typical Finnish wind farm have a better net-negative impact on climate than the commercial forest area on which it was built?

The typical Finnish wind farm represents a virtual wind farm that:

a) is located on-shore on the Finnish territory in North Ostrobothnia,
b) consists of 10 HAWTs (horizontal axis wind turbines) manufactured by Vestas and Nordex Group,
c) is built on a commercial forest area,
d) includes one transformer (substation) station to which the wind turbines were connected via underground cables,
e) requires 20 hectares of land,
f) is representative of the modern fleet of wind turbines.

The data collected for this study consists of the LCA reports conducted by wind turbine manufacturers that were audited by third parties (see for example Vestas, 2019). In some cases, turbine LCA was commissioned by a wind turbine manufacturer and conducted solely by a third-party (see for example Russ Reid-McConnell, 2020). Other data were retrieved through academic journals, data collection institutions and geographic information systems (GIS) software.

The structure of the thesis is following: At first, the study's most crucial terminology is introduced. Second, a very general introduction into wind power's technical side is followed by another general introduction to the current state of wind power in Finland. These general introductions are followed by a comprehensive evaluation of wind power's climate impacts, including the evaluation of climate impact of individual wind turbine's life-cycle phases. The following chapter on carbon sequestration (CS) of trees and soils bring closer to the readers the science of climate change mitigation through non-scientific means. Once the basic concepts are introduced, it is time to familiarize the readers with methodology, through which this thesis answers the three thesis questions answered in the following chapter – the findings. The results are then discussed in the discussion chapter. Any limitations identified in this thesis are brought forward together with suggestions for further research in the "Limitations and suggestions for further research" chapter. In addition, GIS analysis supporting the methodology chapter is put into appendices chapter located after the references chapter.

This study is conducted in cooperation with the Finnish Wind Power Association (FWPA), who commissioned it. The relationship between the researcher and the organisation was of a sponsorship character, meaning a financial reward was agreed on upon finalizing the thesis. The author of the thesis does not find any conflict of interests that would decrease the credibility, integrity and independence of the work conducted.

2 INTRODUCTION TO THE STUDY'S TERMINOLOGY

The purpose of this chapter is to create an understanding of concepts that are generally associated with conducting (life-cycle) environmental assessment of products and services. After reading the following subchapters, the readers should be able to understand the following concepts and their associated terms: LCA, CF, GWP (100 years) and (wind turbine) EPBT. In addition, the readers should also be able to comprehend the close relationship between LCA and CF.

2.1 Life-Cycle Assessment

The LCA is an internationally recognized voluntary environmental analysis tool evaluating the environmental impacts of a product or service (Jolliet, Myriam Saade-Sbeih, Shaked, Jolliet, & Crettaz, 2016, p. 7). The tool assesses environmental impacts of a product or service across its whole life-cycle, i.e., from raw material extraction to waste management (Baumann & Tillman 2004, p. 9). As such, it forms an essential part of circular economy (Contreras, 2015).

Evaluating the environmental impacts of a product or service throughout its entire life-cycle allows for a holistic understanding of the product's or service's impacts (Jolliet et al., 2016). With the help of the analysis, uncovering the "environmental hot-spots" may provide a fertile ground for improvements of product's or service's environmental performance (Baumann & Tillman, 2004). LCA may assist in scrutinizing the environmental impacts of already existing products and services or of not yet existing products and services in the design/planning phase (Jolliet et al. 2016, p. 7).

The most common and reasonable boundary for conducting LCA is cradle-to-grave (i.e., full life-cycle assessment). This means that the product's or service's life-cycle begins with raw material acquisition and ends with waste management. Partial LCA, such as gate-to-gate (manufacture) may be conducted as well. However, such LCA might lead to spill-overing or exporting the environmental impacts to other LCA phases of the product's or service's life-cycle. In other words, the holistic overview of environmental impacts prevents LCA practitioners to focus solely on one life-cycle phase (e.g., manufacturing) while ignoring the possible negative impacts of such improvement on waste management or other LCA's phases. (Jolliet et al. 2016, pp. 1, 10.) Therefore, in considering the full, cradle-to-grave LCA, allows the commissioners or decision-makers to make reasonable improvements of a product or service.

Jolliet et al. (2016) further claimed that conducting full LCA is time and resource (financially) consuming. In order to reduce the time and resources used, Horne, Verghese and Grant (2009) suggested to conduct "streamlined LCA", which, apart from other characteristics, simplifies the LCA study while simultaneously reduces the time and financial resources. The International Organisation for Standardization (ISO) provides LCA practitioners with general principles and framework for conducting LCA. According to the organisation, LCA represents:

> *"- - compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle - -." (ISO 14040:2006, 2006)*

There are currently more than two ISO standards working with LCA. For example, while ISO 14040:2006 addresses the "Principles and framework" for conducting LCA, the ISO 14044:2006 takes on LCA's "Requirements and guidelines". Presented in Klöpffer et al. (2014, p. XII), the ISO 14040:2006 defines the four stages for conducting LCA in the following way:

1. Goal and scope definition
2. Life cycle inventory analysis
3. Life cycle impact assessment (LCIA)
4. Interpretation.

The standard has also been criticized by various authors for its lack of detail in describing the tool as well as for the lack of guidance in undertaking different phases of the assessment (Baumann & Tillman, 2004 and Jolliet et al., 2016). For instance, the ISO 14040:2006 only provides headlines for impact categories such as resource use, ecological consequences, and human health (see for example Baumann & Tillman, 2004).

Apart from the environmental domain of life-cycle assessment, the assessment may also be used in other domains – for example in the economic domain (Life cycle costing – LCC) or social domain (Social life cycle assessment – S-LCA). The Life-cycle sustainability assessment (LCSA) brings together the environmental, economic, and social domains, or in other words the "triple bottom line". The LCSA of a product provides a holistic understanding of a product's or service's life-cycle in all the three domains. (UNEP/SETAC Life Cycle Initiative, 2012.) Before continuing to the "CF" chapter, there are four crucial concepts of LCA to be still introduced in this chapter. These are:

a) Functional unit
b) System boundary
c) Environmental indicators, and
d) Global Warming Potential (GWP 100 years)

The concepts are important to comprehend for furthering the reader's understanding of this study.

2.1.1 Functional unit

The first one is functional unit, which quantitatively describes the function of the product (or service) studied. The FU represents a value based on which all calculations in the impact assessment phase of LCA are made. (Arzoumanidis, D'Eusanio, Raggi & Petti, 2020.) A real case example of how a functional unit can be defined was brought from LCA of a wind turbine manufactured by the company Vestas (V105-3,45 MW):

> *"1 kWh of electricity delivered to the grid by a 100MW wind power plant." (Vestas 2017a, p. 14)*

The environmental impacts of this wind turbine were related to the above presented FU. In deconstructing the FU of that specific wind turbine, we could say that when a 100MW wind power plant produced 1 kWh of electricity that was delivered to the grid, that 1 kWh of electricity impacted, for example, the climate (global warming potential), water quality (e.g., eutrophication potential) or human health (human toxicity) to a specific (numerical) extent (Vestas 2017a, p. 15).

In that specific LCA report of the V105-3,45 MW turbine the wind power system was expected to emit 4,8 grammes (g) of CO_2 to the atmosphere for every 1 kWh of electricity it produced. Important there is to note that first, the 4,8 g of CO_2 equivalent 1 kWh included full life-cycle CO_2 emissions of the studied wind power system and second, the final GWP value is based on specific methodological choices made in the LCA report of the V105-3,45 MW wind turbine (plant).

Despite the fact the abovementioned FU mentioned "100 MW wind plant", the important factor there is that the results related to *"1 kWh of [produced] electricity delivered to the grid"*. A way to depict those impacts on a single turbine scale is to relate the environmental impacts per 1 kWh of electricity produced to the average amount of electricity produced in a year by single wind turbine. As an example, in Eq. (1), a single V105-3,45MW (Vestas 2017a, pp. 36 and 51) turbine's impact on climate over turbine's baseline (20 year) lifetime could be calculated as follows:

Impact on climate of the V105-3,45MW (20-year lifetime =

14 987 000 (kWh of electricity produced per year by a single V105-3,45 MW turbine)

* (1)

4,8 (g CO_2e/kWh of the V105-345MW turbine)

*

20 (turbine lifetime in years)

The Eq. (1) shows that the V105-3,45 MW turbine 20-year CF was 1 438 752 kilograms of CO_2 or 1,4 tonnes (t) of CO_2. In conclusion, (i) the greater the amount of electricity produced by a wind power (farm or a turbine) and (ii) the lower the amount of grams of CO_2 emitted per 1 kilowatt hour (kWh) of produced electricity by the same system is, (iii) the lower the impact on climate the wind power (farm or a turbine) has.

2.1.2 System boundary

The second LCA related concept is system boundary. The creation of product's or service's system boundary is guided by the goal and scope defined in LCA. The result of this process is a flowchart. The flowchart depicts the study's technical system, where boundaries, such as "cradle-to-grave", are set. (Baumann & Tillman 2004, pp. 25-26.)

According to Baumann and Tillman (2004, p. 26), only flows that are "environmentally relevant" are included in the system boundary. Examples of environmentally relevant flows introduced by the same authors were "use of scarce materials" as well as "emissions of substances", which are considered harmful.

Horne, Verghese and Grant (2009) stated that if a system is to be analyzed, then boundaries to that system are necessary and need to be identified carefully. The need to carefully identify boundaries of a studied system stems from the fact the boundaries impact (Verghese & Grant, 2009):

1) resource and data collection,
2) type of data to be collected, and
3) environmental impacts that are going to be assessed in the study.

An example of a flowchart in Figure 1 below was derived from Schreiber et al. (2019, p. 565), who in their comparative LCA of different wind turbine types provided the readers with a well-illustrated cradle-to-grave system boundary of a wind turbine. The included system boundary consisted of supply of raw materials, manufacturing, transportation, wind turbine assembly and its operation, maintenance, and finally, decommissioning, that is dismantling and waste disposal (Schreiber et al. 2019, p. 565).

According to ISO (14044, 2006) as cited in Edelen, Ingwersen, Rodríguez, Alvarenga, de Almeida and Wernet (2017, p. 2), the elementary input flows (or *inflows*) refer to material, energy or space resources that are utilized directly from the environment and used for the processes included in the product's system boundary. Interestingly, the elementary flows also refer to *outflows*, that is to material, energy or space resources that are returned back to the environment. In the wind farm case, electricity to the grid and emissions to air, land and water are all representing the system's *outflows*.

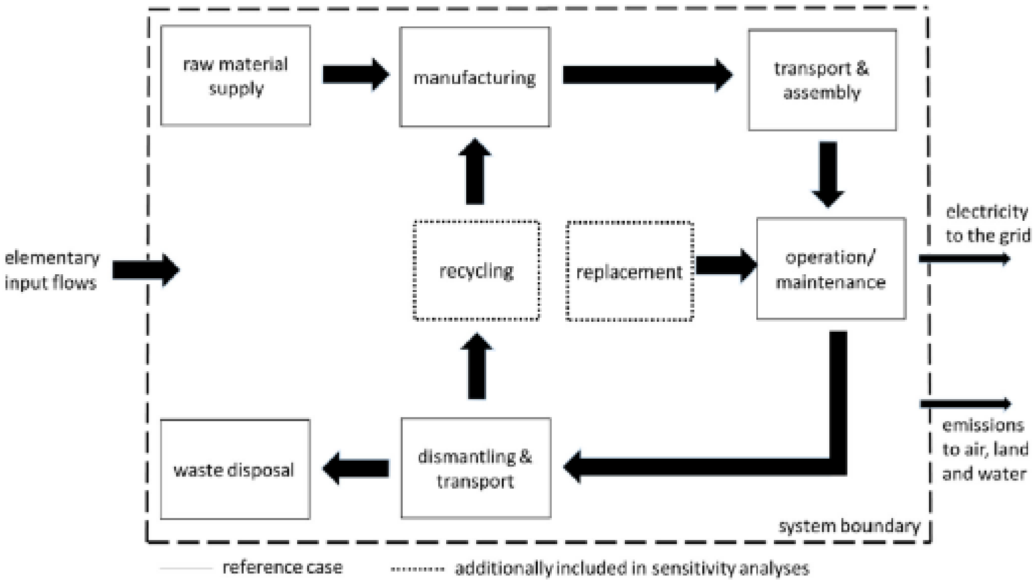


FIGURE 1 LCA system boundary of analyzed on-shore wind turbines in Schreiber et al. 2019, p. 565

2.1.3 Environmental indicators

The third concept regards LCA's environmental (characterisation) indicators, which are sometimes named as "environmental impact categories" or simply "impact categories" (Baumann & Tillman, 2004, Vestas 2017a, p. 15 and Curran 2012, p. 24). Environmental indicators help LCA practitioners to translate environmental loads into environmental impacts in the "life-cycle impact assessment" stage of conducting an LCA (Baumann & Tillman 2004, p. 144). Some of the indicators are acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), human toxicity or chemical oxygen demand (COD) (Baumann & Tillman 2004 and Vestas 2017a, p. 15). For the purpose of the thesis, the most important indicator was GWP, which is introduced in the following chapter.

2.1.4 Global Warming Potential

The last introduced concept of LCA focuses on the global warming potential. In LCA, GWP represents a characterisation indicator, which denotes the potential contribution of a substance – in this case of greenhouse gas(es) - to climate change (Baumann & Tillman 2004, p. 149).

GWP of different GHGs can be calculated for time spans of 20, 100 and 500 years. In this Master's Thesis, the GWP was always calculated for the lifespan of 100 years. Although CO_2 is recognized as the main greenhouse gas presented under GWP (Curran 2012, p. 542), there are other greenhouse gases presented under GWP, such as:

a) Methane (CH_4)
b) Nitrous oxide (N_2O),
c) Chlorofluorocarbons (CFCs),

d) Hydrofluorocarbons (HFCs),
e) Hydrochlorofluorocarbons (HCFCs),
f) Perfluorocarbons (PFCs),
g) Carbon tetrachloride (CCl_4),
h) Methyl chloroform (1,1,1-trichloroethane), and
i) Sulphur hexafluoride (SF_6).
(Wright et al., 2011; UNEP, n.d.; Myhre et al., 2013 and Forster, 2007.)

Nevertheless, in order to define the multitude of GHGs presented under GWP, all of the GHGs in GWP are related to CO_2. In other words, GWP depicts a ratio of CO_2 in relation to other GHGs. The ratio is based on the amount of heat a GHG (except CO_2) is capable of trapping in the atmosphere. The amount of heat (value) trapped is then compared with the amount of heat trapped by similar mass of CO_2 (Holtsmark 2015, p. 199). The GWP of a substance was in Baumann and Tillman (2004) defined as:

> *"- - the ratio between the increased infrared absorption it [for example CH_4] causes and the increased infrared absorption caused by 1 kg of CO_2."* *(p. 149)*

In other words, the ratio relates other GHGs solely to CO_2. The CO_2 value is always 1 kilogram (kg) that is equivalent (CO_2e or CO_2eq) to kg of other substance presented in GWP (Baumann & Tillman 2004, p. 510). However, the value (1 kg of CO_2) may also be represented in grams of CO_2 (Wright et al. 2011, p. 68). The following subchapter introduced the CF in which the GWP plays an essential role (Jolliet et al. 2016, p. 12).

2.2 Carbon Footprint

This chapter will introduce to the readers what CF (analysis) stands for.

Throughout decades, many authors have tried to provide a definition of the term CF (Wiedmann & Minx, 2008; Wright et al., 2011). Wiedmann and Minx (2008) provided the following definition of the CF:

> *"The carbon footprint is a measure of the exclusive total amount of carbon dioxide [CO_2] emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product." (p. 4)*

The "indirect" and "direct" nature of GHG emissions is of special importance when studying the climate impact of a renewable energy source that operates without direct GHG emissions. In addition, Jolliet et al. (2016, p. 12) reached the same conclusion as Wiedmann and Minx (2008) in that CF scrutinizes the indirect and direct GHG emissions but extended the subject of the study from product to human activity and business as well.

However, the presented definition only recognized one GHG: CO_2. As already noted in the previous chapter, apart from CO_2, the GWP recognizes many other GHGs. However, according to Wiedmann and Minx (2008, p. 5), the other GHGs were either not based on the carbon (C) molecule or were difficult to quantify. Although some of the reviewed studies for this thesis did use the word "CF", they referred to the GWP's CO_2e (see for example Bonou et al. 2016, p. 330 and Besseau et al. 2019, p. 282).

This example also emphasizes the fact that CF is often tightly linked to the GWP by using GWP's "mid-point" impact (Wiedmann & Minx 2008, p. 2), that is "g", "kg" or "t" of CO_2e. Weidema et al. (2008) argued that the most common unit for measuring the results of CF is CO_2e. However, CF may also be expressed as a "pressure indicator" declaring the amount of C emissions (Wiedmann & Minx 2008, p. 2).

There has, however, been a debate over what GHGs should be included in the CF. While some of the authors agreed only on the inclusion of CO_2 (see e.g. Wiedmann & Minx, 2008), other authors suggested the addition of other GHGs, such as CH_4 (Wright et al., 2011). As Wright et al. (2011, p. 62) noted, little consensus has been achieved when it comes to defining the CF and some of the most common areas of conflict have been over the metrics, methods or over the CF's life-cycle perspective. In addition, Wright et al. (2011) not only emphasized but also justified the need for such unity in defining the CF by stating that:

> *"A clear, workable and universally accepted definition is fundamental to the development of national and international targets, legislation and standards." (p. 62)*

Weidema et al. (2008, p. 3) indicated that the disunity or the lack of universally agreed definition of CF stems from the fact research on CF has been promoted and diffused mostly by for-profit companies, non-governmental organisations (NGOs) as well as by different private initiatives. Despite this, the same authors claimed that CF has received large amount attention from the public, partially due to the increasing awareness about global warming and partially because of its simplicity and therefore easiness to understand and put results of the indicator into context. Nevertheless, because of its simplicity, Weidema et al. (2008, pp. 3-4) argued that the CF does not provide its audience with a well-informed and holistic description of the product's or service's environmental impacts. This is something LCA is capable of, yet, as Weidema et al. (2008, pp. 3-4) argued, the complexity and detail-focused nature of LCA is more difficult to not only grasp, but also to communicate to the general public.

In the context of conducting full (cradle-to-grave) LCA, when including all the GHGs, Wright et al. (2011, pp. 61, 69) suggested to refrain from using the term CF. Instead, the term "climate footprint" was proposed. According to the same authors, the "climate footprint" would reflect the presence of other non-C based gases as well.

2.3 Energy Payback Time

The EPBT (or EPT) denotes a time period for which an energy source (in this case a wind turbine or a wind farm) needs to operate to recover the same (equivalent) amount of energy that was used during the turbine's or farm's entire life-cycle – from cradle-to-grave (Guezuraga et al. 2012, p. 38). The EPBT uses wind turbine's or farm's "net energy value" (without energy losses) of electricity produced as the basis for reaching turbine's or farm's "breakeven" point. The point is reached once turbine's or wind farm's produced energy and their energy consumed are equal. (Guezuraga et al. 2012, p. 38 and Vestas 2017a, p. 75.) The EPBT value is expressed in months (Chipindula, Botlaguduru, Du, Kommalapati & Huque 2018, p. 11 and Vestas 2011, p. 62).

Contrary to the full-life cycle approach, Kadiyala, Kommalapati and Huque (2017, p. 58) stated that EPBT considers only the production (assuming manufacture) and operation (assuming turbine's or farm's operation and maintenance) of the wind electricity generation system, i.e. of a turbine or a wind farm. In consequence, the proposed system boundary of EPBT by Kadiyala et al. (2017, p. 58) left out other life-cycle stages, such as raw material extraction, transportation, and end-of-life treatment. It is nevertheless important to note that in their article, Kadiyala et al. (2017) did not specify what are the boundaries for "production" and "operation" phases of LCA.

Other authors, such as Weinzettel, Reenaas, Solli and Hertet (2009) were in consensus not only with the definition but also with system boundary of EPBT proposed by Guezuraga et al. (2012), thereby confirming the inclusion of wind turbine's or entire farm's full life-cycle. The definitions by Guezuraga et al. (2012) and Weinzettel et al. (2009) were also cited in Demir and Taşkın (2013, p. 258) and Kaldellis and Apostolou (2017, p. 77), which only increased the credibility of the proposed method for calculating the EPBT. In summary, the EPBT scrutinizes the energy balance of a wind turbine or a farm (Vestas 2017a, p. 75).

Chipindula et al. (2018, p. 12) found that with increasing nominal (rated) power (also known as "nameplate capacity") of a wind turbine, that is the maximum power output of a turbine, the EPBT decreases. This trend is shown in Figure 2 below representing turbines with various nameplate capacity. Please note only the onshore wind turbine category wind turbines is relevant to this Master's Thesis.

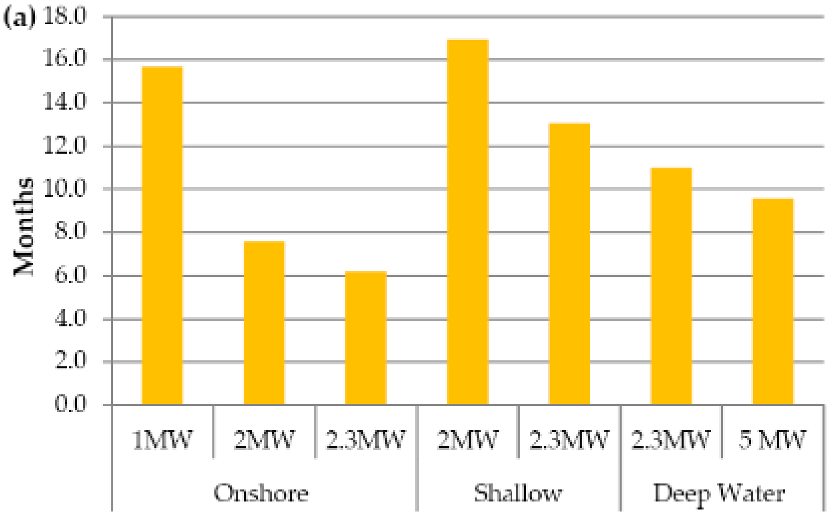


FIGURE 2 The wind turbine size-dependent impact on EPBT (in months) placed in three different areas as depicted in Chipindula et al. (2018, p. 12)

As shown in the Figure 2 above, doubling the turbine's nameplate capacity cut the EPBT in half. However, adding 300 kilowatts (kW) represented a less striking improvement in turbine's EPBT. Therefore, the Figure 2 suggested that the greater the increase in turbine's nameplate capacity, the shorter the amount of time needed to produce the equivalent amount of electricity.

3 WIND POWER

In this chapter, wind power-associated terms, the current state of Finnish wind power as well as wind power's climate impacts are introduced. In addition to that, wind power's climate impacts are shortly compared to other energy sources.

3.1 Wind turbine structure and placement

Generally speaking, wind turbines can be divided into two turbine types: HAWT and VAWT. HAWT stands for "horizontal axis wind turbine" and VAWT for "vertical axis wind turbine". The following section reviewed only HAWTs as only these were included in the typical Finnish wind farm. Kadiyala et al. (2017, p. 57) argued that HAWT are the most widely adopted wind power generation systems due to their outstanding electricity generation ability when compared to VAWT. The same authors further claimed that VAWTs are usually adopted in smaller wind power projects due to their lower electricity generation ability when compared to HAWT. The Figure 3 demonstrated the contrast between HAWT and VAWT:

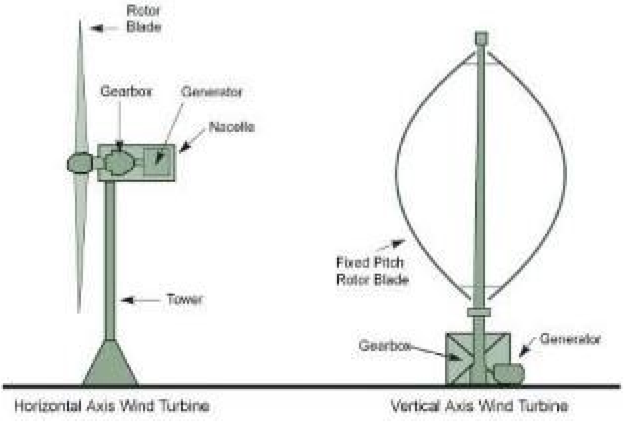


FIGURE 3 Example of a horizontal axis wind turbine (HAWT) (left) and vertical axis wind turbine (VAWT) (right) and their associated components (Plug in India, 2019)

The following Figure 4 also provides the readers with a brief outline of the terms associated with wind turbine measurements. The depicted turbine was Enercon's E126 wind turbine as shown in Saffour and Omar (2010):

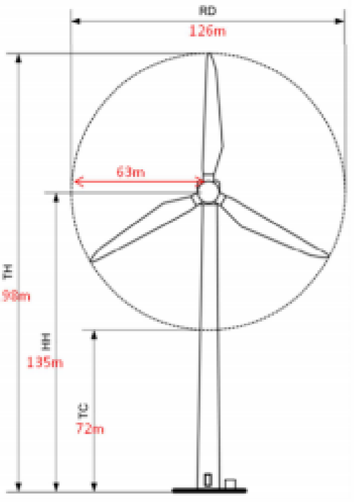


FIGURE 4 Illustration of the terms associated with wind turbine's dimensions: RD = rotor diameter; TH = tip height; HH = hub height; TC = tip clearance.

There have been three designated areas for installing the HAWTs – on-shore and off-shore in shallow water and off-shore in deep water. While on-shore and off-shore shallow water wind turbines are attached to the Earth's surface (personal communication of Byrne and Houlsby as cited in Beuckelaers 2017, p. 4), deep water wind turbines float in the water (Weinzettel et al., 2009). In addition to the floating deep-water turbines, Xu, Larsen, Shao, Zhang, Gao and Moan (2021) conducted a comparative analysis of floating (mooring) systems in shallow waters, thereby exploring the possibility of floating wind turbines in shallow water as well. However, the greatest emphasis in this thesis was on on-shore wind turbines because of which off-shore wind turbines were not discussed in any greater detail.

3.2 Turbine grid connection and nominal (rated) power

The basis for calling wind power a renewable energy source comes from the fact that wind turbines convert air's kinetic energy into rotational kinetic energy (Royal Academy of Engineering, 2010). The wind turbine's generator placed in the turbine's nacelle turns the mechanical (rotational) kinetic energy into electricity (Demir & Taşkın 2013, p. 253). The electricity produced by wind turbine(s) is collected via underground cables to a substation (or transformer station) in which the electricity is transformed and sent to an electricity grid (DNV GL 2019, p. 11). In case of off-shore wind turbines, there is a "middleman" between the turbines(s) and the (on-shore) substation – the off-shore substation. The following Figure 5 illustrated this turbine-grid relationship:

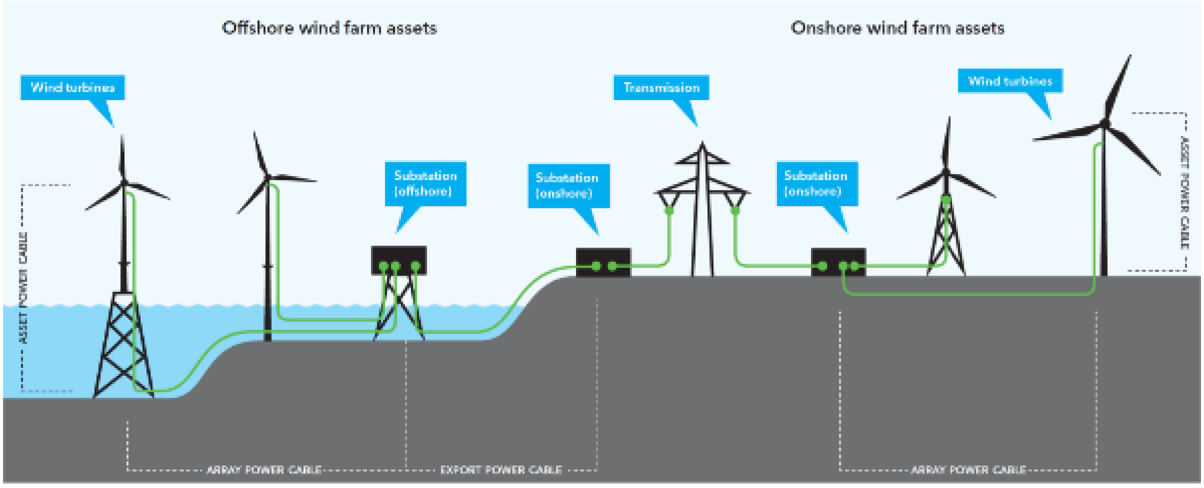


FIGURE 5 Illustration of the off-shore and on-shore wind turbines' connection to the local electricity grid (DNV GL 2019, p. 11)

When speaking of wind turbine's nominal (rated) power/nameplate capacity, according to Vattenfall Oy (2021), wind turbine's nameplate capacity is reached when the wind speed is about 12-14 meters per second (m/s). In other words, if turbine's nameplate capacity is 4,2 megawatts (MW), at wind speeds of about 12-14 m/s, the turbine reaches its maximum production capacity, i.e. nameplate capacity. The wind speed at which a wind turbine produces its rated power is also referred to as "rated wind speed" (Beig & Muyeen, 2016).

Therefore, at optimal environmental conditions (one of these being wind speed), the turbine's nameplate capacity or nominal (rated) power can be reached, yet not exceeded as shown in the Figure 6 below (Besseau et al. 2019, p. 279). Before introducing the following Figure 6, two terms had to be introduced to the readers - these were "cut-in wind speed" and "cut-out wind speed". The first term refers to a situation during which a turbine begins to rotate and so produce electricity. A typical cut-in wind speed of Vestas's turbines is three meters per second (m/s) in both, on-shore, and off-shore wind turbines (Vestas, 2022e & 2023). The second term stands for a wind speed at which wind turbine ceases its operation using either mechanical or aerodynamic braking systems (the latter is the primary braking system of the wind turbine) (Navin kumar, Rajendran, Vasudevan & Balaji 2020, p. 3970). For on-shore wind turbines, this can be 25 m/s (Vestas, 2022c), in some cases 26 m/s (Nordex SE, 2023).

The Figure 6 below derived from Besseau et al. (2019, p. 279) shows cut-in and cut-out wind speeds of Vestas's V90 on-shore wind turbine with nameplate capacity of 2000 kW (2 MW). The figure shows that the turbine began its operation at its cut in wind speed of 4 m/s and ceased its operation at 25 m/s. Furthermore, the turbine's maximum power output was reached at rated wind speed of about 12,5 m/s and according to the turbine's manufacturer the turbine should sustain its maximum power output until 25 m/s, which is where the turbine should engage its braking system to prevent turbine damage as a result of very high wind conditions (Vestas, 2011b.)

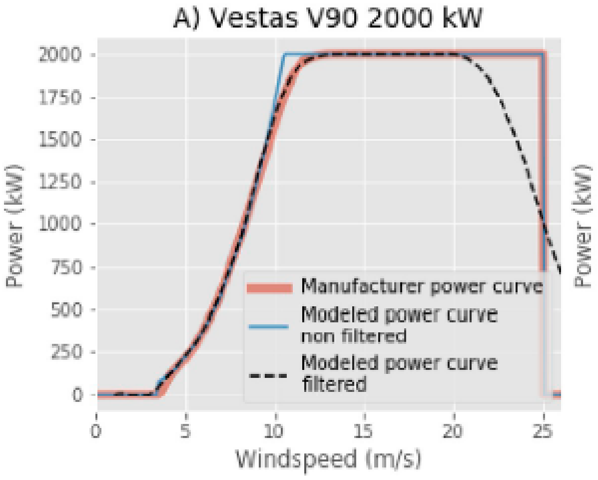


FIGURE 6 The utmost output of electricity produced by Vestas's V90 wind turbine as modelled in Besseau et al. (2019, p. 279).

3.3 Wind power in Finland

In the last decade, wind has become a significant energy source in Finland, one of the reasons being that the Finnish climate is suitable for harnessing energy from the wind (Leino & Joensuu 2021, p. 2). As of December 2020, there were 821 operating wind turbines in Finland. Their utmost electricity generating capacity (also known as *nominal* or *rated power*) was 2586 megawatts (MW). In the same year, Finnish wind power production covered about 10% of the total Finnish electricity consumption, more specifically 7,8 terawatt hours of electricity. (Leino & Joensuu, 2021.)

In 2019, the 754 of Finnish wind turbines had a nominal capacity of 2284 MW (AFRY Finland Oy 2020, p. 7). Throughout the year, the wind turbines did not produce electricity at their rated wind speed as wind conditions varied. In the same year, the average capacity factor of Finnish wind turbines built between 2011 and 2018 was 33% (Finnish Wind Power Association [FWPA], n.d.a). The capacity factor represented a percentage at which the turbines produced electricity at their rated wind speed in relation to hours of a whole year (VTT Technical Research Centre of Finland [VTT], 2020). In practice, the 754 wind turbine's nameplate electricity generation capacity per year was about 20 007 840 megawatt hours (MWh) (2284*24*365) out of which 33% represented 6 602 587,2 MWh, or 6 602,58 GWh. Thus, in 2019, approximately 6 602 GWh of electricity was produced by wind turbines operating in Finland.

On average, Finnish wind turbines are capable of producing almost double the amount of energy during winter months than during summer months (Huotari, 2020 & VTT, 2020). According to Huotari (2020), the capacity factor (or efficiency) of Finnish wind farms in July represented on average only half of the efficiency of wind turbines in winter months. Such fact creates a situation where greater electricity consumption during winter months is accompanied by greater electricity production of the Finnish wind farms. As such, it is possible to claim wind power is a suitable energy production form in cold climates and according to the FWPA (n.d.b), wind power already represented the most cost-effective source of energy.

In recent years, Finland has been experiencing a steady increase in the construction of new wind farms. Between 2020 and 2022, 645 wind turbines were constructed and their total nominal power was 3403 megawatts (MW) (FWPA, 2021, 2022a & 2023). Once we compare these to the 756 turbines installed between 1993 and 2019 with a nominal power of 2288 MW, we can observe the massive pace of technological development as well as the enormous speed of construction of wind farms. As a result, never before has Finland been facing such a massive increase in importance of wind power (AFRY, 2020). The vast majority of Finnish wind turbines have been built on land (on-shore). The number of wind turbines built on the sea (off-shore) has been falling behind onshore wind turbines yet there has been an interest in building offshore wind farms in Finland too (FWPA, 2021).

Figure 7 below illustrates the yearly increase in gigawatt hour of produced electricity by wind power in Finland. The steeply increasing trend could be explained by the already mentioned popularity of wind power construction in Finland.

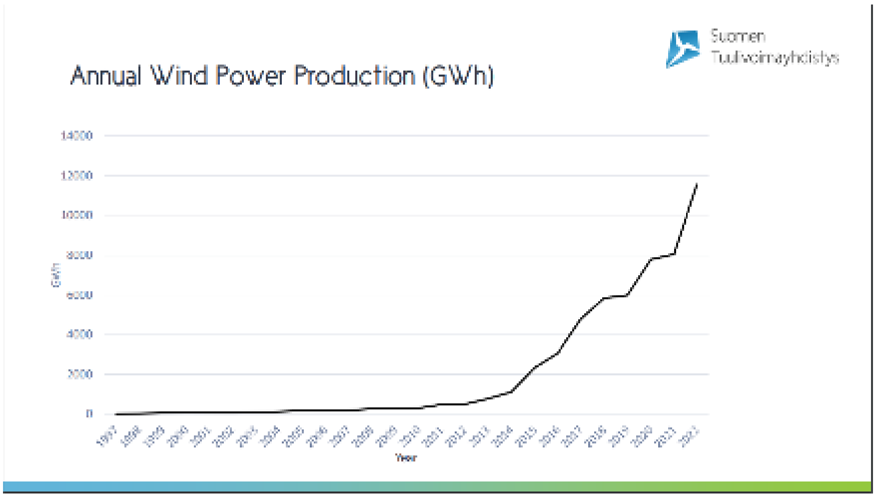


FIGURE 7 Yearly wind power production in gigawatt hour (GWh) (FWPA, 2023)

The increasing amount of electricity produced by Finnish wind turbines has also been considerable considering the whole Finland’s energy mix. According to the preliminary results of Official Statistics of Finland (2021a), in 2020, Finnish (82%) and foreign (18%) energy sources combined together (100%) supplied the Finnish energy grid with 81,5 terawatt-hours (TWh) of electricity. Of the domestic 82% (66,6 TWh) of electricity produced, 52% (34,7 TWh) of electricity was supplied by RESs out of which hydro power and wind power (23%) made the largest increase in supplied electricity, by 45% and 23% respectively. When compared to the year 2019, the total amount of electricity produced by Finnish wind turbines in 2020 increased by 32%, from 5985 (GWh) to 7 970 (GWh) or 7,9 TWh of electricity. The 7,9 TWh of electricity represented 12% of the total Finland’s electricity supply. (OSF, 2021a.)

The FWPA (n.d.c) claimed that in Finland, the wind industry’s objective has been to reach at least 30 TWh of annual wind power production by 2030. According to the same source, this corresponded to 30 percent of the total electricity consumption in Finland. Furthermore, in the memorandum by Leino and Joensuu (2021, p. 2), it has been predicted that the cumulative capacity (in MW) of installed wind turbines would increase twofold by the end of 2023.

3.4 Climate impact of wind power

3.4.1 Defining “indirect” and “direct” GHG emissions

At first, based on the reviewed literature, “indirect” and “direct” GHG emissions are defined in the following way (see for example Bhandari et al. 2020, p. 1; Kaldellis & Apostolou, 2017 or Schreiber et al., 2019):

1) Indirect GHG emissions were all GHG emissions associated with each and every life-cycle phases of the studied wind turbines, such as raw material extraction, manufacture, transportation, installation, operation (maintenance) and decommissioning.
2) Direct GHG emissions were all GHG emissions associated solely with the wind turbine’s electricity production phase, such as using air’s kinetic energy and transforming this energy into electricity through wind turbine. This phase excludes maintenance (or service) during wind turbine’s operation phase.

The need to define “indirect” and “direct” GHG emissions stemmed from the necessity to, first, emphasize the fact that air’s kinetic energy, which leads to spinning of wind turbine’s blades while transforming this energy into usable electricity comes with no GHG emissions. Secondly, it was important to differentiate direct GHG emissions of wind power from other energy sources that emit direct GHG emissions during their electricity production phase, such as coal, biomass, oil, or even nuclear power as water vapor is a greenhouse gas.

However, in using input-output LCA (IO-LCA) to study CF of a typical Chinese wind farm, Ji and Chen (2016) assigned the studied wind farm with direct emissions as well. In the same study, the wind farm’s direct emissions represented scientific research, construction, electric equipment, and machinery (p. 254). Furthermore, the same authors also criticized other LCA studies for applying the so called, Process Life Cycle Analysis (PLCA), which according to them could overlook important factors in firm’s supply chain interactions and at the same time could cause errors in emission calculations (p. 251).

The literature review showed that most of the reviewed studies of LCA of wind power and wind power related LCA literature reviews performed the so called, “conventional LCA”, which studied wind turbine’s life-cycle phases set in the system boundary (Kadiyala et al. 2017, p. 57). Thus, the PLCA (conventional LCA) as criticized by Ji and Chen (2016) seemed to be more widely spread LCA practice than IO-LCA.

3.4.2 Carbon footprint of on-shore HAWTs

Wind power has been presented as a sustainable and renewable energy source together with hydropower, geothermal energy, solar energy, or biomass (Gareiou, Drimili & Zervas, 2021). It is often recognized as C-free energy source because its energy source – wind - powers the turbine's blades through its kinetic energy (Royal Academy of Engineering, 2010). Such recognition is, however, misleading and might lead to a biased perception that the electricity production phase of a wind turbine is free not only from direct but also from indirect emissions. This is not the case as there are environmental impacts, such as air pollution (release of greenhouse gases) associated with each and every life-cycle stages of the wind turbine - from "raw material extraction" to turbine's "end-of-life" treatment. Thus, wind power is free from direct emissions because it utilizes wind as an energy source and the process of electricity production does not release any fumes to the atmosphere (direct emissions). However, indirect GHG emissions are presented also during turbine's operation (electricity production) phase (Demir & Taşkın 2013, p. 253), which is partially illustrated in the following Figure 8 borrowed from Mendecka and Lombardi (2019, p. 473)

Figure 8 provides a fairly detailed description of wind turbine's life-cycle phases. The figure presents LCA's system boundary of on-shore and off-shore wind turbines reviewed in Mendecka and Lombardi (2019) while following the structures of ISO 14040 and 14044. The reviewed LCA studies applied "1 kWh of electricity generated by wind turbines" as their functional unit and the environmental indicators were acidification potential, eutrophication potential, GWP and cumulative energy demand (CED).

Figure 8 uses a "cradle to grave" boundary for determining the environmental impacts. In this case, the study began with "raw materials extraction" followed by transportation of raw materials to a "raw material" processing facility. From this facility, the processed materials continued to another facility in which wind turbine components were manufactured. The manufactured components were then transported to the wind turbine site, where parts of the wind turbine were constructed together. Once this step was completed, the wind turbine began to operate (produce electricity). The wind turbine operation phase involved maintenance. The indirect nature of GHG emissions resulting from maintenance was, as already noted, partially illustrated in this step with raw materials representing an inflow in "WT operation". Nevertheless, "emissions to air" as a result of (i) transportation of raw materials by maintenance crew to the site or, (ii) in case raw materials were already present at the site, transportation of the maintenance crew to the site, were left out from the Figure's 8 system boundary altogether.

In Figure 8, "background system" refers to all the processes regarding the production of flows entering the system (primary energy, raw materials, and water) while addressing the exiting flows (emissions). "Foreground system" considered the manufacture, assembly, and operation of the turbine. The last step depicts the wind turbine's "end of life" in which wind turbine materials were either recovered through recycling or disposed as a waste to, for example, landfill.

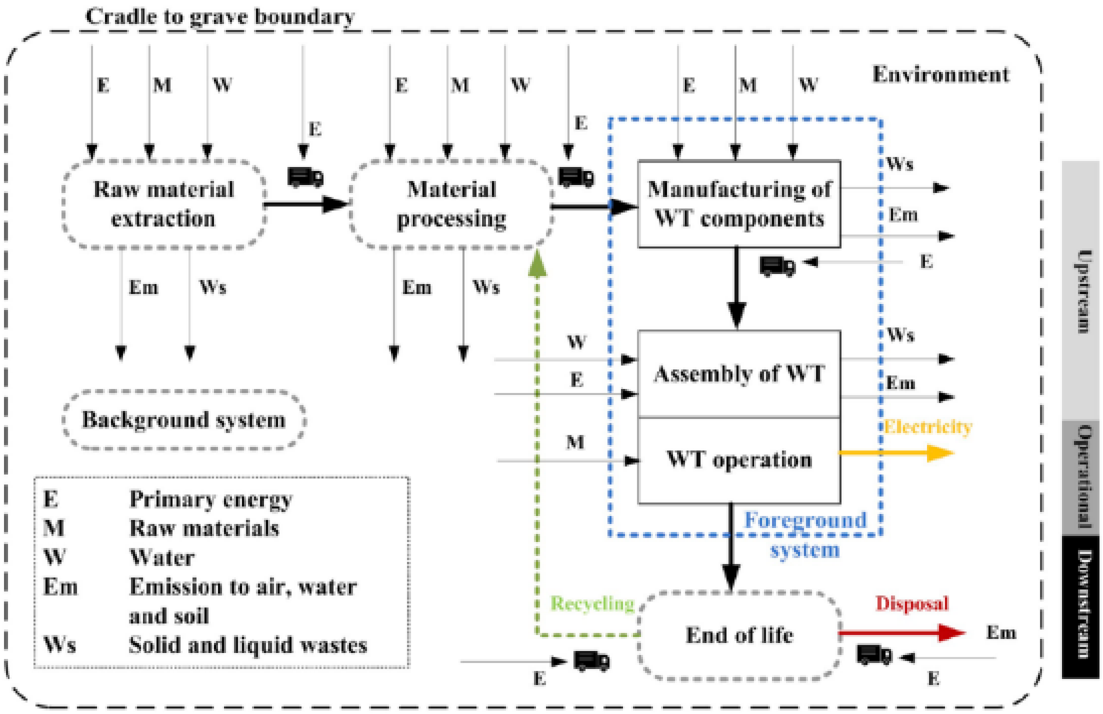


FIGURE 8 A fairly detailed system boundary of a wind turbine as presented in Mendecka and Lombardi (2019, p. 473).

Concerning maintenance in detail, indirect GHG emissions in wind turbine operation phase are born because wind turbine's need for maintenance, which include (at minimum) transportation to the turbine for turbine or farm regular check-ups (Schreiber et al., 2019). For example, in LCA study of Vestas's V105-3,45 MW wind turbine, the estimated transportation of the maintenance crew to one wind plant/farm was 2880 km per year (Vestas 2017a, p. 39). Additional environmental impacts stemming from maintenance are born once there is a need for oil replacement, greasing of parts (preventive maintenance) or when some of the turbine's parts need to be replaced (Siemens Gamesa Renewable Energy 2014, p. 12 and Greco, Sheng, Keller & Erdemir 2013).

Nevertheless, the amount of indirect GHG emissions contributing to the GWP (100 years) indicator as a result of turbine maintenance was found to be negligible, especially when compared to other life-cycle phases of a wind turbine, such as turbine manufacture (see for example Vestas 2017a, p. 59, Demir & Taşkın 2013, p. 254 or Oebels & Pacca 2013, p. 65). The negligible impact of indirect emissions stemming from turbine maintenance during turbine's operation phase was even more apparent once compared to direct GHG emissions of fossil fuel based powerplants. According to Turconi, Boldrin and Astrup (2013), direct GHG emissions stemming from fossil fuel-powered plant operation (electricity production phase) accounted for majority of the life-cycle GHG emissions of the studied fossil-fuel power plants. In the same study, the represented fossil fuels were hard coal, lignite, natural gas, oil.

Thus, regardless of the variability in wind's availability, as wind is used as the major turbine's on-site energy source, then significant environmental impacts stemming from the electricity production phase are avoided. The on-site availability of wind makes the whole energy-production process a lot simpler too as there is not a need to obtain fuel from external sources, which, in the example of wood or coal, brings additional environmental impacts related to extraction, processing and transportation of fuel to the powerplant(s).

3.4.3 Climate impact of wind turbine life-cycle phases

In literature review of LCA studies of wind turbines published in the past 20 years conducted by Bhandari et al. (2020, p. 8), the authors noted that the most common LCA boundary for wind power should be "cradle-to-grave". However, the same authors found a large inconsistency among methodological choices among the reviewed studies, more specifically in terms of the reviewed studies' assumptions, limitations and boundary setting made in their LCAs (p. 3). In another literature review of LCA of off-shore and on-shore wind turbines by Arvesen and Hertwich (2012, p. 5997) noted that the only life-cycle phase common to all the reviewed studies was "manufacturing phase". Such fact further emphasized the discrepancy among the LCA studies, which also hindered direct comparisons among the studies.

As an example, in the studies of Chipindula et al. (2018, p. 6) and Oebels and Pacca (2012, p. 3), the wind farm's substation (or transformer station) was excluded from the system boundary and as a result from the LCA study itself. Contrary to these authors, Bonou et al. (2016, p. 334) as well as Vestas (2017a, p. 12) did include substation in assessing wind power's environmental impacts.

The discrepancy in life-cycle phase-assignment of GHG emissions has its roots in methodological differences of the reviewed LCA studies of wind turbine. As already mentioned, Bhandari et al. (2020, p. 3) pointed out that there were discrepancies in LCA studies of wind turbines and the methodological differences among the literature reviewed by Arvesen and Hertwich (2012) and LCA of wind turbine conducted by Garrett and Rønde (2013) and Oebels and Pacca (2012) served as an example of such phenomenon. For example, when LCA's system boundary in the study of Garrett and Rønde (2013) was related to the system boundary introduced in Figure 8 above (Mendecka and Lombardi 2019, p. 473), Garrett and Rønde (2013, pp. 39 and 44) merged three life-cycle stages – raw material extraction, material processing and manufacture of wind turbine components – into one stage: manufacture. Nevertheless, this did not prevent Garrett and Rønde (2013, p. 39) from conducting a full LCA – from raw material extraction to wind turbine decommissioning.

The following paragraphs introduce to the readers some of the wind turbine life-cycle stages and their impact on climate. Climate impact of wind turbine installation and operation phases were not included in the paragraphs below because of their either minimal or non-existing impacts on the GWP indicator. However, the transportation stage was shown to represent one of the less GHG intensive life-cycle stages of wind turbine. In addition to the below presented stages, the environmental impacts of transformer station (or substation) - an integral part of wind farms – are also discussed.

3.4.3.1 Manufacture

When speaking of environmental impacts of various wind turbine life-cycle stages, various authors observed that manufacturing of on-shore wind turbine(s) dominated the overall GHG emission intensity of all wind turbine's life-cycle phases. Hence, manufacturing had the greatest impact on climate change. (Arvesen & Hertwich 2012, p. 5999; Vestas 2017a, p. 59; Bhandari et al., 2020; Guezuraga et al., 2012; Oebels & Pacca, 2013 and Schreiber 2019, p. 570.). For example, in conducing LCA of a fictional wind farm in Brazil, Oebels and Pacca (2013, p. 65) found that over 90% of all GHG emissions were attributed to wind turbine production. The same authors (p. 65) claimed that wind turbine manufacturing itself was not responsible for high amounts of GHG emissions. Instead, the same authors argued that large amounts of CO_2 were emitted due to material production of raw steel as well as due to material production process of steel and cement. Another literature review of LCA of wind power conducted by Arvesen and Hertwich (2012, p. 5999) demonstrated that the most GHG intensive part of on-shore wind power was assigned to manufacturing of the wind turbine itself while maintenance and operation took a much smaller part in wind turbine total life-cycle GHG emissions.

In strike contrast to the manufacturing phase, wind turbine installation (construction) and operation (including maintenance) were found to be only marginally GHG intensive. In other words, when compared to the wind turbine's manufacture phase, their impact on climate was negligible. To show the striking difference on an example, Garrett and Rønde (2013) conducted LCA of Vestas's V80 2,0 MW GridStreamer^{TM} wind turbines and found that the GWP of turbine manufacturing phase was 10,8 g CO2e/kWh while plant setup (installation of one turbine) had a GWP value of 0,2 g CO2e/kWh and operation 0,4 g CO2e/kWh.

3.4.3.2 End-of-Life

Garrett and Rønde (2013, p. 41) further discovered that not only "manufacturing" but also end-of-life life-cycle stage of wind turbine's life-cycle represented one of the most significant stages of wind power. The end-of-life phase, also called "decommissioning", represented the final life-cycle phase in most of the reviewed studies. Arvesen and Hertwich (2012) stated that in turbine's end-of-life stage, large part of materials used by wind turbine would either remain part of the wind power system(s) or would be recycled. According to Vestas (2017a, p. 32), waste management options for its V105-3,45 MW wind turbine were: recycling, energy recovery as a result of material incineration, reuse of turbine components, and last, material landfilling. In contrast to this variety of waste management options, some LCA studies of wind turbine(s) considered as recycling options solely "landfill" and material "recycling" (see for example Wang et al., 2019 and Demir & Taşkın 2013, p. 258).

In LCA, recycling of wind turbine materials while compensating for an equivalent amount of virgin materials is known as "avoided burden" (Schreiber et al. 2019, p. 562) or "avoided burden method" (Arvesen & Hertwich 2012, p. 6002). Through this method, the climate impact of wind turbine is generally reduced because the raw materials used in the turbined are projected to be reused, thus avoiding the extraction of equivalent amount of raw materials to produce another product (Arvesen & Hertwich 2012, p. 6002 and Schreiber et al. 2019, p. 562). As an example, in LCA of Vestas's V80 2,0 MW wind turbine, GHG emission reduction from recycling of wind turbine parts was associated with negative impact on climate (GWP), concretely with -3,8 g CO_2e/kWh. This could be considered as a significant reduction when compared to the same study's impact of manufacturing phase, which was 10,8 g CO_2e/kWh. (Garrett & Rønde, 2013, p. 44.)

3.4.3.3 Transportation

In IO-LCA studying the CF of typical Chinese wind farm, Ji and Chen (2016, p. 253) found that transportation had negligible impact on the wind farm's CF. In LCA study of 2 MW wind turbine, Ghenai (2012, pp. 29 and 31) concluded that the impact of transportation on climate was negligible. In LCA of Vestas's V105 3,45 MW wind turbine, the manufacturer considered the impact of transportation during all life-cycle stages of their product and found that according to their data, transportation contributed by about 8% to the GWP (Vestas 2017a, p. 82). When speaking of the impact of transportation per turbine's life-cycle impact category (e.g. Eutrophication potential, Human toxicity potential etc.) Vestas (2017a, p. 76) found that transportation's contribution was reasonably significant and ranged between 1% and 33% (impact category dependent). In addition to Ji and Chen (2016) and Ghenai (2012), Vestas (2017a, p. 82) also provided the readers with approximate amount of kilometers per each of the wind turbine life-cycle stage.

3.4.3.4 Overall life-cycle GHG emissions of wind power

The full life-cycle GHG emissions of a wind turbine, i.e. all life-cycle phases considered, are discussed in this last subchapter. It is important to mention that all of the studies below set the expected wind turbine lifetime to 20 years.

In studying 2,3 MW and 3,2 MW on-shore wind turbines, Bonou et al. (2016, p. 331) discovered that full life-cycle GHG emissions of their 2,3 MW wind turbine were 6 g CO_2eq/kWh and of the 3,2 MW turbine 5 g CO_2eq/kWh. Chipindula et al. (2018, p. 10), who studied virtual on-shore wind farm with turbines having nameplate capacities of 1 MW, 2 MW and 2,3 MW found that the whole life-cycle climate impact of the 1 MW turbine was 7,13 g CO2eq/kWh, of the 2 MW the value was 6,86 g CO2eq/kWh and the largest, 2,3 MW turbine, impacted the climate by emitting 5,63 g CO2eq/kWh throughout its whole life-cycle. Vestas (2015) assessed the environmental impacts of its on-shore V110-2.0 MW wind turbine with CF of 7,2 g CO2eq/kWh (p. 14). Another study of Vestas's wind turbine (Vestas, 2017) study discovered that the 3,45 MW wind turbine's impact on climate was 4,8 g CO2eq/kWh (p. 53). When considering the more modern, powerful and larger wind turbines, Vestas' turbine types, namely the V150-4,2 MW and V150-6,0 MW, V162-6,2 MW and V172-7,2 MW, the company reported the CF of these turbines to be respectively 7,3; 7,6; 6,1 and 6,2 g CO_2e/kWh (2022a, p. 14; 2022b, 2022c, 2022d).

3.4.4 Transformer station

The transformer station (or substation or site transformer) forms an integral part of any wind farm. The station transforms wind farm's medium voltage electricity (33 kilovolt (kV)) to high voltage electricity (110 kV) so that the electricity can be transferred to the electricity grid (Russ & Reid-McConnell 2020, p. 30). Bhandari et al. (2020, p. 6) noted that apart from studying single wind turbine's impact on the environment, conducting LCA of wind farms was also essential as wind farms consisted of other crucial components, one of these being the transformer station.

The study of Vestas's V150-4,2 MW wind turbine included the transformer station in the study and found that the whole life-cycle GWP of the station was about 1 percent. The study included raw material extraction, manufacture, transportation, service and disposal in their analysis and the data were provided either by published EDP's or by the station's manufacturer (Vestas 2019, pp. 86 & 123). Another study examined the GWP of transformer's station in wind farm consisting of Nordex Group's N149/4.0-4.5 MW wind turbines. In the same study, manufacturing of the station was excluded and only raw material extraction and transportation to the station's manufacturing facility was considered (Russ & Reid-McConnell 2020, p. 30). A study by Oebels and Pacca (2013, pp. 63-64) and Wang, Wang & Liu, 2019 left the transformer station entirely from their study of an on-shore wind farm in Brazil. Thus, the inclusion of transformer station in LCA studies of wind farms varied.

3.4.5 Effects of wind turbine development on turbine CF

Research found a link between the increase in turbine's nominal power and turbine's environmental impacts. Bonou et al. (2016), who conducted LCA of four Siemens Wind Energy (currently Siemens Gamesa) on-shore and off-shore 2015 state-of-the-art wind turbines observed that increasing the nominal power of wind turbines came with lowering GHG emissions. In the same study, the abovementioned turbines were compared to smaller on-shore (2.3 MW) and off-shore (4.0 MW) geared turbines. The finding of Bonou et al. (2016) was in line with an extensive review by Kadiyala, Kommalapati and Huque (2017), who reviewed LCA studies of predominantly HAWT located on-shore and off-shore. According to the same authors (p. 57), large wind electricity generation systems, which had their nominal power between 0.25 and 5 MWs were environmentally superior to their medium sized (0.1 – 0.25 MW) and small counterparts (less than 0.1 MW). According to Besseau, Sacchi, Blanc and Pérez-López (2019, p. 282), the electricity production capacity of a wind turbine had a direct influence on turbine's CF while the size of the turbine – meaning its nominal power - had an indirect influence on the CF. In conclusion, Bhandari, Kumar and Mayer (2020) noted that due to the advancements in wind technology, the life-cycle emissions of wind turbines are expected to decrease in the future. Therefore, due to the rapid development of the wind turbine technology, GHG emissions are expected to decrease in the future as well.

The finding of Bhandari et al. (2020) was in accord with the study of Besseau et al. (2019) who in their study of the Danish wind turbine fleet (on-shore and off-shore combined) found that from 1980 till 2030, the average GWP value of the Danish wind turbine fleet decreased from 40 g to 13 g of CO_2 per kWh of produced electricity. Their findings are illustrated in Figure 9 below, which depicted on-shore and off-shore wind power's GHG reductions on a time scale from 1980 till 2030. Thus, Figure 9 included future projections of wind turbine GHG reductions estimated by the same authors.

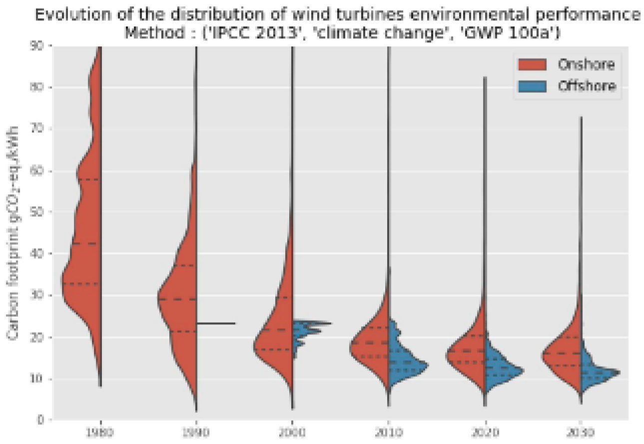


FIGURE 9 The impact of technological evolution on the CF (GWP 100y) of wind turbines (Besseau et al. 2019, p. 283)

In addition to the literature presented above, additional factors lowering life-cycle impacts of wind power technology in general could be industry's sustainability commitments (see for example Vestas, 2020) or the conduct of LCA reports themselves to increase manufacturer's and industry's understanding of environmental hotspots related to wind turbines.

3.4.6 Wind power and other energy sources

In the literature review conducted by Kaldellis and Apostolou (2017, p. 80), the authors concluded that even the highest GWP values of studied on-shore and off-shore wind turbines demonstrated low GWP values when compared to other energy sources. Based on the same study's findings, in their whole life-cycle, off-shore (average 15.6 g CO_2e/kWh per turbine) and on-shore (average 9.0 g CO_2e/kWh per turbine) wind farms had lower GWP value than other RESs. Examples of other RESs presented in Kaldellis and Apostolou (2017) were hydroelectric plants (15- 40 g CO_2e/kWh), nuclear plants (15-50 g CO_2e/kWh) and photovoltaics (50- 100 g CO_2e/kWh).

Furthermore, in another literature review of RESs, Sokka et al. (2016) found that the GHG emissions related to the life-cycle of solar panels and solar collectors were 32–79 g CO_2eq/kWh (solar panels) and 11–68 g CO_2eq/kWh (solar collectors). In the same study, the authors reviewed literature on wind energy as well, with GHG emissions ranging from 4 to 68 g CO_2eq/kWh.

In the comparative study of non-RES (black coal, lignite, natural gas and nuclear) and RES (wind, hydro and photovoltaic) in the Czech Republic, Šerešová et al. (2020, p. 5) found wind power was presented to have the lowest operating lifetime of all presented energy sources. The CF of wind power presented by the same authors was 19 g CO_2eq/kWh. The CF value was relatively higher than CF values presented in Bonou et al. (2016, p. 330), Guezuraga, Zauner and Pölz (2012, p. 41) and Kaldellis and Apostolou (2017, p. 82). In addition, Šerešová et al. (2020, p. 8) also discovered that in the Czech Republic, black coal fired powerplants were responsible for 1004 grams of CO2e/kWh followed by lignite (901 grams) and natural gas (440 grams).

4 CARBON SEQUESTRATION OF FINNISH FORESTS AND SOILS

The typical Finnish wind farm is built on a commercial forest area. This means that forest environments are disturbed by the wind farm's construction. In this chapter, the reviewed literature on sequestration and storage of C by forest environments – trees and soils in particular – is introduced. This chapter strongly relates to answering the third thesis question: Does the typical Finnish wind farm have a better net-negative impact on climate than the commercial forest area on which it was built? Before continuing any further it is important to clarify that the term "forest environment(s)" referred to forest vegetation, such as trees or moss, as well as to forest soils.

4.1 Introduction to carbon and soil organic carbon sequestration

Forest environments, in particular trees and forest plants (forest vegetation), take on, or in other words sequester, CO_2 from the atmosphere through process named photosynthesis. Photosynthesis denotes a process through which energy from the sun (light energy) is transformed into chemical energy. Because of such process, chemical energy is used to transform water and CO_2 into organic matter. When photosynthesis takes place, what is left of the chemical compound CO_2 is solely C.

Photosynthesis is a source of nutrition for vegetation in general but in our context for forest vegetation, such as trees and forest plants (excluding fungi). In consequence, photosynthesis also functions as of nutrition for other organisms living in biosphere, such as animals and humans too. Photosynthesis is therefore vital to maintaining life on Earth (Lambers & Bassham, 2021 and Nunes, Meireles, Pinto Gomes & Almeida Ribeiro, 2020.) C as a chemical compound can be stored into different environments but the most important environments in this study were terrestrial biosphere (or simply biosphere) and lithosphere.

The biosphere includes all living (forest) organisms such as plants and trees (Thompson, Gates & Thompson, 2022) while the lithosphere includes Earth's crust as well as Earth's upper mantle and it may reach depths of about 100 kilometers

(Britannica, 2020). Both of these environments form an important part of the GCC, which refers to C that is flowing and transforming itself via complex series of reactions, for example through photosynthesis and organic decomposition (Carlson et al., 2001, Hannah, 2015 and Bartlett, Rusch, Kyrkjeeide, Sandvik & Nordén 2020, p. 14). The fast GCC is occurring in a matter of decades and millenniums among the four major components of the Earth (atmosphere, biosphere, lithosphere and hydrosphere) (Carlson et al., 2001 and Hannah, 2015). In consequence, CS conducted by terrestrial vegetation but also by soils (introduced later) forms an integral part of GCC. Pukkala (2020) noted that forests take on C from the atmosphere, which is later on stored in:

a) the trees themselves as "living tree biomass",
b) dead vegetation,
c) animals and their wastes as "dead organic matter" (GEMET, 2021), and
d) in wood-based products.

However, not only trees but also forest soil, and soils in general, are sequestering C. The CS by soils is called "soil organic carbon sequestration" (SOCS). Forest environments, such as forest vegetation and soils, represent a significant (organic) C reservoirs (Carlson, Bates, Hansell & Steinberg, 2001). These reservoirs have the ability and capacity to release and to become a "C source" as well as to accumulate C through so called, "C uptake" and thus become a "C sink" (Alexandrov, 2008). Thus, the reservoirs may function either as C sinks in cases, where intake of C is greater than C outflow, or as a C source if more C is released than stored (Alexandrov, 2008). The above presented photosynthesis makes CS into C sinks possible.

4.1.1 Defining CS

A more elaborated definition of CS comes from the literature. In Sparks (2003), the CS was defined as a long term storage of C that is locked in the terrestrial and aquatic biosphere, such as the oceans (Galloway, 2003), soils, vegetation as well as in geologic formations, such as different kinds of rock formations.

CS by already existing forest environments is different from geoengineering approaches removing CO_2 from the atmosphere, such as the CO_2 removal. According to Harding and Moreno-Cruz (2019) the CDR refers to various engineered and natural-based CO_2 removal and storage techniques at the production and post-production stages (once CO_2 is already in the atmosphere). The same authors claimed that this approach has the ability to produce "negative net-emissions". Examples of the CDR techniques include human-induced afforestation, direct air capture or ocean alkalinization (Morrow et al., 2020).

The following chapter introduced the science related to tree and soil CS. Nevertheless, the typical Finnish wind farm operated in a commercial forest and because of this the nature of such forest differed from forests that were planted for the purpose of the CDR (Grant, Hawkes, Mittal & Gambhir, 2021).

4.1.2 CS of trees

On Finnish soils, trees grow on mineral as well as on peatlands. About 80% of trees grow on mineral soils, making mineral soils the dominant type of soil on which trees grow. (Kauppi et al. 1997, p. 15.) Finnish forests consist mainly of boreal forests, which represent over 80% of the Finnish land area. The majority (90%) of this forest type is represented by coniferous trees, namely Norway spruce (*Picea abies Karsten*) and Scots pine (*Pinus sylvestris L.*). (Räike, Kortelainen, Mattsson & Thomas 2012, p. 189.) When the amount of C in trees grow, trees become C sinks, meaning that they store more C than they release (Soimakallio, 2017). Fortunately, according to Ilmastopaneeli, Finnish trees function as C sinks, hence cooling the climate (Seppälä et al. 2015, p. 4).

Trees sequester C from the atmosphere via abovementioned process named photosynthesis. Through this process, CO_2 is transformed into C and stored in trees, including their roots. Via CS, CO_2 serves as a source of nutrition for the trees. However, storing CO_2 is not an endless process meaning the process of C storage in vegetation has its limits and as such it occurs only for a certain period of time. (Nunes, Meireles, Pinto Gomes & Almeida Ribeiro, 2020.)

In Kauppi et al. (1997, p. 15), who conducted a study on Finland's forest C reservoirs, the authors calculated that the C stock of living trees on mineral soils and peatlands covering area of 209 000 km^2 of Finland's area was 618 Teragrams (Tg) (Teragram = 10^{12} g). The study included only trees that were larger than 1,35 meters (1997, p. 15). In the same study (p. 16), from a land-size perspective, the amount of C stored inside of trees per one square meter of mineral soil was, on average, 3,4 kg C m^{-2}, that is the same as 3,4 kg C m^2, because m^{-2} equals to $1/m^2$.

4.1.3 Harvested wood products

According to UNECE (n.d.), harvested wood products (HWPs) are wood-based materials retrieved from forests with wide range of applications: from furniture and plywood to paper and energy use. HWPs naturally contain C once sequestered by trees. As already noted in the article by Räike et al. 2012, p. 189, Norway spruce and Scots pine dominated the Finnish boreal forest type.

According to Metsä Wood (2022a) calculators, one 1 m^3 of plywood made of Metsä's (Finnish) spruce stored about 730 kg of CO_2. Data for plywood made of Finnish pine were not provided by the same source. Nevertheless, on a general level, Metsä Group (n.d.) claimed that 1 m^3 of wood stored approximately 1000 kg of CO_2, which could also be formulated as 1000 kg CO_2e/m^3. As plywood represented a type of HWP (Iordan, Hu, Arvesen, Kauppi & Cherubini, 2018), it could be assumed its C content was lower than Metsä Group's estimate of 1000 kg CO_2e/m^3 because of the plywood being processed (Metsä Wood, 2022b).

Frühwald (2020) estimated that the transformation of C into CO_2 via oxidization creates about 917 kg of CO_2 per 1 m^3 of wood. The same author also described the logic behind this process – 1 m^3 of wood weights about 500 kg and about 50 % of its structure is C. Thus, about 250 kg is C. Once oxidized, i.e. adding oxygen, via e.g. burning process, 1 kg of C becomes 3,67 kg of CO_2. In consequence, the 250 kg of C presented in 1 m^3 of wood is multiplied by 3,67 resulting in 917 kg of CO_2 emitted per 1 m^3 of wood.

4.1.4 SOCS

Soils represent a greater C pool than vegetation (Oberle, 2016). According to Lehmann et al. (2020) as cited in Cano Bernal, Rankinen and Thielking (2022, p. 1) the SOCS represents one of the main tools to reduce C concentration in the atmosphere. In addition, the same author noted that most of the "organic C" on Earth was observed in soil. In Lal, Negassa and Lorenz (2015) soil was also labelled as "terrestrial C pool".

In Lal et al. (2015), SOCS was defined as the process of:

> " - - transferring CO2 from the atmosphere into the soil of a land unit through units plants, plant residues and other organic solids, which are stored and retained in the unit as part of the soil organic matter (humus)".

In other words, as CO_2 is taken up by, for example, vegetation via photosynthesis and stored in a form of C, SOCS denotes a process, where C begins its path in plants, plant residues and other solids and goes on to become part of the soil organic matter (SOM). Thus, the SOM is generally formed from dead trees, overstory (tree canopy) and understory (forest vegetation under the forest canopy such as moss, light-depleted and low-light requiring small trees or shrubs) plants, fungi, bacteria as well from as animals. SOM enriches the soil with C that is stored there as soil organic carbon (SOC) (Bartlett et al. 2020, p. 16 and Sumnall, Fox, Wynne & Thomas 2017, p. 187). In Maiti and Ghosh (2020, p. 702), it has been estimated that about 90% of terrestrial plant biomass is not processed by herbivores and thus becomes part of the SOM. Biological processes such as root and plant (litter) decay (decomposition) involving the physical breakdown of products of microbial and plant origin also enriches the soil of C (Bhattacharyya, Ros, Furtak, Iqbal and Parra-Saldívaras 2022, p. 4 and Onarheim, 2018 as cited in Bartlett, Rusch, Kyrkjeeide, Sandvik & Nordén 2020, p. 16).

According to Condron, Stark, O'Callaghan, Clinton and Huang (2010) as cited in Bhattacharyya et al. (2022, p. 5) decomposition of the SOM is performed by "soil microbial community" consisting primarily of bacteria, fungi, actinomycetes (bacteria) and protozoa (organisms) (Laybourn-Parry & Diaz, 2019) as well as by earthworms (Lundell, Mäkelä, de Vries & Hildén, 2014). Bhattacharyya et al. (2022, p. 9) also concluded that the decomposition rate of SOM by soil microbial community was influenced by other (natural) factors such as temperature, humidity, oxygen, nutrient availability and by anthropogenic factors too. Furthermore, the same authors also noted that the SOM and SOCS were fully dependent on soil microbial community's structure, abundance and other factors.

The decomposition of the SOM by soil microbial community releases CO_2 back to the atmosphere through microorganism perspiration (Selin, 2019) or through so called, heterotrophic respiration (Bartlett et al. 2020, p. 16). This process only partially releases C back to the atmosphere and the rest of it stays in the soil (Bartlett et al. 2020, p. 16).

In the context of this study, anthropogenic factors reduced the amount of vegetation on the typical Finnish wind farm's site through wood logging activities allowing the construction of the typical Finnish wind farm (Bhattacharyya et al. 2022,

p. 9). Soimakallio, Kalliokoski, Lehtonen and Salminen (2021, p. 11) noted that wood harvesting activities contributed to climate change by increasing GHG emissions stemming from litter decay, deadwood and SOM. Peltoniemi, Mäkipää, Liski and Tamminen (2004) found that forest clear-cutting activities put the SOC stock to a minimum after 20 years. This is due to the lack of the trees providing the soil with C either via photosynthesis or tree-sourced plant products (for example litter or deadwood). In addition to this, Dormann et al. (2020) found a positive correlation between light availability and understory plant specie-richness. In the absence of trees, the diversity of understory plants would increase yet environmental conditions, such as temperature, humidity or nutrient availability impacting decomposition rates (Bhattacharyya et al. 2022, p. 9) and thus CO_2 release rates (Soimakallio et al., 2021) would most likely change.

4.1.5 SOCS in northern regions and Finland

Lehtonen and Heikkinen (2015) estimated the magnitude of C presented in soils of southern and northern Finland and found that southern Finland (0,508 Mg of C (C) per hectare (ha)) held less C than northern Finland (0,797 Mg C/ha), or 508 000 and 797 000 kg of C. In Søgaard et al. (2019) as cited in Bartlett et al. (2020, p. 17), Norwegian forest soils held about 15 kg C per m^2. When the latter was converted to hectares it was found Norwegian forest soils held a lot smaller amounts of soil C (150 000 kg C/ha) than Finnish soils. However, a closer look at the data observed from GLOSIS - GSOCmap (v1.5.0) (Global Soil Organic Carbon Map) provided by FAO (2019) suggested the opposite may be true as Norwegian soils were depicted to be much richer in C than Finnish soils.

According to Søgaard et al. (2019) as cited in Bartlett et al. (2020, p 18), soils of Norwegian forests hold three to four times more C than forest tree biomass and understory plants. This example provided some knowledge about the magnitude and importance soils play in C storage. Last, Bartlett et al. (2020, p. 18) also estimated that forests located in northern Europe tend to have higher stocks of soil C than the rest of boreal forests globally.

Finnish forests consist of peat land with organic surface layer (one third of forest land) and of mineral soils (two thirds of forest land) (Vaahtera et al. 2021, p. 18). The amount of C in peat land and forest soil was estimated in Kauppi et al. (1997, pp. 15-16), who concluded that peatland (18,3 kg C/m^2) held significantly higher amount of C than forest soil (3,9 kg C/m^2) for the same size of land area including land and water area. Living trees held the lowest amount of C (2,7 kg C/m^2) and were thus considered in the same study to be the smallest C reservoir with the same land parameters (Kauppi et al. 1997, pp. 15-16).

5 INTRODUCTION TO THE DATA AND METHODOLOGICAL CHOICES

In this chapter, the data collection method, characteristics of the typical Finnish wind farm as well as the pathways leading towards answering the three research questions are introduced. The pathways are based on the reviewed literature, personal communications with Luke's researcher and on official documents related to planning of Finnish wind farms.

5.1 Data collection

5.1.1 Wind turbine LCA

One of the sources in conducting this study consisted of secondary data for wind turbines collected from two sources. The first source regarded LCA reports of wind turbines manufactured by two manufacturers – Vestas and Nordex Group. Most of the reports were published online by the wind turbine manufacturers and were thus freely accessible to anyone interested in the topic. The reports were either conducted by the manufacturers themselves and audited by a third-party (see for example Vestas, 2011 & 2017b) or conducted and audited solely by a third (independent) party (see for example Siemens Gamesa Renewable Energy, 2020).

The second source of secondary data considered academic articles retrieved from academic journals (predominantly from Elsevier's ScienceDirect). Some of the articles represented a literature review on the topic of wind turbine's or wind farm's LCA (see for example Bhandari et al., 2020), others conducted LCA of either fictional (see for example Schreiber et al., 2019) or existing wind power sites (see for example Bonou et al., 2016 and Chipindula et al., 2018). The fictional and real-life studies of same type wind turbines or farms studied either wind turbines or farms in different global environments. However, no study assessed life-cycle impacts of various wind turbine types in the global or Finnish context. Despite this, a sufficient amount of literature for conducting this Master's Thesis was available.

5.1.2 Data collected via "Geographic information system" software

A GIS analysis was conducted in order to retrieve the amount of m^3 of wood presented in the typical Finnish wind farm's area. The analysis was conducted through GIS software - QGIS (version 3.26.0-Buenos Aires). The analysis is described in further detail as part of appendix (see Appendix). Raster data for the analysis were collected from the Natural Resources Institute Finland (Luke). The "web map service" (WMS) "Paikkatietoikkuna" and FWPA's online map service were used in the analysis to retrieve the exact location of the analyzed wind farm areas.

5.1.3 Environmental Impact Assessment reports

An important part of data collection for this thesis consisted of the environmental impact assessment (EIA) reports of Finnish wind farms conducted by three consulting companies – FCG Finnish Consulting Group, Ramboll Finland Oy and Sitowise Oy. The reports were used to gain grater understanding of wind farm's infrastructure and of its technical aspects too.

5.1.4 Others

Other data were collected via personal communications with Luke's researcher – Juhani Marttila specialized in forest and wood production technology. Academic literature discussing wind power and its climate impacts was also one of the data sources. Other academic sources consisted of science focusing on:

a) tree CS and SOCS of peatlands and mineral soils,
b) storage of C and of SOC,
c) tree biomass expansion and
d) determining C amount in a certain amount of wood biomass.

5.2 Framing the "typical Finnish wind farm"

In the context of this study, the "typical Finnish" wind farm represents a wind farm, which:

a) is located on-shore on the Finnish territory in North Ostrobothnia (Pohjois-Pohjanmaa),
b) consists of 10 HAWTs (horizontal axis wind turbines) manufactured by Vestas and Nordex Group,
c) is built in a commercial forest area (mineral soils and peatlands),
d) includes one transformer (substation) station to which wind turbines were connected via underground cables,
e) requires 20 hectares of land,
f) is representative of the modern fleet of wind turbines.

The following paragraphs justified the choices made in framing the "typical Finnish" wind farm.

5.2.1 Location

According to the FWPA (2022c), region with the largest number of wind turbines in 2021 was North Ostrobothnia (Pohjois-Pohjanmaa) because the amount of wind turbines represented 37% of the whole Finnish wind power capacity. The same region had the largest concentration of wind turbines in Finland in previous years as well (Mikkonen, 2021).

In Finland, according to the Finnish Environmental Administration (Ympäristöhallinto) (2020 & 2021), wind farms can be built in many different places, from the more general areas such as commercial forest area and natural parks to more specific areas such as permanent settlements, recreational areas or holiday settlements. According to the Natural Resources Institute Finland (Luke) (2019), in 2019, 8,7 % of North Ostrobothnia's total area consisted of protected forests and of protected poorly productive forest land (in Finnish "kitumaa"). The two protected areas were in forest protection statistics labelled as "forest" (Luke, 2019). According to the forest's protected area statistics class area (in Finnish "Metsien suojelualuetilastoinnin (METI) alueluokittelu"), the two protected areas (or simply "forests") were protected under the 1A, 1B, 1C (Statutory protected areas) and 2A and 2B (Biodiversity conservation sites in commercial forests) area class protection (Metsiensuojelualue- ja METSO-tilastointi -työryhmä, 2014 & 2015).

On the basis of the above presented statistics, the small amount of protected forest area in North Ostrobothnia suggested that more than 90% of land area consisted of unprotected forest area. For that reason, under certain wind power favoring conditions, such as wind speed, wind power developers could harness the potential unprotected forests offer to them.

In addition to this, the typical Finnish wind farm was built on commercial forest area. According to Finnish Ministry of Agriculture and Forestry, commercial forest soil types were categorized into three types: mineral soils, groves and swaps (peatlands). Trees grow on each of the above presented types of lands and their growth depends on, for example, site fertility and moisture, light availability and temperature (Finnish Ministry of Agriculture and Forestry, n.d. and Stora Enso Metsä, 2023). In this Master's Thesis, mineral soils and peatlands were considered because groves were not represented in North Ostrobothnia. The need to specify these three types of land was for the fact that according to Kauppi et al. (1997), peatlands and mineral soils stored different amounts of C (Kauppi et al., 1997).

5.2.2 The number of wind turbines in the typical Finnish wind farm

There were 10 wind turbines in the typical Finnish wind farm. This number was based on the average number of wind turbines: the average number of turbines per wind farm installed between the years 2015 and 2022 in whole Finland was 9,97 (FWPA, n.d.d).

In Finland, a wind farm developer is obliged to conduct the Environmental Impact Assessment (EIA) overseen by the "Centre for Economic Development, Transport, and the Environment" (in Finnish ELY-keskus) when the number of wind turbines exceeds 10 and the total power generation capacity (i.e. nominal power) exceeds 45 MW (Leino & Joensuu, 2021 and Engström & Kinnunen, 2019, p. 2). Because of this fact, the study's commissioner – the FWPA – suggested the number of wind turbines in the typical Finnish wind farm to be set at 10.

Nevertheless, the conduct or lack of conduct of the EIA would not increase nor decrease the farm's environmental impacts. In consequence, the magnitude of environmental impacts was thus assumed to always be proportional to the size of wind turbines in a wind farm. Furthermore, conduct or lack of conduct of the EIA had no impact on findings of this Master's Thesis.

5.2.3 Wind turbines types

According to the FWPA's (2023) Finnish wind power statistics, two large wind turbine manufacturers: Vestas (61%) and Nordex Acciona (23%) clearly dominated the Finnish wind power market in terms of the installed wind turbines as of 31.12.2022. The company Nordex Acciona is also represented under the names of "Nordex Group" and "Nordex SE" and as such these names were used interchangeably in this thesis.

For that reason wind turbines manufactured by these two companies were chosen to operate in the imaginary typical Finnish wind farm. Based on the percentages presented above (61% for Vestas and 23% for Nordex Acciona), the chosen wind turbine types for this study were selected according to the ratio 3:1, i.e. three turbines were manufactured by Vestas and one by Nordex-Acciona. The following wind turbine types and their amount represented in the typical Finnish wind farm were introduced below:

a) 1x Vestas V126-3,45 MW
b) 1x Vestas V136-3,45 MW
c) 2x Nordex Acciona N149/4.0-4.5 MW
d) 2x Vestas V150-4,2 MW
e) 4x Vestas V162-6,2 MW

As for Vestas, a type indicator (e.g., (V)126) described, first, the turbine's rotor diameter (e.g. V126 meant rotor diameter of 126 meters) and second, the 3,45 MW described the turbine's nominal rated power reached at turbine's rated wind speed. The same logic was applied to Nordex's wind turbine as well. The above presented wind turbines were selected for the following reasons:

a) to include only those wind turbine types, which, by the time the thesis was conducted, were operating in Finland,
b) to compensate for the non-availability of LCA reports of newer wind turbine types that were installed or were planned to be installed in Finland, such as the

Nordex Group's N163/5.X or GE Renewable Energy's Cypress 5,5-158 (FWPA, 2022c & 2022d).

c) to present modern state-of-art technology of installed wind turbines in Finland, which could provide more up-to-date insights for researchers, the wind energy industry and policymakers alike,
d) Vestas and Nordex Group represented one of the most prominent wind power industry actors globally as well. The companies not only designed and manufactured but also serviced installed wind turbines. (Nordex SE, 2022 and Vestas, 2021.)
e) to make this Master's Thesis' findings somewhat relevant even after a decade after its completion as even the oldest turbines included in the study were assumed to be operating by 2040,

In terms of the amount of the presented wind turbine types, four Vestas's V162-6,2 MW turbines were chosen because these turbine types represented one of the most modern wind turbine types ever installed in Finland (FWPA, 2022c and 2022d). Two Vestas's V150-4,2 MW turbines were selected because this type of turbine was constructed on a massive scale between 2019 and 2021 (FWPA, 2022d). By including five turbines in the farm, study aimed at preserving future research opportunities as well as, to a certain degree, the study's timelessness.

Two Nordex Acciona's N149/4.0-4.5 turbines were installed in the typical Finnish wind farm because they were also widely represented in Finland between 2019 and 2021, right after Vestas's V150-4,2 MW turbine. In addition, together with the V150-4,2 MW, they also represented the more modern, hence more powerful, on-shore wind turbines.

The last two turbines manufactured by Vestas – the V126-3,45 MW and V136-3,45 MW - filled the remaining space in the typical Finnish wind farm. Their inclusion in the typical Finnish wind farm was based on both, factual and pragmatic reasons. Factual reason considered the fact these turbines were still operating as of May 2022, with both types being installed last time on the Finnish territory in 2017 (AFRY, 2020 & FWPA, 2022d). Pragmatic reason could be described as the availability of LCA reports of these slightly older turbines and the non-availability of LCA reports of Vestas's most modern turbines currently under construction in Finland (FWPA, 2022c).

Other wind turbine manufacturers such as Enercon, Siemens Gamesa (before "Siemens Wind Power") or Alstom (GE) were also represented yet their common share accounted to 14% and their share was thus significantly smaller than Vestas's or Nordex Acciona's share (FWPA, 2023). Because of this, turbines manufactured by these companies, although existing and operating in Finland, were not included in the study.

The inclusion of the slightly older wind turbines, such as Vestas's V126-3,45 MW and Vestas's V136-3,45 MW was done for the sake of increasing the diversity of the data as well as for respecting the nature of the study by including only those turbines that were installed in Finland. Inclusion of a newer wind turbine from the same manufacturer, such as of the V136-4,2 MW, would not correspond to the "typical Finnish" wind farm's setting as this wind turbine type was, according to the available sources, represented only in Åland islands (Vestas, 2020). In contrast to the V136-4,2 MW, this study's chosen turbine types – the V126-3,45 MW and V136-3,45 MW - were widely represented on Finnish territory. Although this Master's Thesis was not representative of the most modern wind turbine types planned to be installed or already installed in Finland, it still has the potential to provide the readers with meaningful insights into the environmental impacts of Finnish wind power.

5.2.4 Wind farm lifetime

For the sake of clarity and result precision, the design lifetime in the studied LCA reports (20 years for Vestas and 20 years (sensitivity analysis) for Nordex Group) was chosen as the typical Finnish wind farms operating lifetime. This lifetime was the only common turbine lifetime considered across all of the LCA reports of the typical Finnish wind farm's wind turbines (Vestas 2017b, 2017c, 2019 & 2023 and Russ-Reid McConnell 2020).

However, it could be argued the 20 year typical Finnish wind farm's turbine lifetime was highly underestimated and far from reality. In EIAs of Finnish wind farms, turbine operational lifetime was assumed to reach 25-35 years (see for example Sitowise Oy (2022, p. 21) and if turbine machinery was renewed, the lifetime was supposed to reach 50 years (Sitowise Oy 2022, p. 21; Ramboll Finland Oy 2019, p. 20 and FCG Finnish Consulting Group 2022, p. 106).

5.2.5 Transformer station

The inclusion and amount of transformer stations was decided on the basis of the following facts. At first, all of the retrieved LCA reports of the studied wind turbines included one (1) transformer station (or substation) in calculating the environmental impacts of their wind turbines (Vestas 2017b, p. 29; 2017c, p. 29; 2019, p. 27 & 2023, p. 25 and Russ & Reid-McConnell 2020, p. 38). Second, after reviewing EIA of two Finnish wind farms – Yli-Olhava's wind farm (Yli-Olhavan tuulivoimapuisto) (Ramboll Finland Oy, 2020) and Lasor's wind farm (Lasorin tuulivoimapuisto) (FCG Finnish Consulting Group Oy, 2021) – it was concluded that one (1) transformer station in the typical Finnish wind farm was sufficient when the number of turbines located in the same wind farm was taken into account.

Thus, the transformer station was found to be an essential component in designing the typical Finnish wind farm. The inclusion of the station was expected to increase the eligibility and credibility of this study.

5.2.6 Other justifications

The results of the study were always referred to as the "typical Finnish wind farm". In other words, the results did not refer to individual turbines that were specified above. All of the studied wind turbine LCA reports clearly stated that the results of their studies were not intended to be used in comparative assertions, which were intended to be disclosed to the public (Vestas, 2017b, p. 3 & 2017c, p. 3; 2019, p. 3 & 2023, p. 3 and Russ and Reid-McConnell 2020, p. 11). This in practice meant that the studied wind turbines' environmental indicators such as the GWP or their EPBTs could not directly be compared with each other. Therefore, readers of this Master's Thesis were kindly asked to refrain from comparing any of the presented wind turbine environmental performance data.

This choice had its basis not only in the manufacturers' statement but also in the nature of the studied LCA reports. The spotted differences in system boundaries and in other methodological choices of the studied wind turbines' LCA reports provided a clear indicator of incompatibility and incomparability of the studied turbines' environmental performance.

In consequence, if an LCA study of Vestas's turbine was compared with a turbine manufactured by Nordex Group, such comparison would lead to a biased understanding of the turbines' environmental performance.

The methodological differences among the studied LCA reports were introduced and partially discussed in the methodology part.

5.3 The study's methodology

The following subchapters aimed at explaining the methodological choices made in order to successfully answer the three research questions. Part of the methodology was based on personal communication with Juhani Marttila, Luke's researcher of forest and wood production technology. Methodology-supportive literature consisting of EIA reports was also introduced during the process.

5.3.1 Climate impact of the typical Finnish wind farm

In order to answer the first research question: "What is the typical Finnish wind farm's impact on climate?", LCA reports of the wind turbines forming the typical Finnish wind farm had to be first, individually examined and second, collectively compared. The focus was on facts, methodological choices and assumptions made in those reports.

According to Vestas (2019, p. 123), wind turbine lifetime, electrical losses and wind turbine availability of a wind turbine or farm represented crucial parameters affecting the wind farm's FU (electricity production per 1 kWh) and thus the GWP value itself. The same author presented other parameters affecting the GWP value significantly too. In a descending order (from highest to lowest impact on GWP), these were the turbine hub height (20-30%), blades (15-25%), foundation (10-15%), nacelle (10-15%) and gear and mainshaft (about 10%).

On the basis of the examination and comparison of LCA reports of the typical Finnish wind farm's wind turbines, the most impactful methodology and assumptions related differences in these reports were found to be in turbines' hub height, blades and electrical losses. The most striking differences considered the hub height - from 105 meters to 155 meters – and electrical losses - 10,5% for Vestas's wind turbines and 25% for the Nordex's turbine. Differences in blade length varied between 63 and 79 meters. (Vestas 2017b, 2017c, 2019, 2023 and Russ & Reid-McConnell 2020.)

The initial idea in this thesis was to adjust these methodological choices to a selected baseline wind turbine, the V162-6,2 MW. This turbine was found by this thesis to be the most future proof wind turbine currently installed in Finland (see for example FWPA, 2022c & 2022d). The adjustment would have unified the methodological choices and assumptions and allowed for direct comparisons of the GWP indicator of the five wind turbine types in the typical Finnish wind farm.

However, this idea had many flaws, which were introduced in the points below:

1) Adjusting turbine hub height, blade length and electrical losses to the baseline wind turbine was not possible due to difficulties in calculating their proportionate magnitude. The following questions clarified such statement:
    a) How much GWP should be decreased or added to the turbines, once we had turbine hub heights of 105, 117, 132, 149 and 155 meters (Vestas 2017b, 2017c, 2019 & 2023 and Russ & Reid-McConnell, 2020) ?
    b) Should turbine with 149 meter hub height have greater GWP due to the increased material requirements related not only to the tower but also to its foundation (Vestas 2019, p. 77)? This question was also found to be ambiguous as greater turbine hub height had greater electricity generation capability in low wind conditions, which led to an increase in turbine's capacity factor (Bhandari et al. 2020, p. 8). Increase in hub height followed by an increase in turbine's capacity factor led to a decrease of the turbine's own CF per kWh of produced electricity because the FU of the five wind turbine LCA reports' considered impacts per 1 kWh of produced electricity delivered to the grid (Vestas 2017b, 2017c, 2019, 2023 and Russ Reid-McConnell 2020). The same logic could be applied to blade length in which increase of the swept area caused increase in the turbine's electricity generation capacity although more material had to be used to produce the blades themselves.
2) Methodology for calculating a common CF of various wind turbine types does not exist. Methodology creation addressing the common CF of five different wind turbine types in this Master's Thesis was outside of the thesis resource scope. Creation of such methodology would most likely need to involve LCA professionals having access to LCA databases of the wind turbine companies. In order to avoid creating space for any major credibility issues regarding the result of the typical Finnish wind farm's CF, unadjusted GWP (100 years) values for 20 year turbine lifetime retrieved from LCA reports of the typical Finnish wind turbine types could be applied. In conclusion, the lack of methodology calculating the common CF of various wind turbine types did not pose a threat to calculating the CF of the typical Finnish wind farm.
    a) The nature of this thesis was to find the most common wind turbines in Finland and place them to the virtual typical Finnish wind farm. Because of different types, the selected turbine types were naturally of different sizes in e.g. hub height, nominal capacity and blade length. This fact naturally created a challenge

    regarding the already presented adjustment of methodological choices. Throughout the literature review, no study to this date has ever conducted LCA of a wind farm consisting of various wind turbine types. Thus, it comes at no surprise that there was no methodology available that would allow for calculating a common CF of different wind turbine types.

    b) Size of turbine hub height was also a choice made in the LCA reports because Vestas and Nordex offered various hub height options of the same wind turbine type (see for example Russ & Reid-McConnell 2020, p. 13 and Vestas 2023, p. 72).
    c) The nature of this thesis was also contradicting the way wind farms in Finland are generally built - by using only one wind turbine type per wind farm. Nevertheless, the decision to set electrical losses of virtual wind farms in Vestas's LCA reports to 10,5% and to 25% in Nordex's LCA report - far away from each other – was decision the LCA practitioners made in the LCA reports of the typical Finnish wind farm's wind turbines. Although this would be remarkably interesting to study, figuring out the difference in CF between the two turbine manufacturers regarding the amount of electricity losses delivered to the grid was out of this thesis scope.
3) As already noted, Vestas (2019, p. 123) brought forward the percentage of GWP impacts of hub height, blades, foundation and others. However, using these percentages in the adjustment could not override the ambiguity related to the increase in size, which would cause an increase in turbine electricity production capability (Bhandari et al. 2020, p. 8). In addition, although the percentage in Vestas (2019, p. 123) considered turbine's whole life-cycle, the percentage itself could not tell what the GWP should be if turbine's hub height increased by 50 meters.

In conclusion, on the basis of the above presented points, adjusting the methodological choices of the selected wind turbine types in the typical Finnish wind farm was found to be not feasible. Creation of a methodology calculating the common CF of all the turbine types was found to be out of this study's scope. It was assumed that such act would have also endangered credibility of the results in much greater way than if the CF of each individual turbine types was not adjusted.

If any unification was to be conducted, unifying the wind turbine parameters (hub height, blade length, nacelle, gear, mainshaft and many others) to represent a single wind turbine with set turbine parameters (e.g. hub height of 149 meters) would require not only a work with an LCA software but also access to databases and data collected on-site by the wind turbine manufacturers. Such process would not be called approximation or adjustment of wind turbine parameters to a baseline wind turbine. Instead, the process would involve creation of completely new wind turbine consisting of the five selected wind turbines in the typical Finnish wind farm. Nevertheless, any of these acts presented in this paragraph was also considered to be entirely out of this Master's Thesis scope.

In consequence, original GWP values of the typical Finnish wind farm's wind turbines, in which 20 year turbine lifetime was considered, were applied. The same wind turbine lifetime was applied because in Vestas (2019, p. 123), lifetime was found to be one of the most prominent factors affecting the GWP of a wind turbine. The following Table 1 below disclosed the GWP values of the selected wind turbines. Please note that the 20 year lifetime of the Nordex Group's wind turbine was retrieved from Russ & Reid-McConnell's (2020) sensitivity analysis of the N149/4,0-4,5 MW wind turbine.

TABLE 1 GWP of the typical Finnish wind farm's wind turbines as presented in Vestas (2017b, 2017c, 2019 and 2023) and sensitivity analysis of Russ Reid-McConnell (2020)

Turbine type	V126-3,45 MW	V136-3,45 MW	V150-4,2 MW	N149/4,0-4,5 MW	V162-6,2 MW
GWP (100y) (g CO_2e/kWh) (20 year lifetime applied)	6,4	7,6	7,3	9,2*	6,2

The (Eq. 2) calculating the climate impact of the typical Finnish wind farm was following:

$$\text{Climate impact of the typical Finnish wind farm (GWP 100, g } CO_2e\text{/kWh)} = \frac{\begin{matrix} 4 * \text{GWP 100 of V162-6,2 MW)} \\ 2 * \text{GWP 100 of V150-4,2 MW)} + \\ 2 * \text{GWP 100 of N149/4,0-4,5 MW)} + \\ 1 * \text{GWP 100 of V136-3,45 MW)} + \\ 1 * \text{GWP 100 of V126-3,45 MW)} \end{matrix}}{\text{the total number of HAWTs in the typical Finnish wind farm}} \tag{2}$$

5.3.2 EPBT of the typical Finnish wind farm

The EPBT was used to retrieve the time (period) in which the same amount of energy that was used during product's life-cycle was retrieved by a wind turbine (Guezuraga et al. 2012, p. 38). The EPBT was calculated through "return-on-energy". According to Russ and Reid-McConnell (2019, p. 60), the RoE represented an estimate of wind farm's energy efficiency and in Vestas (2023), RoE was an indicator of wind turbine's energy balance (energy used vs. energy produced).

In Vestas's LCA reports (Vestas 2017b, p. 75; 2017c, p. 73; 2019, p. 73 and 2023, p. 67), two types of calculations were applied in calculating the turbine's efficiency (RoE):

1. Net energy payback (months) (also known as "net return-on energy approach" and
2. Primary energy payback (months).

In the LCA report of the Nordex Group's turbine, different formula for calculating the RoE was used. Simultaneously, the same authors stated that there was no unified method of measuring the RoE (Russ and Reid-McConnell 2020, p. 60). Both of the Vestas's formula's for calculating the "net energy payback" included wind plant's lifetime (20 years) (see for example Vestas 2023, p. 67). The LCA report of the Nordex Group's turbine did not include plant lifetime in their calculations of the EPBT. On the other hand, Nordex Group's calculations included turbine net AEP (Russ Reid-McConnell 2020, p. 60).

Values from the first calculation presented above - "net energy payback" - for Vestas's turbines were retrieved because unlike the second approach (primary energy payback), the net energy payback was independent of country's electricity grid mixes (Vestas 2019, p. 73). The electricity grid mixes applied in Vestas (2017b, 2017c, 2019 and 2023) considered mixes of USA, Europe and China. The aim of this Master's Thesis was to calculate the EPBT of the typical Finnish wind farm. Affecting the EPBT value of this wind farm by electricity mixes of two large fossil-fuel consuming countries outside of Europe would bring unreliable and incorrect results. Thus, the absolute indicator – net energy payback – independent of any relative conversions (unlike the second approach) was selected.

Table 2 below introduced the EPBT of the five wind turbine types in the typical Finnish wind farm.

TABLE 2 EPBT and EPBT affecting indicators presented in EPBT related calculations in Vestas (2017b, 2017c, 2019 and 2023) and Russ Reid-McConnell, 2020)

Turbine type	V126-3,45 MW	V136-3,45 MW	V150-4,2 MW	N149/4,0-4,5 MW	V162-6,2 MW
EPBT (moths)	6,5	7,5	7,6	7,7	6,5
Lifetime (years, only Vestas)	20	20	20		20

AEP (only Nordex)				11 768 MWh	

Because there were different kinds of calculations presented in the LCA reports of Vestas and Nordex wind turbines (see for example Vestas 2023, p. 67 and Russ & Reid-McConnell 2020, p. 60), the only way to calculate the EPBT of the typical Finnish wind farm was to use results from Vestas's first formula (net energy payback) and results from Nordex's RoE formula (initially an EPBT formula). Thus, no adjustments of the formulas presented in Vestas or Nordex to include either turbine lifetime or AEP could be made. However, the EPBT results put forward by the two manufacturers in their LCA reports showed reliable and comparable results (see table 2 above) and thus the EPBT results of the two different formulas could be put together.

The formula (Eq. 3) for calculating the EPBT of the typical Finnish wind farm was following:

$$\begin{gathered}\textit{EPBT (in months) of the typical Finnish wind farm} = \\[1em] 4 * \textit{EPBT of V162-6,2 MW} + \\ 2 * \textit{EPBT of V150-4,2 MW} + \\ 2 * \textit{EPBT of N149-4.0-4.5MW} + \\ 1 * \textit{EPBT of V136-3,45MW} + \\ 1 * \textit{EPBT of V126-3,45MW} \\ / \, 10 \textit{ (total number of HAWTs in the typical Finnish wind farm)}\end{gathered} \tag{3}$$

As in the previous case, this formula also considered the amount of wind turbine types in the farm. The sum of EPBT of the wind turbines was then divided by 10, which represented the amount of turbines in the farm. The result was average EPBT of the typical Finnish wind farm.

5.3.3 Net impact of the typical Finnish wind farm

In this subchapter, methodology for answering the question "Does the typical Finnish wind farm have a better net-negative impact on climate than the commercial forest area on which it is built?" is introduced to the readers. In other words, the wind farm's impact on climate that occurred through lost CS potential of trees and soils as a result of constructing the typical Finnish wind farm was evaluated.

CF from 20 year electricity production phase of the typical Finnish wind farm was compared with CF of the Finnish electricity mix (in producing the equivalent amount of electricity as the typical Finnish wind farm). The result of this comparison was avoided CO_2 emissions of the typical Finnish wind farm. The amount of trees cut (in m^3) to make space for the typical Finnish wind farm was also considered and the potential wood's use evaluated. Important to clarify was that "forest environment" was defined in this thesis as a forest area consisting of trees and tree roots as well as of forest soil.

5.3.3.1 The wind farm’s land area

The land area size of the typical Finnish wind farm was approached from the perspective of “land area required per single wind turbine”. The total “wind farm area size” was not relevant because wind turbines in Finland are not built right next to each other, thus leaving a rather significant portion of land untouched (see for example Ramboll Finland Oy, 2014 or Ramboll Finland Oy, 2019). By knowing the area needed to construct a single wind turbine, there was no need to consider a scenario under which the typical Finnish wind farm’s turbines were placed under a so called, partial disposition plan (in Finnish “osayleiskaava”). Partial disposition plan means a plan, in which a project – in this scenario a wind farm – has a reserved piece of land set with boundaries. Inside of that bordered piece of land, a wind farm is projected on a map in a detailed way. In consequence, only the area on which the wind turbines were built, including the infrastructure and other land-use, needed to be specified in this subchapter.

In the following paragraphs, three wind power projects’ land area requirements are introduced. The projects were Tornimäki wind power project, Lasor wind farm project and Palokangas wind farm.

In EIA of the Tornimäki wind farm project located in Parajuli (Tornimäen tuulivoimahanke, Padasjoki), the amount of required land-use changes per single turbine in the same project was estimated to be from 1,5 to 2 hectares (FCG Finnish Consulting Group 2022, p. 34). For a wind farm of 10 turbines (the typical Finnish wind farm), the required land area would range from 15 to 20 hectares.

The FCG’s estimate consisted of the construction of:

a) turbine’s foundation,
b) assembly area,
c) access/service roads connecting the turbines with each other inside the farm,
d) service buildings,
e) transformer station,
f) warehouse,
g) parking lot and
h) site barrack area

(FCG Finnish Consulting Group 2022, p. 34).

Whether the presented estimate of 1,5-2 hectares included existing access roads, new access roads or both was not clear from the text presented by FCG Finnish Consulting Group (2022, p. 34). The assumption made in this thesis was that it included both, existing and new access roads.

In addition to vegetation clearing for new access roads, a usual practice in wind farm construction regards the widening of existing roads to 10-15 meters. Because of this, it was assumed that the FCG’s estimate, which was considered to be an “expert opinion”, included such practice in its estimate (FCG Finnish Consulting Group 2022, p. 35). Nevertheless, the construction of new access roads was also regarded as one of the greatest uncertainties in the 1,5 to 2 hectare per turbine because some pre-existing road infrastructure on a wind farm site is usually present.

In another project – EIA of the Lasor's wind farm project - the estimated amount of land for the construction of the (i) turbine's foundation and (ii) turbine service area was about 6000 m^2, or 0,6 hectares per single wind turbine. The rest of the required area reserved for access (service) roads, service buildings, warehouse was not specified. The required land area size for transformer station was estimated to be between 0,5 and 1 hectares. (FCG Finnish Consulting Group Oy 2021, p. 35.)

The last wind power project's area requirements introduced concerned the Palokangas wind farm. In an impact assessment report of the same project it was noted that the average amount of area required for single wind turbine including the construction of access (service) roads was about 6000 m^2. The same report also noted that transformer station required about 0,5 hectares of land area. (FCG Suunnittelu ja tekniikka Oy 2016, p. 15.)

On the basis of the above presented literature, the land area estimate from Tornimäki wind farm project was chosen to represent the "area per single wind turbine" in the typical Finnish wind farm. The chosen land area size per single wind turbine was two (2) hectares per wind turbine. In consequence, the area that underwent clear-cutting to construct the typical Finnish wind farm was 20 hectares.

In this study it was assumed that the estimate from the Tornimäki's wind farm project included not only the construction of entirely new access roads to individual wind turbines but also the construction work related to widening existing roads on the site. In addition to this, it was also assumed that the underground electricity cables put along the newly constructed roads as well as the widened existing roads were also included in the Tornimäki's wind farm's land use estimate of 1,5-2 hectares per one wind turbine.

The estimate from the Tornimäki wind farm project was selected for several reasons. The main reason was that the EAI report provided the description of the land use needs in the greatest detail when compared to the other two presented projects (Lasor and Palokangas). Another reason concerned the year in which the document was prepared (in 2022) for the fact it was assumed it included the most recent land area use requirements for the most modern wind turbine types. Additionally, the land area of 2 hectares per wind turbine including the abovementioned points from a) to h) was chosen because of this study's timelessness. The recent trend of increasing wind turbine rotor diameter (thus turbine's swept area too) as well as turbine hub height (Vestas, 2022b,2022c,2022d) only supported such decision.

5.3.3.2 Electricity transmission lines

The land-area size required for the construction of above-the-ground electricity transmission lines from the typical Finnish wind farm to Fingrid's national electricity transmission line (electricity grid) was not included in this study. The large uncertainties presented below supported such decision:

a) the length of the transmission lines from the farm's transformer station to Fingrid's electricity grid (sometimes not required if a wind farm was built next to electricity transmission line) (FCG Finnish Consulting Group 2022, p. 31),
b) the type of the electricity transmission line from the wind farm, for example 110 kilovolts (kV) or 400 kV (Sitowise Oy, 2022, p. II),

c) the differences in width among 110, 220 and 400 kV transmission lines (Fingrid Oyj, n.d.),
d) the type of soil on which the transmission lines were built (peatland or mineral soil),
e) the amount of forest clear cuts due to the construction of the transmission line (the transmission lines could pass through other environments, such as fields).

Although the above-the-ground electricity transmission lines represent a crucial element in a successful electricity production of any kind of wind farm, the great uncertainties presented above coupled with the view their inclusion was out of the thesis's scope resulted in leaving them out from this study.

5.3.3.3 Net AEP of the wind farm

Not constructing the typical Finnish wind farm required producing the equivalent amount of electricity by the typical Finnish wind farm elsewhere. In order to find out how much electricity needed to be produced by the Finnish electricity mix, in this subchapter, the typical Finnish wind farm's net AEP was calculated.

A 20 year period was selected in finding out the total amount of avoided CO_2 emissions by the typical Finnish wind farm within its designed lifetime.

Despite the knowledge of the impacts affecting turbine's AEP presented in the methodology chapter (electrical losses), adjusting the methodological choices affecting the net AEP of the selected Vestas's and Nordex Group's turbines through calculations to reach a more comparable net AEP was found to be out of this study's scope. Thus, a non-adjusted net AEP value for the 20 year period (the typical Finnish wind farm's lifetime) was calculated in the Eq. (4):

$$\textit{Net 20 year AEP of the typical Finnish wind farm's wind turbines} =$$

$$\begin{gathered}
4 * 21\,568\ (MWh) * 20\ (years)\ (V162\text{-}6{,}2\ MW) + \\
2 * 14\,692\ (MWh) * 20\ (years)\ (V150\text{-}4{,}2\ MW) + \\
2 * 10\,457\ (MWh) * 20\ (years)\ (N149\text{-}4.0\text{-}4.5\ MW) + \\
1 * 13\,239\ (MWh) * 20\ (years)\ (V136\text{-}3{,}45\ MW) + \\
1 * 14\,360\ (MWh) * 20\ (years)\ (V126\text{-}3{,}45\ MW)
\end{gathered} \tag{4}$$

On the basis of this calculation, the typical Finnish wind farm's net AEP for 20 year period was found to be 3 283 380 MWh, or 3 283 000 000 kWh.

5.3.3.4 Avoided CO_2 emissions of the wind farm

Once the typical Finnish wind farm's 20 year net AEP was retrieved, the value from "*emission factor for electricity consumed in Finland - real time data*" was used. The value considered CF of electricity that was not only consumed from Finnish electricity sources but from other sources as well via electricity imports from Sweden, Norway, Russia and Estonia. The abovementioned emission factor provided a better overall picture of the Finnish electricity mix's CF because the factor took into account the constant energy trading from and into Finland. As a result, energy from different sources is usually mixed. (Fingrid Oyj, n.d.a.)

The CF of imported electricity was facilitated by the creation of country-specific emission coefficients of electricity importing countries defined by the International Energy Agency (Fingrid Oyj, n.d.a). In addition to these, a quick insight into Fingrid's dataset for "Net import/export of electricity - real time data" showed that Finland was not found to be a self-sufficient electricity producer (Fingrid Oyj, n.d.c).

The emission factor was collected continuously every three minutes throughout the year. According to Fingrid Oyj (n.d.a), the energy sources included in the emission factor were emission free-sources (nuclear, wind, solar and hydroelectric), combined heat and power (district heating and industry), Finland's power reserves and other, unspecified, energy sources. Only direct CF resulting from the use-phase of the abovementioned electricity sources was considered (Fingrid Oyj, n.d.a).

Emission factor data was retrieved from Fingrid's Open Data website. To increase the credibility of the data retrieved, the data considered full year's emission factor. Therefore, the data retrieval period consisted of data from 29.12.2021 (00:01) to 29.12.2022 (23:58:00). The average amount of grams of CO_2 per 1 kWh emitted by the considered energy sources in Finland and abroad was found to be 59,9815275, rounded off to 60 g CO_2e/kWh (Fingrid Oyj, n.d.d). The extracted value above was multiplied by the typical Finnish wind farm's 20 year AEP to find out the amount of avoided (not emitted) CO_2 emissions (Eq. 5 resulting from the typical Finnish wind farm's 20 year operation:

The Finnish electricity mix's CF after the production of
equivalent amount of electricity produced by the typical Finnish wind farm in 20 years
(CO_2/20 years) =

60 (CF of the electricity consumed in Finland
(Emission factor for electricity consumed in Finland - real time data)
(g CO_2e/kWh)) (Fingrid Oyj, n.d.d) (5)
***
3 283 000 000 (the typical Finnish wind farm's 20 year net-AEP (kWh))

Based on the Eq. (5), the CF of the Finnish electricity mix after the production of the equivalent amount of electricity as the typical Finnish wind farm was 196 980 000 000 g CO_2/20 years, or 196 980 t CO_2/20 years. As solely the use-phase life-cycle CF was considered in the data collected from Fingrid, this in practice meant that RESs (defined by Fingrid as "emissions free" sources) had no impact on climate change, i.e. their CF was 0 (g CO_2/kWh). (Fingrid Oyj, n.d.a). The omission of all the other life-cycle phases of the electricity sources considered in Fingrid's emission factor had to be strongly emphasized and discussed in the discussion part of the thesis. Because the CF of the typical Finnish wind farm considered whole life-cycle CO_2e/kWh emissions, whatever the result regarding the avoided CO_2 emissions by the typical Finnish wind farm, at this point it has already become clear that the amount would represent the *lowest possible amount* of avoided CO_2 emissions. The actual "real" amount of avoided CO_2 emissions was thus expected to be higher.

In conclusion, bringing the whole life-cycle emissions of the Finnish electricity mix in Fingrid's emission factor would have also brought more clarity and credibility to the result itself.

Furthermore, to allow for comparison of the Finnish electricity mix's CF and CF of the typical Finnish wind farm, the 20 year CF of the same farm had to be retrieved using the following Eq. (6). The comparison was possible because the typical Finnish wind farm's FU was set to be "g CO_2e/kWh" (see for example Vestas, 2023).

$$\textit{The typical Finnish wind farm's CF (20 year lifetime) (g } CO_2\textit{/20 years) =}$$

$$\textit{the typical Finnish wind farm's net AEP (20 years) (kWh)} \\ * \\ \textit{the typical Finnish wind farm's CF (GWP100, g } CO_2e/kWh) \tag{6}$$

The CF of the typical Finnish wind farm can be found in the Findings section of the thesis. Finally, through the following equation, the amount of avoided CO_2 emissions of the typical Finnish wind farm could be retrieved via Eq. (7):

$$\textit{Avoided } CO_2 \textit{ emissions by the typical Finnish wind farm's operation (t } CO_2\textit{/20 years) =}$$

$$\textit{196 980 (The Finnish electricity mix's CF after the production of} \\ \textit{equivalent amount of electricity produced} \\ \textit{by the typical Finnish wind farm in 20 years (t } CO_2\textit{/20 years))} \\ - \\ \textit{The typical Finnish wind farm's CF (20 year lifetime) (t } CO_2\textit{/20 years)} \tag{7}$$

The result considered the lowest amount of avoided CO_2 emissions because as already noted, the CF of the Finnish electricity mix considered only the electricity production phase of non-renewable energy sources.

5.3.3.5 Short- and long-term land-use changes at the wind farm's site

Short- and long-term land-use changes affecting the lost tree CS potential and lost SOCS potential on the constructed typical Finnish wind farm's site were not considered in this thesis. The decision not to include these land-use changes was based on the following reasons:

1) only the net climate impact of the typical Finnish wind farm throughout the construction and operation phase was considered. What actions were conducted at the wind farm's site at the end of the farm's operation was considered to be out of the scope of this study because these actions were a subject to great uncertainties and assumptions,
2) the establishment of the duration of short-term land-use changes was not feasible. As its name indicated, "long-term" denoted a state in which parts of the wind farm's site (e.g. turbine foundation, widened and new access roads) would continue their existence after the wind farm's operation, i.e. they would not be dismantled nor landscaped. The duration of "long-term" land-use changes was therefore difficult to establish and justify. Long-term land-use changes also had strong implications regarding the

amount of lost tree CS and SOCS, which in consequence impacted the net impact of the typical Finnish wind farm,

3) the length of the existing widened and newly constructed access roads was a subject to great uncertainty as these are highly site-specific,
4) turbine foundation, whose lifetime exceeded the typical Finnish wind farm's lifetime. According to Sitowise Oy (2022) and FCG Finnish Consulting Group, 2022), foundation's lifetime is about 50 years, and the foundation could either be left on the site to landscape or removed. If left, such act would have prevented SOCS and tree CS. Yet again the question was whether 50 year lifetime should be considered as long-term (greater than the typical Finnish wind farm's lifetime although still limited) as well as what the amount for lost CS potentials should be.

In conclusion, dividing the lost CS potentials between short- and long-term was assumed to bring uncertainties about their potential duration and thus magnitude. Their consideration would have also brought greater uncertainty to the results of the third thesis question as well.

5.3.3.6 Trees

In this subchapter, methodology related to retrieving the rate of tree CS on the typical Finnish wind farm's site as well as the amount of CO_2 incinerated as a result of tree cutting activities on the same site is introduced. The CS rate and storage of understory plants was excluded from this study because of the great uncertainties associated not only with the amount of understory plants in the typical Finnish wind farm area but also with specie-related diversity impacting C rates. Inclusion of these types of plants as well as the also considered to be out of this Master's Thesis scope. Furthermore, differences in tree CS on mineral soils and peatlands were also not considered in this thesis.

Data from Finnish Biodiversity Info Facility (n.d.) as well as data collected from Luke (n.d.b) uncovered a strong presence of White birch (*Betula pubescens)* in the North Ostrobothnia region. For that reason, birches were also included in this study. Thus, the idea was to consider (Norway) spruce, (Scots) pine and (White) birch in this study.

5.3.3.6.1 Determination of tree carbon stock and share of incinerated wood retrieved from the wind farm

Determining the tree carbon stock at the wind farm

Open-source GIS programme QGIS (version 3.26.0-Buenos Aires) was used to retrieve the average amount roundwood in m^3 on the typical Finnish wind farm's land-area of 20 hectares. Data from Natural Resources Institute Finland (Luke, n.d.a) on "volume, the growing stock 2013, 2015 and 2017 (m3/ha)" was applied to land-areas inside of existing wind farms located in the North Ostrobothnia. A detailed step-by-step description of the GIS analysis can be found in the thesis's **Appendix.** The GIS analysis unveiled that on the typical Finnish wind farm's land there is about 1493,4 m^3 of roundwood per 20 hectares (1493,4 m^3/20 ha), which is about 74,67 m^3/ha. The amount of roundwood in m^3 is also known as "stem volume". The GIS analysis considered only the amount of roundwood retrieved from the site. The method for determining the tree C stock and its application was based on personal communication with Luke's researcher of forest technology and wood material solutions, Juhani Marttila.

According to Lehtonen, Mäkipää, Heikkinen, Sievänen and Liski (2004), estimates of C stock can be retrieved through the expansion of the total amount of roundwood to reach the total amount of tree biomass through biomass expansion factors (BEFs). In the same article (p. 214), BEFs of Scots pine, Norway spruce and birch could be determined through stand age for either Scots pine, Norway spruce or broadleaved dominated forests. Important to note that the C stock on the typical Finnish wind farm's area was retrieved using stand age data of Scots pine dominated forest. Scots pine was selected because according to Luke's statistics database (Luke, n.d.b), Scots pine was most widely represented in North Ostrobothnia and thus dominated the region. In addition, the results from Luke's database did not distinguish among the various types of spruce, pine and birch.

Stand age of forests in North Ostrobothnia between the years 2014 and 2018 was retrieved using Luke's database (Luke, n.d.e) "Age of forest stands on forest land (1000 ha)". The mean age of the forests was found to be 64 years. Because Scots pine was designated as the dominant tree specie in the region, the mean age belonged to that tree specie.

The mean age value served to retrieve the BEF value from the article of Lehtonen et al. (2004, p. 214) in which BEF values for different tree age groups were presented. In order to expand the amount of roundwood retrieved from the typical Finnish wind farm's site by other tree components (bark, living and dead branches, coarse and small roots, stump and foliage), the amount of roundwood retrieved from the wind farm (1493,4 m^3/20 ha) was multiplied by BEF of 0,710. The value (0,710) represented BEF of Scots pine in Scots pine dominated forest found in the article of Lehtonen et al. (2004, p. 214). The result of Eq. (8) represented dry tree weight (in tonnes), which included roundwood, bark, living and dead branches, coarse and small roots, stump and foliage (Lehtonen et al. 2004, p. 213).

The Eq. (8) was following:

$$\begin{gathered}
\textit{Biomass (tonnes) of the trees (Scots pine dominated)} \\
\textit{in the typical Finnish wind farm' site (incl. roundwood, stump, branches, roots, bark and} \\
\textit{foliage) =} \\
\\
\textit{0,710 (BEF, age of stand 60-69 years)} \\
* \\
\textit{1493,4 (The amount of roundwood (}m^3\textit{/ 20 ha) in the typical Finnish wind farm)}
\end{gathered} \tag{8}$$

Based on the Eq. (8), the amount of biomass on the typical Finnish wind farm was found to be 1060,31 tonnes.

Furthermore, once the total biomass in tonnes of the dominant and thus representative tree specie in the typical Finnish wind farm was retrieved, the C content of the total biomass of Scots pine had to be found. Weighted C content of Scots pine, which included the tree's aboveground parts (foliage, roundwood, dead and living branches, bark and aboveground stump) and belowground parts (belowground stump, coarse and small roots) was calculated in the article of Bārdule, Liepiņš, Liepiņš, Stola, Butlers and Lazdiņš (2021, p. 5).

The C content of Scots pine and thus the C amount of the forest retrieved from the typical Finnish wind farm was retrieved using the following Eq. (9):

$$\begin{array}{c}\textit{C content of the trees (in tonnes) (Scots pine dominated) in the typical Finnish wind farm's}\\ \textit{site (incl. roundwood, stump, branches, roots, bark and foliage)} =\\[1em] \textit{1060,31 (Biomass (tonnes) of the trees (Scots pine dominated)}\\ \textit{in the typical Finnish wind farm' site}\\ \textit{(incl. roundwood, stump, branches, roots, bark and foliage))}\\ *\\ \textit{(535,5 (weighted C content of Scots pine (whole tree, median value)}\\ \textit{(Bārdule et al. (2021, p. 5)}\\ /\\ \textit{1000)}\end{array} \qquad (9)$$

The result of Eq. (9) was 567,8 tonnes of C. The C content of Scots pine presented in the article of Bārdule et al. (2021, p. 5) was represented in g of C per kg of biomass. Based on this proportion, in the above presented Eq. (9), the value for weighted C content of Scots pine had to be divided by 1000 because the typical Finnish wind farm's total biomass was represented in tonnes.

Determining the share of non-incinerated wood

To find out the proportion of C that was stored in long-lasting products, such as the HWPs, roundwood biomass represented in tonnes had to be retrieved first. This step followed the same method presented in Lehtonen et al. (2004, p. 213), who first converted the stem (roundwood) volume represented in m^3 to dry weight of biomass in tonnes.

However, because the value for converting roundwood volume to dry weight of roundwood was not directly presented in the same article, the value had to be retrieved first via the below presented Eq. (10). "B_i" was defined as dry weight of the tree component (biomass) and "t" was defined as time specified in years, which in the typical Finnish wind farm's case was 64 (the mean age of forest stands in North Ostrobothnia between the years 2014 and 2018). Parameters "a" and "b" had stem values of 0,4194 and -0,0798.

$$\begin{array}{c}B_i\,(t) = a + b * e^{-t/100}\\ B_i\,(64) = 0{,}4194 - 0{,}0798 * e^{-64/100}\\ B_i\,(64) = 0{,}4194 - 0{,}0798 * e^{-0{,}64}\\ B_i\,(64) = 0{,}4194 - 0{,}0421\\ B_i\,(64) = 0{,}3773 \textit{ (number rounded off)}\end{array} \qquad (10$$

Then, the total biomass content solely in roundwood retrieved from the typical Finnish wind farm's 20 hectare area was retrieved in Eq. (11):

$$\begin{gathered}\textit{Roundwood biomass (in tonnes) in the typical Finnish wind farm} = \\[1ex] 1493{,}4\ \textit{(the amount of roundwood (m}^3\textit{/ha)} \\ \textit{in the typical Finnish wind farm} \\ * \\ 0{,}3773\ (B_i\ (64))\end{gathered} \tag{11}$$

The result of Eq. (11) was 563,46 tonnes (number rounded off) of (roundwood) biomass. Moreover, the following step was the same as in retrieving the C content of the total amount of tree biomass retrieved from the wind farm described above. Hence, the total biomass content found in roundwood had to be multiplied by the weighted mean C content of Scots pine in the following Eq. (12):

$$\begin{gathered}\textit{C content of roundwood (in tonnes) in the typical Finnish wind farm's site} = \\[1ex] 563{,}46\ \textit{(Roundwood biomass (in tonnes) in the typical Finnish wind farm)} \\ * \\ \textit{(535,5 (weighted C content of Scots pine (whole tree, median value)} \\ \textit{(Bārdule et al. (2021, p. 5)} \\ / \\ \textit{1000)}\end{gathered} \tag{12}$$

The result of Eq. (12) was 301,8 tonnes of C. According to Salminen (2023), about half of tree biomass is C, which confirmed the validity of the result. Again, the weighted C content had to be divided by 1000 to ensure the comparability between biomass in tonnes and the weighted C content value in Bārdule et al. (2021, p. 5).

However, according to UNECE (n.d.), HWPs also consist of paper, and this was important to take into account because according to Marttila (personal communication), paper does not have a long life-span. Thus, based on Luke's dataset: "Total roundwood removals by forest ownership category and region (maakunta) 2015-" (Luke, n.d.d) the average amount of logs of pine, spruce and hardwood (birch and other broadleaved) cut in North Ostrobothnia between 2016-2020 was 1 649 000 m^3. The average of "grand total" considering logs, pulpwood and energy wood was 6 459 000 m^3. Therefore, the proportion of logs to grand total was 25,5 %. The following equation (Eq. 13), which was based on result of Eq. (12), considered only logs for long-term storage:

$$\begin{gathered}\textit{C content of roundwood (in tonnes) in the typical Finnish wind farm} \\ \textit{stored in HWPs with long life-span} = \\[1ex] 301{,}8\ \textit{(C content of roundwood (in tonnes) in the} \\ \textit{typical Finnish wind farm's site (20 ha)} \\ * \\ 0{,}255\ (25{,}5\ \%)\end{gathered} \tag{13}$$

Thus, the amount of C stored in long-lasting wood (logs) in the typical Finnish wind farm was found to be 77 tonnes (numbers rounded off).

Once the C amount of long-lasting wood was retrieved, it was time to calculate how much wood presented on the typical Finnish wind farm's site was incinerated.

Determining the share of incinerated wood

As the:

a) C content of the forest on the wind farm, including their parts (roundwood, dead and living branches, foliage, coarse and small roots, bark and stump) as well as the
b) C content of solely roundwood stored in long-term HWPs

were retrieved, the amount of C in the tree parts deemed for incineration was retrieved through the Eq. (14) below:

The amount of C stored (in tonnes) in the incinerated tree biomass
in the typical Finnish wind farm =

567,8 (C content of the trees (in tonnes) (Scots pine dominated)
in the typical Finnish wind farm's site
(incl. roundwood, stump, branches, roots, bark and foliage)) (14)
–
77 (C content of roundwood (in tonnes)
in the typical Finnish wind farm
stored in HWPs with long life-span)

The resulting value of Eq. (14) was 490,8 tonnes of C. The value consisted of C stored in short-lasting roundwood (pulpwood and energy wood) having short life-span, stump, branches (dead and living), roots (coarse and small), bark and foliage.

When wood is incinerated, C takes the form of CO_2 via oxidization (Frühwald (2020) and this was considered in the following subchapter.

C stock: C to CO_2 conversion

Last, but not the least, to find out the amount of CO_2 emissions resulting from incineration of the tree biomass consisting of short-lasting roundwood (pulpwood and energy wood), stump, branches (dead and living), roots (coarse and small), bark and foliage, a conversion factor of 3,67 (44/12) introduced in the expert opinion of Frühwald (2020) and in Salminen (2023) was applied in the following Eq. (15).

CO_2 emissions from the incineration of wood retrieved
from the typical Finnish wind farm
(excl. roundwood with long life-span) (t CO_2)=

$$\begin{gathered}\textit{490,8 (the amount of C stored (in tonnes)}\\ \textit{in the incinerated tree biomass}\\ \textit{in the typical Finnish wind farm)}\\ *\\ \textit{3,67 (the C to } CO_2 \textit{ conversion factor) (see for example Frühwald (2020) and Salminen}\\ \textit{(2023).}\end{gathered} \tag{15}$$

The result of Eq. (15) was found to be 1801,2 tonnes of CO_2. In other words, 1801,2 tonnes of CO_2 (1801,2 t CO_2) were released to the atmosphere due to the incineration of the wood for energy purposes retrieved from the typical Finnish wind farm of 20 ha.

5.3.3.6.2 Determining the loss (change) of tree CS on the wind farm's site

The method for retrieving the CS potential of the selected tree types growing on the typical Finnish wind farm's area is presented in this subchapter. The method was based on personal communication with Luke's researcher, Juhani Marttila.

In calculating the loss of CS potential on the wind farm, it was important to consider a different point of view as in the previous subchapter determining the C stock on the farm. In this case, rather than focusing on the already existing C stock of all the living trees in the wind farm's area before the typical Finnish wind farm was built, the loss of CS potential was approached in a way the typical Finnish wind farm was already constructed. The wind farm's existence lead to the inability of the forest on the wind farm's site to sequester more C, which was named the "lost CS potential".

In consequence, it was important to simulate the lost CS potential through hypothetical growth of the forest's growing stock. Drain, which included roundwood removals and natural decay also had to be considered in the calculations because of the hypothetical continuity of the forest management practices in the wind farm's area. Furthermore, cuttings of the roundwood retrieved from the farm used as HWPs were also considered as the lost CS potential via cuttings: C that would otherwise be stored in HWPs was also lost because the typical Finnish wind farm was built. Important to note was that type and duration of forest management practices on the site were not considered in this study.

Calculating the lost CS potential of the growing stock based on net annual increment

In the absence of the typical Finnish wind farm, it was important to not only consider the annual increment (growth) of forest in that area but also the management of the forest involving tree cuttings that would occur as part of forest management practices in that area. For that reason, "net annual increment" - the ratio between tree fellings (m^3) and tree increment (m^3) - had to be calculated (European Environment Agency, 2021). In order to calculate the net annual increment, data from Luke's database were retrieved. In the calculation, the following two datasets were involved:

1) "Annual increment of growing stock on forest land and on poorly productive forest land" (unit: m^3/ha/year) (Luke, n.d.c), and

2) “Total drain by forest ownership category and region (maakunta), 2015-“ (unit: (1 000) m^3/year) (Luke, n.d.f).

Average values from the years 2016–2020 were considered for both of the datasets because this represented the most recent data on annual increment of growing stock available. The region considered in both of the datasets was North Ostrobothnia.

The first dataset considered pine, spruce, birch and “other broadleaved” tree species and their sum of m^3 per year was considered in this study. The second dataset considered pine, spruce and hardwood (birch and other broadleaved). The first dataset considered not only the forest land but also poorly productive forest land, such as peatlands. Including this dataset was crucial because of the fact three out of ten wind turbines were constructed on (undrained) peatland.

The annual drain in the second dataset included roundwood and naturally decaying trees retrieved from the wind farm. As a result, drain represented tree biomass and C taken away from the wind farm’s area either naturally or via human intervention. The annual drain had to be divided by the land area of North Ostrobothnia (in ha) because the dataset (Total drain by forest ownership category and region (maakunta), 2015-) considered data for the whole region. Doing so allowed the comparability of the values for annual increment and annual drain. Once the value for net annual increment of wood per hectare per year was found, the value was multiplied by 20, which represented the typical Finnish wind farm’s land area.

Important to note was that the net annual increment was calculated for roundwood because Luke’s datasets considered only roundwood. The roundwood was later on expanded with BEF to include other tree parts holding C and contributing to the forest’s CS. The net annual increment was calculated using the following Eq. (16 and 17):

$$\begin{gathered}\textit{Net annual increment of roundwood}\\ \textit{in North Ostrobothnia } (m^3/ha/year) = \\[1em] 3{,}5 \textit{ (Mean annual increment of the forest on the wind farm's site } (m^3/ha/year) \\ - \\ 8\,054\,000 \textit{ (Annual average drain of forest in North Ostrobothnia } (m^3/year)) \\ / \\ 3\,683\,022 \textit{ (land area of North Ostrobothnia (in ha (National Land Survey, 2023))}\end{gathered} \tag{16}$$

The result of Eq. (16) was 1,32. Then, the resulting value of Eq. (16) was multiplied by 20 (ha) - the typical Finnish wind farm’s land area:

$$\begin{gathered}\textit{Net annual increment of roundwood}\\ \textit{on the typical Finnish wind farm's site } (m^3/\,20\ ha/year) = \\[1em] 1{,}32 \textit{ (Net annual increment of roundwood}\\ \textit{in North Ostrobothnia } (m^3/ha/year)) \\ * \\ 20 \textit{ (ha) (area of the typical Finnish wind farm)}\end{gathered} \tag{17}$$

Based on the Eqs. (16 and 17), the net annual increment in the typical Finnish wind farm's 20 ha area was found to be 26,4 m^3/20 ha/year. The next step was to convert the net annual increment of wood retrieved from the previous Eq. (17) to dry biomass weight (in tonnes) via multiplying the m^3 of wood with BEF value found in the article of Lehtonen et al. (2004, p. 214). As the mean age of forests in North Ostrobothnia was retrieved in the previous subchapter (64 years), the BEF value of 0,710 for Scots pine dominated forests from the article of Lehtonen et al. (2004, p. 214) was applied in Eq. (18) to obtain dry weight of all the tree components: roundwood, stump, foliage, branches (dead and living), roots (coarse and small) and bark.

Biomass (tonnes) of the net annual increment of forest (Scots pine dominated)
on the typical Finnish wind farm's site
(incl. roundwood, stump, branches, roots, bark and foliage) =
(18)
0,710 (BEF of age of stand 60-69 years (Lehtonen et al. 2004, p. 214))
*
26,4 (Net annual increment of roundwood
on the typical Finnish wind farm's site (m^3/20 ha/year)

The result of Eq. (18) was 18,74 tonnes of biomass. Once the biomass of the net annual increment was known, the amount of tree biomass consisting of roundwood, stump, branches (dead and living), roots (coarse and small), bark and foliage was converted to C via study of Bārdule et al. (2021, p. 5), who calculated the weighted C content of Scots pine through biomass and C content of each of the tree parts. Because the weighted C content of biomass was expressed as g of C in kg of biomass, the weighted C content value had to be divided by 1000 to ensure comparability of the amount of biomass in tonnes. The biomass to C conversion was conducted through the following Eq. (19):

C content of the net annual increment of forest
(in tonnes) on the typical Finnish wind farm's site
(incl. roundwood, stump, branches, roots, bark and foliage) =

18,74 (Biomass (tonnes) of the net annual increment of forest
(Scots pine dominated) (19)
on the typical Finnish wind farm's site
(incl. roundwood, stump, branches, roots, bark and foliage)
*
(535,5 (weighted C content of Scots pine (whole tree, median value)
(Bārdule et al. (2021, p. 5)
/
1000

The resulting value of Eq. (19) was 10,03 tonnes of C. The value from Eq. (19) represented lost CS potential of the growing stock on the typical Finnish wind farm based on the net annual increment. The second part of the lost CS potential was calculated in the following paragraphs.

Calculating the lost CS potential of long-lasting HWPs

The existence of the typical Finnish wind farm also caused a loss in CS potential of HWPs because of the inability to cut roundwood used for long-lasting HWPs. To calculate the lost CS potential of long-lasting HWPs, the following dataset was retrieved from Luke's website: "Total roundwood removals by forest ownership category and region (maakunta) 2015-" (Luke, n.d.d). The dataset considered the same years as in the calculation of the lost CS potential of the growing stock (2016-2020) as well as the same region (North Ostrobothnia).

The dataset took into account roundwood removals of three types of wood: logs, pulpwood and energy wood. According to Juhani Marttila (personal communication) paper does not have a long lifespan and for that reason, only logs could be considered for long-term storage of C. Thus, the average value of roundwood removals of logs between the above-specified years of all the tree species (pine, spruce and hardwood (birch and other broadleaved)) in the dataset was considered. The average amount of roundwood removals of logs was 1 649 000 m^3/year for the whole North Ostrobothnia region.

As in the previous Eq. (16), the value had to be divided by the amount of ha in the same region in order to get the amount of long-lasting roundwood per single ha. Last, the value per single ha was multiplied by 20 to get the amount of roundwood removals per typical Finnish wind farm's area. The following Eq. (20) and Eq. (21) addressed this fact:

$$\begin{gathered}\textit{Roundwood removals of long-lasting roundwood}\\ \textit{(logs only) (m}^3\textit{/ha/year) =}\\ \\ \textit{1 649 000 (m}^3\textit{/year) (removals of logs in North Ostrobothnia –}\\ \textit{pine, spruce and hardwood considered)}\\ /\\ \textit{3 683 022 (land area of North Ostrobothnia (in ha (National Land Survey, 2023))}\end{gathered} \tag{20}$$

The result of Eq. (20) was 0,44 m^3/ha/year in North Ostrobothnia.

$$\begin{gathered}\textit{Roundwood removals of long-lasting roundwood}\\ \textit{(logs only) from the typical Finnish wind farm (m}^3\textit{/ 20 ha/year) =}\\ \\ \textit{(Roundwood removals of long-lasting roundwood}\\ \textit{(logs only) (m}^3\textit{/ha/year)}\\ *\\ \textit{20 (ha) (area of the typical Finnish wind farm)}\end{gathered} \tag{21}$$

The result of Eq. (21) was 8,95. In other words, the amount of roundwood removals of long-lasting roundwood (logs only) from the typical Finnish wind farm was 8,95 m^3/ 20 ha/year. The next step was to convert the amount of roundwood removals (logs only) in the typical Finnish wind farm (20 ha/year) to dry weight of biomass (in tonnes).

Before doing so, the B_i (biomass of dry weight component) value had to be again retrieved first through the formula Eq. (22) below presented the article of Lehtonen et al. (2004, p. 214). The parameters “a” and “b” had stem values of 0,4194 and -0,0798. “B_i” was defined as dry weight of the tree component (biomass) and “t” was defined as time specified in years (64 years: the mean age of forest stands in North Ostrobothnia between the years 2014 and 2018).

$$\begin{gathered} B_i\,(t) = a + b * e^{-t/100} \\ B_i\,(64) = 0{,}4194 - 0{,}0798 * e^{-64/100} \\ B_i\,(64) = 0{,}4194 - 0{,}0798 * e^{-0{,}64} \\ B_i\,(64) = 0{,}4194 - 0{,}0421 \\ B_i\,(64) = 0{,}3773 \text{ (number rounded off)} \end{gathered} \tag{22}$$

The result of Eq. (22) was 0,3773. Now, dry weight (biomass) of the long-lasting roundwood (logs only) removed every year from the typical Finnish wind farm was acquired via the following Eq. (23):

$$\begin{gathered} \textit{Biomass (in tonnes) of long-lasting roundwood (logs only)} \\ \textit{retrieved form the typical Finnish wind farm} = \\[1em] 0{,}3773 \; (B_i \textit{ of 64 years}) \\ * \\ 8{,}95 \; \textit{(Roundwood removals of long-lasting roundwood} \\ \textit{(logs only) from the typical Finnish wind farm } (m^3/\,20\ ha/year)) \end{gathered} \tag{23}$$

The result of Eq. (23) was 3,37 (tonnes) of biomass. Then the long-lasting roundwood’s (logs only) biomass was converted to C via the weighted mean C content in Scots pine (g of C on kg of biomass) Bārdule et al. (2021) in the following Eq. (24). Because the weighted C content of biomass was express as g of C in kg of biomass, the weighted C content value had to be divided by 1000 to ensure comparability of the amount of biomass in tonnes.

$$\begin{gathered} \textit{C content of long-lasting roundwood (in tonnes) (logs only)} \\ \textit{retrieved form the typical Finnish wind farm} = \\[1em] 3{,}37 \; \textit{(tonnes of biomass long-lasting roundwood} \\ \textit{(logs only) from the typical Finnish wind farm } (m^3/\,20\ ha/year) \\ * \\ 535{,}5 \; \textit{(weighted C content of Scots pine (whole tree, median value)} \\ \textit{(Bārdule et al. (2021, p. 5))} \\ / \\ 1000 \end{gathered} \tag{24}$$

The result of Eq. (24) was 1,8 tonnes of C. Therefore, there was 1,8 tonnes of C in 3,37 tonnes of long-lasting roundwood retrieved from the typical Finnish wind farm of 20 ha every year (1,8 C/20 ha/year).

Lost CS potential of the forest in the typical Finnish wind farm

In order to retrieve the entire lost CS potential of the forest on which the typical Finnish wind farm was built, first the C of the growing stock based on the net annual increment and C of long-lasting roundwood (logs only) was put together in the following Eq. (25).

C content of the lost CS potential on the typical Finnish wind farm =

10,03 (C content of the net annual increment of the forest
(in tonnes) on the typical Finnish wind farm's site (25)
(incl. roundwood, stump, branches, roots, bark and foliage)
+
1,8 (C content of long-lasting roundwood (in tonnes) (logs only)
retrieved form the typical Finnish wind farm)

The result of Eq. (25) was 11,83 tonnes of C. Then, the resulting C value was converted to tonnes of CO_2/ 20 ha/year via C to CO_2 conversion factor of 3,67 introduced in Frühwald (2020) and Salminen (2023) in Eq. (26).

Lost CS potential of the typical Finnish wind farm's forest (t CO_2/20ha/year)
=

11,8 (C content of the lost CS potential on the typical (26)
Finnish wind farm)
*
3,67

Based on the Eq. (26) above, the lost CS potential of the typical Finnish wind farm's forest was found to be 43,3 tonnes of CO_2 per 20 hectares per year, or 43,3 t CO_2/20 ha/year. Third, and last, in Eq. (27), the value for lost CS potential on the typical Finnish wind farm had to be retrieved for 22 years because the lost CS potential began with the typical Finnish wind farm's construction phase and continued throughout its operation:

Lost CS potential of the typical Finnish wind farm's
forest in 22 years (t CO_2/20ha/22 years)

(27)
43,3 (Lost CS potential of the typical Finnish
wind farm's forest (t CO_2/20ha/year))
*
22 ((years) construction and operating lifetime the typical Finnish wind farm)

The result of Eq. (27) was 952,6 t CO_2/20ha/22 years. Hence, the lost CS potential of the typical Finnish wind farm's forest (net annual increment and HWPs together) was 952,6 t CO_2/20ha/22 years.

5.3.3.7 Soils

Vaahtera et al. 2021, p. 18 noted, approximately one third of Finnish forest land consists of peatland and two third of mineral soils. In addition, Kauppi (1997, p. 15) claimed that 80% of timber grew on mineral soils while the rest on peatlands. Thus, it was likely that Finnish wind farms have generally been constructed on both of these forest land types. On the basis of the above presented knowledge, it was decided that 70% (14 ha) of the typical Finnish wind farm was built on mineral soil and 30% (6 ha) on peatland.

The subchapter below introduced the methodology for evaluating losses of SOC and of SOCS potential. These two losses were included in this study to provide a more credible evaluation of the environmental impacts related to soil C cycle and its interconnectedness with land-use changes at the typical Finnish wind farm's site.

Last, it had to be acknowledged that the soil started to release CO_2 and ceased sequestering CO_2 within the typical Finnish wind farm's construction process, which according to Ramboll Finland Oy (2019, p. 20) usually takes two (2) years. For that reason, the two years were added to the typical Finnish wind farm's lifetime despite the fact the soil was impacted gradually.

Important to note was that the magnitude of existing C stocks of soils on the typical Finnish wind farm's site was not essential to consider because the focus was on the SOCS and loss of SOC during the wind farm's construction and essentially its operation as well. Hence, there was no need to include the amount of C in the soil after the typical Finnish wind farm's operation.

5.3.3.7.1 Lost SOC on the typical Finnish wind farm's site

It was important to note that to stay within the thesis's scope, any uncertainties related to non-linearity of annual soil CO_2 release were not taken into account and so in this thesis, C in a form of CO_2 was released linearly from the soil (every year the same amount) for 22 years.

Peatland

Seppälä et al. (2010) calculated SOC stocks' release rate on forestry (for the purpose of growing trees) drained peatlands in Finland. The same authors (p. 27) found that forestry drained peatlands were an average net CO_2 source of 141 g CO_2/m^2/year. This value was chosen to represent the SOC rate of C loss on the wind farm's site. Once converted to ha, the value was 1 410 000 g CO_2/ha/year. The value also had to be converted to tonnes of CO_2/ha/year, which resulted in 1,41 t CO_2/ha/year. The peatland was a source of CO_2 for the period of 22 years, which was based on the typical Finnish wind farm's construction and operating lifetime. The period of 22 years was also chosen due to the perceived non-existence of academic literature specifying the average time period in which SOC stocks on peatlands would decrease to a minimum.

The Eq. (28) considered the 22 year release of CO_2 from peatland:

$$\textit{CO}_2\textit{ release rate of forestry drained peatland (22 years)}$$
$$\textit{(t CO}_2\textit{/ha/22 years) =} \qquad (28)$$

1,41 (CO_2 release rate of peatland (t CO_2/ha/year))
*
22 ((years) construction and operating lifetime the typical Finnish wind farm)

The result of Eq. (28) was 31,02 t CO_2/ha/22 years. The decision was that 30% of the typical Finnish wind farm's land area was constructed on a peatland, i.e. six (6) ha of the total 20 ha land area. The following Eq. (29) took that into account:

CO_2 release rate of forestry drained peatland in the typical Finnish wind farm =

31,02 (CO_2 release rate of forestry drained peatland
(22 year lifetime) (t CO_2/ha/22 years))
* (29)
6 (30% of the typical Finnish wind farm's land area (in ha))

The result of Eq. (29) was 186,12 t CO_2/6 ha/22 years.

Mineral soil

Release rate of SOC stocks' on mineral soil with clear-cut forest land was retrieved from the article of Kolari et al. (2004) as cited in the article of Lindroos, Mäkipää and Merilä (2022, p. 7). In the article, CO_2 release rate was found to be 400 g CO_2/m^2/year. When converted to ha, the value was 4 000 000 g CO_2/ha/year and when to tonnes per ha per year, the value was 4 t/ha/year.

According to Peltoniemi, Mäkipää, Liski and Tamminen (2004, p. 2078), clear-cutting activities in a forest decreased SOC stocks to a minimum after 20 years from cutting. Thus, the clear-cut forest in the typical Finnish wind farm became a source of CO_2 for the period of 20 years.

Based on this, the value of 4 t/ha/year was multiplied by 20 (years) in Eq. (30) below (Peltoniemi et al. 2004, p. 2078). Because of the decrease of SOC stocks to a minimum after 20 years (the wind farm's operating lifetime), the construction and operating lifetime of the typical Finnish wind farm were not considered together.

CO_2 release rate of mineral soil on the typical Finnish wind farm
(CO_2/ha /20 years) =

4 (CO_2 release rate of mineral soils in t/CO_2/ha/year)
* (30)
20 (years (Peltoniemi 2004, p. 2078))

The result of Eq. 30 was 80 t/CO_2/ha/20 years. The following Eq. (31) considered the decision that 70% of the land area in the typical Finnish wind farm consisted of mineral soil.

CO_2 release rate of mineral soil on the typical Finnish wind farm =

80 (CO_2 release rate of mineral soil
(20 year lifetime) (t CO_2/ha/20 years))
***
14 (70% of the typical Finnish wind farm's land area (in ha)) (31)

The result of Eq. (31) was 1120 t CO_2/14 ha/20 years. Last, in order to receive the releases of CO_2 from SOC stocks of mineral soil and peatland on the typical Finnish wind farm, the releases were counted together in the following Eq. (32):

CO_2 release from SOC stocks of mineral soil and peatland
on the typical Finnish wind farm (t CO_2/20 ha/22 years) =

1120 CO_2 release rate of mineral soil
on the typical Finnish wind farm 8 t CO_2/14 ha/20 years))
+ (32)
186,12 (CO_2 release rate of forestry drained peatland
on the typical Finnish wind farm (t CO_2/6 ha/22 years))

The result of Eq. (32) was 1306,12 t CO_2/20 ha/22 years. Thus, 1306,12 t CO_2 were released in the typical Finnish wind farm's area over 22 years.

5.3.3.7.2 Lost SOCS potential on the typical Finnish wind farm's site

This subchapter introduces methodology related to the losses of SOCS on the wind farm's site. Inability of the forest soils to store C due to soil disturbance (vegetation clear-cutting and ground preparation, e.g. levelling of the ground level) associated with the construction of the typical Finnish wind farm was called "loss of SOCS potential". The result of these actions and the application of crushed stone on a wind farm's site was depicted in Figure 10 below:

FIGURE 10 Land use changes associated with construction of wind farm in Piiparinmäki wind farm in North Ostrobothnia. The picture was taken by the author of this thesis's in summer 2021.

Mineral soil

Lindroos, Mäkipää and Merilä (2022, p. 7) studied SOC stocks of Finnish forests located in various latitudes with Norway spruces and Scots pines of various ages. In the same study the authors found that the mean annual increase in SOC stock of the studied mineral soil with organic layer was 36 g C/m^2/year. Once converted to ha, the value was 360 000 g C/ha/year and to tonnes: 0,36 t C/ha/year. The value in tonnes also had to be converted to CO_2 by the following Eq. (33):

$$\textit{Lost SOCS potential of mineral soils (t } CO_2\textit{/ha/year)} = 0{,}36 \textit{ (Annual increase of C in Finnish mineral soils (t C/ha/year))} * 3{,}67 \textit{ (C to } CO_2 \textit{ conversion rate (see for example Salminen, 2023)} \tag{33}$$

The result of Eq. (33) was 1,32 t CO_2/ha/year. Then the value had to be multiplied by 22 (years) in Eq. (34) below to consider the typical Finnish wind farm's construction phase and operating lifetime:

$$\textit{Lost SOCS potential of mineral soil on the typical Finnish wind farm per 1 ha } (CO_2\textit{/ha/22 years}) = 1{,}32 \textit{ (Lost SOCS potential of mineral soils (t } CO_2\textit{/ha/year)} * 22 \textit{ (years, the typical Finnish wind farm's lifetime)} \tag{34}$$

The result of Eq. 34 was 29,04 t/CO_2/ha/22 years. The following Eq. (35) took into account the decision that 70% of the land area in the typical Finnish wind farm consisted of mineral soil:

Lost SOCS potential of mineral soil on the typical Finnish wind farm per 14 ha (70%)
(CO_2/14 ha/22 years) =

29,04 (lost SOCS potential of mineral soils
(22 year lifetime) (t CO_2/ha/22 years))
** (35)*
14 (70% of the typical Finnish wind farm's
land area (in ha))

The result of Eq. (35) was 406,56 t CO_2/14 ha/22 years.

Peatland

Turunen, Tomppo, Tolonen and Reinikainen (2002) conducted study on the average long-term apparent rate of C accumulation (LORCA) of 1302 peat cores in undrained Finnish mires. In this thesis, it was important to consider "undrained" mires as these kinds of mires were assumed to represent undisturbed mires. The study divided Finland into "raised-bog" (below 63°N latitude) and "aapa-mire" (above 63°N latitude) regions with respective SOCS rates of 26,1 g C m^{-2} yr^{-1} and 17,3 g C m^{-2} y^{-1}.

In this thesis, the decision was to include only the "aapa-mire" region, i.e. SOCS rate of 17,3 g C m^{-2} y-1, because North Ostrobothnia was located mainly above the 63°N latitude (Turunen et al. (2002). Again, the value had to be converted to g C/ha/year: 173 000, and then to t C/ha/year: 0,173. Then, the value in tonnes had to be converted to CO_2 by the following Eq. (36):

Lost SOCS potential of peatlands in aapa-mire region (t CO_2/ha/year) =

0,173 (Annual increase of C in Finnish (36)
peatlands (t C/ha/year)
***
3,67 (C to CO_2 conversion rate (see for example Salminen, 2023))

The result of Eq. (36) was 0,63 t CO_2/ha/year. The resulting value of Eq. (36) had to be multiplied by 22 (years) in the following Eq. (37) to consider the typical Finnish wind farm's construction and operating lifetime:

Lost SOCS potential of peatland on the typical Finnish wind farm per 1 ha
(CO_2/ha/22 years) =

0,63 *(Lost SOCS potential of peatlands in aapa-mire region*
(t CO_2/ha/year) (37)
***
22 (years, the typical Finnish wind farm's lifetime)

The result of Eq. 37 was 13,86 t/CO_2/ha/22 years. The Eq. (38) below considered the decision that 30% of the land area in the typical Finnish wind farm consisted of peatlands:

Lost SOCS potential of peatland on the typical Finnish wind farm per 6 ha (30%)
(CO_2/6 ha/22 years) =

13,86 (lost SOCS potential of peatlands
(20 year lifetime) (t CO_2/ha/22 years)) (38)
*
6 (30% of the typical Finnish wind farm's land area (in ha))

The result of Eq. (38) was 83,16 t CO_2/6 ha/22 years. Last, in order to receive the total lost SOCS potential of mineral soil and peatland on the typical Finnish wind farm, the lost potentials were counted together in the following Eq. (39):

Lost SOCS potential of mineral soil and peatland
on the typical Finnish wind farm (t CO_2/20 ha/22 years) =

406,56 (lost SOCS of mineral soil
on the typical Finnish wind farm 8 t CO_2/14 ha/22 years))
\+ (39)
83,16 (lost SOCS of peatland
on the typical Finnish wind farm (t CO_2/6 ha/22 years))

The result of Eq. (39) was 489,72 t CO_2/20 ha/22 years. Thus, the lost SOCS potential of mineral soil and peatland on the typical Finnish wind farm resulting from the construction and operation of the same wind farm was 489,72 t CO_2/20 ha/22 years.

5.3.4 Calculating the net impact on climate of the wind farm

The previous subchapters introduced various kinds of equations. These equations provided data (values) for the following Eq. (40) through which the net impact on climate of the typical Finnish wind farm was calculated. The Eq. (40) was following:

Net impact on climate of the typical Finnish wind farm
(in tonnes of CO_2) =

Avoided CO2 emissions by the
typical Finnish wind farm's operation (t CO_2/20 years)
−
Lost CS potential (t CO_2/20ha/22 years)
forest in the typical Finnish wind farm
− (40)
Lost SOCS of mineral soil and peatland

on the typical Finnish wind farm (t CO_2/20 ha/22 years)
–
(CO_2 release from SOC stocks of mineral soil and peatland
in the typical Finnish wind farm (t CO_2/20 ha/22 years))
–
CO_2 emissions from the incineration of wood retrieved
from the typical Finnish wind farm
(excl. roundwood with long life-span)

Once the net impact on climate of the typical Finnish wind farm was retrieved, it was important to calculate the net impact of the commercial forest area via the following Eq. (41). This allowed for the comparison of the net impact of the typical Finnish wind farm and of the commercial forest area on which the wind farm was built. Crucial to note was that in the following Eq. (41), the lost CS potential of the forest and lost SOCS potential of the soil represented the *actual sequestered amount* of CO_2 on the unbuilt typical Finnish wind farm's site. In consequence, the same values as in the previous Eq. (40) for lost tree CS and SOCS potentials could not be applied in the following Eq. (41). This was because of the fact the forest and soils were left on the unconstructed wind farm's site sequestering carbon. At some point, it was assumed the forest in the wind farm's site was clear-cut. According to UPM (2023), final felling of trees in a forest is done when the forest's age is between 60 and 80 years. The same author also noted that before the forest reaches such age, tree thinning is conducted twice or three times before the final felling. The decision made in this Master's Thesis was that tree thinning activities are out of this Thesis scope – one of the reasons being that thinning activities were also assumed to have little impact on SOCS. Therefore, names of variables in the Eq. (41) were slightly different to accommodate the fact the focus was on *actual* CS, not *lost* CS potentials. As the final felling age according to UPM (2023) was between 60 and 80 years, the decision was to set the final felling age at 70 years by multiplying the lost CS potentials of trees and soils by 3,18.

Last, in the following Eq. (41) the decision was to include CF of the Finnish electricity mix in producing the equivalent amount of electricity as the typical Finnish wind farm because the typical Finnish wind farm was not constructed and the amount of electricity produced in the farm's 20 year lifetime had to be produced elsewhere.

Net impact on climate of the commercial forest area
on which the typical Finnish wind farm was built (t CO_2/20 ha/70 years) =

(CS potential of
the typical Finnish wind farm's forest (t CO_2/20 ha/22 years))
+
(SOCS potential of mineral soil and peatland
on the typical Finnish wind farm (t CO_2/20 ha/22 years)
*
3,18
(to reach the age of the forest (70 years) at which final cutting occurred on the 20 ha land (t CO_2/20 ha/70 years)

(41)

-

The Finnish electricity mix's CF after the production of
equivalent amount of electricity produced
by the typical Finnish wind farm in 20 years (t CO_2/20 years)

6 FINDINGS

In this section, based on the equations presented in the methodology section, the results of the three thesis questions are presented.

6.1 Impact on climate of the "typical Finnish Wind Farm"

In this section, the CF of the typical Finnish wind farm was calculated. The CF was based on the GWP's 100 year timescale and expressed as CO_2 equivalents per 1 kWh of produced electricity by the same wind farm. The already presented Eq. (2) shows the calculation of the CF of the typical Finnish wind farm:

$$\begin{gathered}\textit{Climate impact of the typical Finnish wind farm (GWP 100, g CO}_2\textit{e/kWh)} = \\ 4 * 6{,}2 \textit{ (V162-6,2 MW)} \\ 2 * 7{,}3 \textit{ (V150-4,2 MW)} + \\ 2 * 9{,}2 \textit{ (N149/4,0-4,5 MW)} + \\ 1 * 7{,}6 \textit{ (V136-3,45 MW)} + \\ 1 * 6{,}4 \textit{ (V126-3,45 MW)} \\ / 10 \textit{ (total number of HAWTs in the typical Finnish wind farm)}\end{gathered} \tag{2}$$

The resulting value of this formula was 7,18 (g CO_2e/kWh)

6.2 EPBT of the Typical Finnish Wind Farm

Through the already introduced Eq. (3), the EPBT of the typical Finnish wind farm was calculated:

$$\textit{EPBT (in months) of the typical Finnish wind farm} =$$

*4 * 6,5 (EPBT of V162-6,2 MW) +*
*2 * 7,6 (EPBT of V150-4,2 MW) +*
*2 * 7,7 (EPBT of N149-4.0-4.5MW) +* (3)
*1 * 7,5 (EPBT of V136-3,45MW) +*
*1 * 6,5 (EPBT of V126-3,45MW)*
/ 10 (total number of HAWTs in the typical Finnish wind farm)

The retrieved value from this formula was 7,06 (months). Therefore, the EPBT of the typical Finnish wind farm was found to be 7,06 months.

6.3 Net-negative climate impact of the typical Finnish wind farm

This subchapter provides numerical result for the third thesis question. The result itself is discussed in the discussion chapter. At first, the "avoided CO2 emissions by the typical Finnish wind farm's operation (t CO2/20 years)" were calculated in Eq. (6):

The typical Finnish wind farm's CF (20 year lifetime) (g CO_2/20 years) =

3 283 000 000 (the typical Finnish wind farm's net AEP (6)
(20 years) (kWh))
*
7,18 (the typical Finnish wind farm's CF (GWP100, g CO_2e/kWh))

The result of Eq. (6) was 23 571 940 000 g CO_2/20 years. When converted to t of CO_2, the result was 23 571,94 t CO_2/20 years. The amount of avoided CO_2 emissions of the typical Finnish wind farm was retrieved via the following Eq. (7):

Avoided CO_2 emissions by the typical Finnish wind farm's operation (t CO_2/20 years) =

196 980 (The Finnish electricity mix's CF after the production of
equivalent amount of electricity produced (7)
by the typical Finnish wind farm in 20 years (t CO_2/20 years))
-
23 571,94 (The typical Finnish wind farm's CF (20 year lifetime) (t CO_2/20 years))

The result of Eq. (7) was 173 408,06 t CO_2/20 years. Therefore, the amount of avoided CO_2 emissions caused by the typical Finnish wind farm's operation was 173 408,06 t CO_2 in a 20 year lifetime. Once all the values for the Eq. (40) were retrieved, the Eq. (40) calculated the net impact on climate of the typical Finnish wind farm:

Net impact on climate of the
typical Finnish wind farm (t CO_2/20 years) =

173 408,06 (Avoided CO_2 emissions by the
typical Finnish wind farm's operation (t CO_2/20 years))

–
952,6 (Lost CS potential of
the typical Finnish wind farm's forest (t CO_2/20ha/22 years))
–
489,72 (Lost SOCS potential of mineral soil and peatland
on the typical Finnish wind farm (t CO_2/20 ha/22 years) (40)
–
1306,12 (CO_2 release from SOC stocks of mineral soil and peatland
in the typical Finnish wind farm (t CO_2/20 ha/22 years))
–
1801,2 (CO_2 emissions from the incineration of wood retrieved
from the typical Finnish wind farm
(excl. roundwood with long life-span) (t CO_2)

The result of the Eq. (40) was 169 767,72 t CO_2. The following Eq. (41) addressed the net impact on climate of the commercial forest area:

Net impact on climate of the commercial forest area
on which the typical Finnish wind farm was built (t CO_2/20 ha/70 years) =

952,6 (CS potential of
the typical Finnish wind farm's forest (t CO_2/20 ha/22 years))
+
489,72 (SOCS potential of mineral soil and peatland (41)
on the typical Finnish wind farm (t CO_2/20 ha/22 years)
*
3,18 (to reach the age of the forest (70 years)
at which final cutting occurred on the 20 ha land
(t CO_2/20 ha/70 years)
-
196 980 (The Finnish electricity mix's CF after the production of
equivalent amount of electricity produced
by the typical Finnish wind farm in 20 years (t CO_2/20 years))

The result of Eq. (41) was -192,393.42 t CO_2/20 ha/70 years.

7 DISCUSSION OF THE FINDINGS

In this section, the three research questions posed are answered and discussed in the context of the theory section. The section is divided into three main subchapters to clearly separate the three research questions from each other.

7.1 Climate impact of the "typical Finnish Wind Farm"

The first thesis question asked what the "typical Finnish" wind farm's impact on climate is. In this thesis it was found that the CF of the typical Finnish wind farm was 7,18 g CO_2e/kWh of produced electricity. In other words, on average, a single wind turbine emitted 7,18 g CO_2e/kWh.

If we were to compare the CF of the typical Finnish wind farm to CF of other wind turbines, Oebels and Pacca's (2013, p. 63) wind turbine of nameplate capacity of 1,5 MW had CF of 7,1 g CO_2e/kWh. In Chipindula et al. (2018, p. 18), the 1 MW wind turbine had CF of 7,13 g CO_2e/kWh and in Vestas (2015), the V110-2,0 MW turbine had CF of 7,2 g CO_2e/kWh. Vestas's V150-4,2 MW wind turbine (the typical Finnish wind farm's turbine) had CF of 7,3 g CO_2e/kWh. The average nameplate capacity of the typical Finnish wind farm ranged from 4,26 MW to 4,36 MW (the Nordex Group's turbine had a nameplate capacity between 4,0 and 4,5 MW). Thus, if we were to compare the CF of the typical Finnish wind farm to CF of wind turbines of similar nameplate capacity, the V136-4,2 MW turbine's CF was found to be 5,6 g CO_2e/kWh, and thus significantly lower than the CF of the typical Finnish wind farm. The already introduced V150-4,2 MW had similar CF as the typical Finnish wind farm. The V150-4,2 MW had significantly greater hub height (155 meters) than the V136-4,2 MW (112 meters) as well as the V150-4,2 MW had slightly greater rotor diameter. The greater CF of the V150-4,2 MW turbine was likely caused by these two factors (Vestas 2019, p. 123). Another Vestas's turbine – the V117-4,2 MW – had CF of 4,4 g CO_2e/kWh. It is hub height (91,5 meters) was, however, dramatically lower than the hub height of the studied wind turbines – the V150-4,2 MW (155 meters) or the V162-6,2 MW (149 meters). Again, hub height was found in Vestas (2019, p. 123) to significantly impact turbine GWP.

On the basis of these comparisons we can conclude that the CF of the typical Finnish wind farm is of similar magnitude as CF of turbines with (sometimes significantly) lower nameplate capacities. However, when compared to offshore wind power (see for example Kaldellis and Apostolou, 2017), to other RES such as hydroelectric or photovoltaics (see for example Kaldellis & Apostolou, 2017 and Sokka et al., 2016) as well as to non-RES such as black coal or natural gas (see for example Šerešová et al., 2020), the CF of the typical Finnish wind farm is in most of these cases substantially lower – from twice as lower than off-shore wind power to about 143 times lower than black coal. Therefore, in the Finnish as well as global context, the CF of the typical Finnish wind farm could still be regarded as one of the most climate friendly conventional RES.

7.1.1 The relationship between CF and turbine nameplate capacity

This subchapter briefly discusses the findings of the already mentioned studies exploring the link between wind turbine CF and nameplate capacity (see for example Bonou et al., 2016, Kadiyala et al., 2017, Besseau et al., 2019 and Bhandari et al., 2020). The thesis found that the typical Finnish wind farm's CF is often higher than the CF of wind turbines with lower nameplate capacity. Also, when same nameplate capacity was considered, the typical Finnish wind farm's CF was also higher than CF of the presented turbines. However, as already mentioned in the previous subchapter, the parameters, such as hub height and rotor diameter were found to have a large impact on turbine GWP. It was therefore assumed that the typical Finnish wind farm's CF was higher mainly because of these two parameters.

7.1.2 Impact of turbine lifetime on CF of the typical Finnish wind farm

The LCA reports of the typical Finnish wind farm's turbines showed that increasing wind turbine lifetime comes with decreased CF (see for example Russ & Reid-McConnell, 2020 or Vestas, 2023). Future design and material improvements could increase turbine lifetime and decrease turbine CF. However, design and material improvements should be regarded as only one part of lowering turbine CF. The other part considers the lifetime – or as Vestas (2019) put it "design lifetime" - set in wind turbine oriented LCA studies.

Throughout this Master's Thesis it became clear that the (baseline) lifetime (20 and 25 years) set in the typical Finnish wind farm's turbine's LCA reports highly underestimated wind turbine lifetime in real-life conditions (see for example Sitowise Oy, 2022; Ramboll Finland Oy, 2019; Vestas 2019, p. 17 and Russ & Reid-McConnell 2020, p. 13 and 56). As a result, the 20 (Vestas's turbine) and 25 year (Nordex's turbine) turbine lifetime had strong tendency to exaggerate and overestimate the studied wind turbine's climate impact. In consequence, the climate impact of the typical Finnish wind farm is greater. This is caused by the fact that the LCA studies of the typical Finnish wind farm's turbine's considered a "virtual" or "exemplary" wind farm. The real-life condition turbine lifetimes were introduced in the paragraph below.

Sitowise Oy (2022, p. 21) claimed that wind turbine lifetime was between 25 and 35 years and through renewal of the turbine machinery the lifetime might reach 50 years. Ramboll Finland Oy (2019, p. 20) claimed that turbine operation lifetime was about 25-30 years with machinery renewal offering the possible of increasing operational lifetime to 50 years. FCG Finnish Consulting Group (2022, p. 106) claimed the turbine lifetime was between 25 to 30 years while newer turbines can extend their lifetime over 30 years. The renewal of the turbine's machinery was also claimed by the same authors to reach 50 years. Ramboll Finland Oy (2019, p. 55) claimed that the lifetime of the turbine's foundation and tower was expected to be 50 years.

However, not only consulting companies, but also wind turbine manufacturers spoke about the real-life wind turbine lifetime: in a press release issued by Vestas (Vestas Wind Systems A/S, 2019), the same company made a 30-year "Active Output Management" service agreement for twenty-one Vestas's V150-5,6 MW turbines in Finland. The press release served as a proof that in the Finnish context, wind turbines can reach operational lifetime of 30 years (and possibly more as well). In addition to this, in the LCA report of Vestas's V150-4,2 MW turbine, Vestas (2019, p. 75) claimed that turbine operational lifetime could reach 30 years and more.

In conclusion, in addition to the design turbine lifetime, a sensitivity analysis of increased turbine lifetime to 35 and 50 years with the above mentioned specifications turbine machinery renewal should be conducted in the future. This would not only present a real-life condition wind turbine lifetime but also improve and promote the wind industry's image.

Last but not least, an interesting factor impacting the turbine's GWP 100 especially during turbine's increased lifetime was turbine maintenance. The frequency and the need to conduct small operations, such as oiling the turbine parts. In case turbine parts need to be replaced due to their wear off was assumed to have strong potential to significantly impact the turbine GWP as these replacement parts have their own life-cycle, i.e. materials for these parts need to be extracted, put together (manufactured) and the final product transported, installed, disassembled and recycled. As noted above, the turbine lifetime could be extended to up to 50 years yet this would mean the renewal (replacement) of the turbine machinery and thus increasing the turbine GWP (see e.g. FCG Finnish Consulting Group, 2022, p. 106). It remains a question to what extent could the increased lifetime to e.g. 50 years cover the life-cycle climate impacts of the newly installed parts prolonging its lifetime?

7.1.3 The impact of different "power modes" on the typical Finnish wind farm's CF

In LCA reports of the Vestas's wind turbine, the authors studied the turbines' environmental impacts in applying a different (lower) power mode. In LCA sensitivity analysis of Vestas's V150-4,2 MW turbine, one of the possible scenarios was to operate the turbine in a 4,0 MW power mode. Decreasing the peak power output of the wind turbine resulted in overall reduction of almost all environmental impacts, including the turbine's GWP 100, when compared to the 4,2 MW power mode – from 7,3 g CO_2e/kWh (4,2 MW) to 6,8 g CO_2e/kWh (4,0 MW). (Vestas 2019, p. 80.) The V162-6,2 MW turbine's sensitivity analysis considered 5,6 MW (6,0 g CO_2e/kWh) and 6,0 MW (5,8 g CO_2e/kWh) power modes and again, the decrease of peak power also led to decrease of the turbine's CF when compared to the baseline peak power of 6,2 MW (6,2 g CO_2e/kWh). Based on these two examples, the decrease in turbine nameplate capacity was directly proportional to turbine's CF.

Contrary to these findings, an increase in turbine peak power through the new power mode can also come with a decrease of turbine's climate impacts. In LCA sensitivity analysis of the V126-3,45 MW and V136-3,45 MW turbines, the maximum power output these two wind turbines was raised from the original 3,45 MW to 3,6 MW. The sensitivity analyses showed that increasing the peak power output of these turbine types resulted in decrease of all of the studied environmental impacts, including the GWP 100. Nevertheless, the decrease of CF as a result of the new power mode was minor: a decrease of 0,4 g CO_2e/kWh for the V126-3,45 MW and decrease of 0,1 g CO_2e/kWh for the V136-3,45 MW turbine (Vestas 2017b, p. 81 & 2017c, p. 79.) The example of this inverse relationship was also found to be in line with the findings of Chipindula et al. (2018) and Wang, Wang and Liu (2019). However, this study did not consider various turbine power modes of the same wind turbine type. The focus was on different turbine types with various nameplate capacities instead. The literature review conducted as part of this thesis found that such focus was the general trend in studies focusing on reducing turbine environmental impacts through turbine nameplate capacity (see for example Chipindula et al., 2018; Wang, et al., 2019; Bonou et al. 2016; Bhandari et al. 2020, p. 8). The conclusions reached in those studies were found to oppose each other and so no conclusive answer to the environmental impacts-nameplate capacity relationship was found (see for example Chipindula, 2018, Wang et al., 2019 and Bonou et al., 2016, Bhandari et al. 2020, p. 8). In fact, there was no study (except the LCA studies conducted by Vestas – see for example Vestas 2023, pp. 70-71) that would have considered environmental impacts of new power modes available in the same wind turbine type.

In consequence, applying any of these new power modes to decrease the CF of the typical Finnish wind farm was found to be unnecessary because the improvement of turbine's climate performance was found to be marginal. Despite this, the new power modes were found to be one of the ways to decrease the typical Finnish wind farm's CF.

Important to mention was the fact that the sensitivity studies of the V150-4,2 and V162-6,2 MW turbines considered different wind speed when applying the new power mode and the impact of wind speed on turbine's climate performance was found to be significant. Vestas (2017b, p. 121) noted that whatever comparisons between wind turbines are made, they should always be conducted in a way that the turbines operate within the same wind class. Furthermore, Vestas (2017c, pp. 17-18) added that wind class determined the amount of electricity produced in a greater manner than turbine's generator rating (or nameplate capacity) (in MW) or turbine's rotor size. Although of the two, only V162-6,2 MW turbine operated in different wind class under the new power mode, the impact of changing wind speed on the new power mode and the subsequence climate impact of such change could be investigated by further research.

7.1.4 Differences in assumptions and methodological choices

The LCA reports of the typical Finnish wind farm's wind turbines applied various assumptions and methodological choices, which allowed them to conduct LCA of a virtual wind farm. These assumptions and choices were thought to be a big challenge in answering the first Master's Thesis research question. However, it was assumed that Vestas (2023, p. 3). who stated that:

> "- - the study is not intended to be used for comparative assertions intended to be disclosed to the public."

was aware of the fact that there were many aspects in reviewing environmental impacts of a wind turbine, such as numbers and formulas, to which outsiders – the public - did not have access to and were not disclosed in the turbine LCA reports (see for example Vestas, 2019). In that case, trying to make any assumptions and thumb-sucked calculations without having the manufacturers' data at one's disposal was believed to significantly increase the chance for calculation and thus results-quality and credibility related errors. The author of this thesis did not have access to the manufacturer's methodology, data, LCA software and formulas in order to conduct the LCA of the selected typical Finnish wind farm's wind turbines. In addition, even if all of these would have been available, a challenge regarding handling these data from the methodological point of view to create credible results would surely have arisen. One solution would have been to create a LCA of an imaginary baseline wind turbine with averaged wind turbine parameters (consisting of parameters of the five wind turbines). This solution could be also enhanced by considering wind turbines manufactured by one manufacturer, such as Vestas, because this would offer a slightly better, yet problematic, comparability of the turbines' LCA reports. Nevertheless, to avoid greater errors, the resulting CF value of 7,18 g CO_2e/kWh consisted of those methodological choices and assumptions the manufacturer's made themselves.

7.1.5 The interconnectedness of LCA indicators

An important outcome made was the fact the climate impact of the wind farm did not provide the readers with a holistic measurement of the typical Finnish wind farm's environmental impacts. In order words, the above presented results of the same wind farm's CF considered only a fraction of environmental impacts wind farm's tend to cause. Thus, LCA environmental indicators, such as acidification potential, eutrophication potential, human toxicity potential or terrestrial ecotoxicity potential to name a few were not considered in this thesis despite the fact these impacts were presented in turbine's life-cycle environmental impacts (see for example Vestas 2019, p. 52). Although the emphasis on alleviating the climate change is understandable, impacting specie biodiversity by other environmental impacts, such as water acidification, eutrophication or groundwater pollution was assumed in this thesis to decrease environment's ability to sequester C and thus to impact climate change.

7.2 EPBT of the Typical Finnish Wind Farm

The second question asked what the EPBT of the "typical Finnish" wind farm is. The EPBT of the typical Finnish wind farm was found to be 7,06 months. When related to studies of wind farms with similar and different wind turbine nameplate capacities, the EPBT of the typical Finnish wind farm was similar to EPBT of turbines with lower nameplate capacities (see for example Guezuraga et al. 2012, p. 40; Bonou et al. 2016, p. 331 and ENERCON GmbH, 2020 (only the 85 and 98 meter tall hybrid tower)). Turbines with similar rated power, such as the Enercon's E138 (the 81 meter tall steel tower), had greater EPBT than the typical Finnish wind farm. (ENERCON GmbH, 2019). Turbines with greater nominal power (6,0 MW and 6,2 MW) than the typical Finnish wind farm scored better on EPBT (see for example Vestas 2022f, p. 67 and Vestas, 2023).

When the EPBT of the typical Finnish wind farm was compared to EPBT of other RES, in their systematic review of studies studying photovoltaic system, Bhandari, Collier, Ellingson and Apul (2015) found that the system's EPBT was 1 and 4,1 years, and thus much greater than EPBT of the typical Finnish wind farm. Another review of RES – hydropower - was conducted by Nautiyal and Goel (2020, p. 8), who found that the EPBT of hydropower ranged from 0,44 years to 2,71 years, yet predominantly over one year. Thus, the typical Finnish wind farm's EPBT in most cases outperformed hydropower.

Important to note was that the above presented studies set different LCA system boundaries. For example, ENERCON GmbH, 2019 and 2020 excluded the raw material extraction. On the other hand, Vestas also considered raw material extraction and processing across its different LCA studies (see for example Vestas 2011, p. 28 or Vestas 2019, p. 26). In addition, turbine parameters, such as hub height or rotor diameter were expected to impact the EPBT due to greater material requirements and processing efforts at the manufacturing site. In addition, larger wind turbines require more effort during their erection and dismantlement.

Furthermore, the EPBT was perceived as an indicator of turbine's energy efficiency that was independent of net AEP. Thus, even though a wind turbine produced a large amount of electricity in a year, a brief look at EPBT of turbines in the typical Finnish wind farm showed no relationship of inverse proportion between the EPBT and AEP (Vestas 2017b, 2017c, 2019 & 2023 and Russ Reid-McConnell, 2020).

An interesting concept worth discussing was the CO_2 payback time, that is the time required to pay the wind turbine's CO_2 emissions. In great majority of the articles reviewed, only one (Chipindula et al., 2018) considered the CO_2 payback time in addition to the more common concept measuring turbine energy production efficiency – the EPBT. In the article of Chipindula (2018, p. 12), an increase in turbine nameplate capacity was found to be indirectly proportional to turbine CO_2 payback time. In the same article (p. 13), the authors compared same sized wind turbine's CO_2 payback time and EPBT on different locations and found that the CO_2 payback time always slightly lower (less time) than EPBT.

7.3 The typical Finnish wind farm's net impact on climate

Based on the results of Eq. (40) and Eq. (41), the answer to the third research question was that the typical Finnish wind farm had a substantially greater net-negative impact on climate than the commercial forest area on which it was built. In fact, of the two, only the typical Finnish wind farm had a net-negative impact on climate. Importantly, the results do not suggest that the typical Finnish wind farm is a carbon sink.

The finding was supported by the result of Eq. (40) in which the typical Finnish wind farm had a net-negative impact on climate of 169 767,72 t CO_2/20 ha/20 years. Thus, the wind farm's existence prevented 169 767,72 t CO_2 emissions that would otherwise be emitted to the atmosphere by the Finnish electricity mix in a 20 year lifetime. In spite of the lost tree CS and SOCS potentials and CO_2 emissions from SOC stock release as well as from the wood incinerated, the typical Finnish wind farm remained strongly climate negative, i.e. climate change alleviative. In contrast, the commercial forest area was found to have a net-positive impact on climate of (-)192 393,42 t CO_2/20 ha/70 years. Thus, in the absence of the typical Finnish wind farm, the forest and soils remained undisturbed and sequestered C for 70 years, however under this scenario the same amount of electricity produced by the farm was produced by the Finnish electricity mix.

As for the climate impact of the commercial forest area, the forest and soils on the unconstructed typical Finnish wind farm would naturally have a net-negative impact on climate if the same amount of electricity did not need to be produced elsewhere. Also, forests and soils would remain climate negative even if CO_2 emissions related to decomposition of tree biomass (natural decay) and of SOM impacted by environmental factors (temperature, humidity, nutrient availability and others) and by the rate of heterotrophic respiration were considered in this thesis (Bhattacharyya et al. 2022, p. 9). If the CF of the Finnish electricity mix was not included in the calculation of the net-negative impact of forest and soils on the wind farm's site, their net-negative impact on climate on 20 ha of land for 70 years would have amounted to 4 586,57 t CO_2/20 ha/70 years. Therefore, even if the same amount of electricity produced by the wind farm did not need to be produced by the Finnish electricity mix, the significant gap between the net impact on climate of the typical Finnish wind farm and the net impact on climate of the forest and soils remained. As the lack of the electricity produced by the typical Finnish wind farm was included in this Thesis, the climate impact of forests and soils was climate positive, i.e., exacerbating climate change. Whether this was the correct way of approaching this task could become a matter of a debate.

7.3.1 Climate impact versus other environmental and social impacts

Although the typical Finnish wind farm had a better net-negative impact on climate than the commercial forest area on which it was built, the results this Master's Thesis arrived at should not be interpreted in a way that cutting the commercial forest and building a wind farm in it is environmentally superior. For example, the actual construction and existence of the typical Finnish wind farm would have caused environmental and social related impacts. Examples of these impacts are impacts on biodiversity emerging not only from cutting of the forest in the wind farm's area leading to the partial destruction of habitat of animal and plant species but also from the raw material extraction and other processes in turbine's life-cycle, which have land-use impacts. Other environmental impacts concern life-cycle impacts documented by the wind turbine manufacturer's in their LCA reports, such as acidification and eutrophication potential of water bodies, human toxicity potential or terrestrial ecotoxicity potential (see for example Vestas 2023, p. 46).

Wind turbine and farm associated social impacts relate at least to the construction (increase of traffic and noise in the wind farm's area) and operation (noise caused by the turbine machinery and aerodynamic noise caused by the wings, security issues in the area during blade-icing events and possible ice falling or aesthetic concerns related to the wind farm's influence on surrounding landscape). Each of these impacts is likely to decrease the acceptability of wind power in Finland and possibly globally as well. In consequence, assessing solely climate impacts of wind power does not provide the society with holistic understanding of various kinds of other impacts wind power has.

7.3.2 The lowest possible net-negative impact on climate

A crucial fact mentioned in the methodology section related to CF of the Finnish electricity mix must be strongly emphasized. The *"emission factor for electricity consumed in Finland - real time data"* collected by Fingrid (n.d.d) considered solely CF of the energy production phase while in the CF of the typical Finnish wind farm, the farm's whole life-cycle CF was considered. Hence, life-cycle CF (CO_2/kWh) consisting of raw material extraction, manufacture, transportation, decommissioning and end-of-life was omitted in Fingrid's data. In addition, Fingrid incorrectly set CF of all RESs to 0 g CO_2/kWh despite the fact e.g., turbine maintenance comes with climate emissions. Wind power (and to lesser or bigger extent other RESs too) is not an emission free energy source. This is not only apparent in wind power's whole life-cycle GHG emissions (GWP 100), but also in cases of regular and unexpected visits at the wind farm's site as part of the maintenance. Apart from changing turbine's greasing substances, the installation of replacement parts was also expected to bring notable environmental impacts because these parts have life-cycle on their own.

In conclusion, if the whole life-cycle CF of the Finnish electricity mix was considered, such act would have increased the CF of the Finnish electricity mix and as a result, the amount of avoided CO_2 emissions by the typical Finnish wind farm would have also increased. For that reason, the calculated amount of avoided CO_2 in this thesis should be regarded as the *lowest possible amount* of avoided CO_2 emissions. Therefore, even through the numerical results of the third research question lacked the inclusion of whole life-cycle CF of the Finnish electricity mix, such fact on its own did not prevent answering the third thesis question. The results were clear enough to establish the conclusion that the typical Finnish wind farm had a substantially better net-negative impact on climate than the commercial forest area on which it was built. Readers should only be advised to treat the numerical results with caution.

7.3.3 The length of lost tree CS and SOCS potentials

In the scenario the typical Finnish wind farm was built, the length of lost tree CS and SOCS potentials was set at 22 years (construction and operation of the farm). It has to be acknowledged in this thesis that the length of the lost CS potential of trees and soils was potentially greater than 22 years especially for turbine foundation, existing widened and new access roads (see for example Sitowise Oy, 2022). As already noted in the subchapter 5.3.3.5 *Short- and long-term land use changes at the wind farm's site,* it was difficult to grasp and justify the length of short- and long-term lost CS potentials on the site for specific reasons mentioned in the same subchapter.

Even if long-term lost soil and tree CS potentials caused by turbine foundation, existing widened and new access roads were considered, it was assumed that such act would have slightly impacted the numerical result of the net impact on climate of the wind farm yet the answer to the third research question would have remained the same. In addition, even if longer lost potentials of 50, 100 or 200 years were considered, the typical Finnish wind farm would still have better net-negative impact on climate than the commercial forest area.

7.3.4 Age of the typical Finnish wind farm's forest

The mean age of the trees in North Ostrobothnia applied in the methodology section was 64 years. Based on the article of Lehtonen et al. (2004, p. 214), trees of ages from 30 to 39 years and 60 to 69 years had the greatest amount of dry weight biomass. Such fact served as a proof that trees do not sequester C at the same rates throughout their lives. The relationship between age and C sequestered is therefore age-dependent. Bartlett et al. (2020) and Bernal et al. (2018) also indicated that trees do not sequester C in the same rate over their whole lives. The age-dependent CS relationship could therefore serve as a climate mitigation tool – by considering the age of the trees during wind farm's planning phase, avoiding areas with mean age of trees of 30-39 and 60-69 years would lessen the wind farm's site-specific climate impacts. However, important to note is that such evaluation should not be based solely on CS of trees but also on the approximate C stock. In this case, the younger the tree (forest), the lower amount of C it holds.

8 LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

In this section, limitations and suggestions for further research are presented.

8.1 Impact of forest management practices on the typical Finnish wind farm's commercial forest area

Retrieving the data on type of the most common forest management practice, the frequency of undertaking such practices as well as the amount of wood retrieved could potentially support the creation of a more realistic overview regarding the amount of C sequestered in the typical Finnish wind farm's area.

8.2 Weighted C content in Latvia

The data for weighted C content were obtained from an article studying the content in Latvia. As a result, there could be some differences in the actual C stock and C sequestration rates on the typical Finnish wind farm's site. However, due to the relative closeness of Finland and Latvia, it was assumed the difference should not be highly significant to decrease the credibility of this study.

8.3 Electricity transmission lines

As already noted in the methodology section, the electricity transmission lines bringing electricity from the typical Finnish wind farm to electricity lines of the Finnish national electricity grid were not considered under the third thesis question. However, future studies could include the transmission lines because the lines are essential components of any wind farm project. Construction of the lines was not only hypothesized to clear large amount of C sinks but the lines themselves were assumed to have a rather significant impact on climate due to the metals used in the line's structure. In a study of a wind plant in Australia, vegetation clearing for electricity transmission lines was found to (at worst-case) increase the wind farm's GWP by 14%. Because of the potential magnitude of these lines on climate impact of a wind farm, the Australian case emphasizes the need to include transmission lines in calculating the GWP of wind farms in general (PE, 2013 as cited in Vestas 2017c, p. 75). In conclusion, the transmission lines inclusion would have certainly provided a more holistic picture of Finnish wind farm projects and of wind farm projects in general.

8.4 Wind turbine electricity production during Finnish winter

Developing more efficient wind turbines is not only a matter of speed or nominal power, but also of operating temperature. As for the turbines in the typical Finnish wind farm, turbine enhancements by cold-climate solutions extend turbine power production in temperatures of up to -30 degrees Celsius (see for example Vestas, 2022c).

For Nordex Group's turbines, most of the Delta4000 series turbines can operate in temperatures as low as –30 degree Celsius if equipped with the "Cold Climate Package" (Nordex SE, 2021b). As for Vestas, the manufacturer offers to its customers a "Vestas Anti-Icing system, which, among other features, uses "electro-thermal heating elements" embedded in the turbine blade (Vestas, 2018b). In addition, the same company provides its customers with "Ice-Assessment" (Vestas Ice-Assessment") through which only turbines that are likely to be affected by ice are equipped with the "Anti-Icing system" (Vestas, 2018b).

According to Vestas (2018b), the Anti-Icing system should offer minimum of 90% electricity production retention rate depending on site and climatic conditions, while according to Nordex Group (Nordex SE, 2021b), the Cold Climate Package offers at best 80% electricity production retention rate. Thus, there are rather significant differences in turbine performance under icing conditions between the two manufacturers.

In this Master's Thesis, the active use of these systems was not considered due to the lack of data and the thesis's limited scope. It could partially be assumed that the active use of these cold-climate solutions would increase the climate impact of the typical Finnish wind farm. Nevertheless, the increased material production caused by the thermal heating elements placed on the turbine's blade could possibly be counterbalanced by the fact the turbine would produce electricity at extremely low temperatures. Thus, future research could conduct an LCA study of wind farm's with and without the heating elements to see, whether the greater material requirements could be compensated by the electricity production at temperatures as low -30 degree Celsius.

8.5 Addressing the end-of-life phase of the wind farm's turbines

As already discussed before, in addressing the end-of-life phase of the turbine, Vestas as well as Nordex Group applied the same method (substitution and avoided-impacts method), which made their LCAs to benefit from the recycled content of the wind turbines (see for example Russ & Reid-McConnell 2020, p.16 and Vestas 2017c, p. 37). However, because of the method's impact on the typical Finnish wind farm's CF it would be interesting to see the CF associated with using none of the approaches for environmental crediting in cases, where the use of recycled turbine content is not possible.

8.6 Environmental factors affecting SOC release rate

Application of the below-specified parameters affecting the SOC stock release and SOCS was found to be out of scope in this thesis. However, future research could take at least some of these points into account.

1) The study of Peltoniemi et al. (2004, p. 2083) demonstrated that the amount of C sequestered into the soil depended on the type of tree growing on it,
2) the amount of SOC stock was, according to the study of Lindroos, Mäkipää and Merilä (2022, p. 6) also site specific, meaning that in the same study, soils in the southern parts of Finland had greater SOC stock than soil in northern parts of Finland,
3) in studying the C balance of different aged Scots pine forests in Finland, Kolari, Pumpanen, Rannik, Ilvesniemi, Hari and Berninger (2004, p. 1114) found that there was no clear evidence of SOC stocks being greater in older forests than younger forests. Contrary to this finding, Peltoniemi et al. (2004) found a direct proportion between tree stand age and the amount of C sequestered,
4) specifying the factors and their magnitude in impacting the decomposition rate of forest biomass in calculating the net impact on climate of any wind farm – examples of these factors are humidity and temperature levels as well as oxygen, nutrient availability and last, but not the least, anthropogenic factors (Bhattacharyya et al. 2022, p. 9).

8.7 SOC release from drained and undrained peatlands

This study did not distinguish between the C release of peatlands from SOC in drained or undrained peatlands. Thus, future studies could consider the net impact on climate of a wind farm by considering both, drained and undrained peatlands.

8.8 Tree CS on mineral soils and peatlands

As already noted in the beginning of the methodology chapter, different rates of tree CS on mineral soils and peatlands were not considered. This represented a limitation to this study yet, at the same time, it represents an opportunity for future research to address these tree CS rate differences on different soil types to acquire slightly more credible results than the ones attained in this Master's Thesis.

The underground electricity cables transforming electricity from wind turbines to the transformer station have a lifetime of about 30 years. When a wind farm reaches the end-of-life phase, the casing tube inside of which the cables were placed could either be left on the site or removed (Sitowise Oy 2022, p. 22). In this Master's Thesis, the decision was to leave the casing tube underground on the site. Therefore, the typical Finnish wind farm's end-of-life phase did not cause a disturbance to the vegetation lying above the underground-placed casing tubes.

The land-area of borrow areas, from which soil was taken during the farm's construction phase was not included in the FCG Finnish Consulting Group's (2022) land-area estimate. For that reason, climate impacts related to the landscaping of any borrow areas were excluded from this study.

8.9 Collection of Fingrid's open data

As already said, data on "Emission factor for electricity consumed in Finland - real time data" was retrieved from Fingrid's website and the period throughout which the data were retrieved considered a one-year period, more specifically from 29.12.2021 (00:01) to 29.12.2022 (23:58:00). It was important to acknowledge in this thesis that the emission factor is a variable factor, which depends on the availability of RESs such as wind or sun. In general, RESs decrease the emission factor.

The suggestion for further research lies in the fact that the share of RESs, such as wind and solar power, are constantly increasing. Because of this, calculating the CF of the Finnish electricity mix five or ten years later was hypothesized to bring different results as well. In addition to this, the Finnish electricity mix's climate impact could also be affected by warmer and cloudier winters, which only increases the importance of re-calculating the CF of the same mix.

8.10 Turbine types in the typical Finnish wind farm – the case of V126-3,45 MW turbine

It should be noted that as a general practice in Finland (and most likely elsewhere too), wind turbines in a wind farm use the same wind turbine type. The typical Finnish wind farm consisted of five wind turbine types of which one was designed to operate in medium wind conditions – the V126-3,45 MW turbine. This had the potential to represent a limitation to this study with regards to the GWP value and the EPBT since both of these values are dependent on the amount of electricity produced by a wind turbine. GWP and EPBT values for operating this wind turbine under low wind conditions was not available in the LCA report (Vestas, 2017b). In conclusion, whether operating this turbine under low wind conditions would have increased or decreased the typical Finnish wind farm's environmental performance (GWP and EPBT) remains a question. Nevertheless, the fact is that even if the GWP and EPBT were significantly different, it would have not changed the typical Finnish wind farm's climate and EPBT results much because the V126-3,45 MW turbine was represented only once in the wind farm.

8.11 Increased wind turbine lifetime – from 20 to 35 and 50 years

As a baseline lifetime or sensitivity analysis lifetime, future LCA studies of wind turbines should consider wind turbine lifetime of 35 and 50 years. This claim is supported by the expert opinions of Sitowise Oy (2022) and FCG Finnish Consulting Group (2022) who claimed that (newer) wind turbines could reach operating lifetime of over 30 years. In addition, wind turbine machinery renewal increased the turbine's operating lifetime to 50 years (Sitowise Oy, 2022; Ramboll Finland Oy, 2019 and FCG Finnish Consulting Group, 2022). The foundation's lifetime was also projected to be 50 years and the lifetime of underground cables was planned to be at least 30 years (FCG Finnish Consulting Group 2022, p. 42).

In consequence, applying greater turbine lifetime would have not only caused a decrease of turbine's CF but also portray a more realistic picture about the CF of wind power in general. Future studies could then study the CF of the typical Finnish wind farm's 35 or 50 year lifetime (including the renewal of turbine machinery).

9 ACKNOWLEDGEMENTS

At first, I would like to express my deep thanks to Heidi Paalatie from the Finnish Wind Power Association for initiating this topic and for her support along the way. Second, I am extremely grateful to my thesis supervisors – Stefan Baumeister and Sami El Geneidy – for their support not only during the negotiation phase with FWPA but also during the thesis writing process itself. My deepest gratitude also belongs to Anssi Lenssu from the University of Jyväskylä for his stunning introduction to the GIS world as well as for his support in the GIS analysis conducted as part of this thesis. I am also eternally grateful to Juhani Marttila, who helped me to understand wood sciences and who encouraged and highly supported me in calculating the C stock and CS potential. I would also like to express my gratitude to my wife – Tuulia Lehtomaja – and to our daughter for their patience and support throughout the thesis-writing journey. Last, but not the last, special thanks belong to Eva Baková for her guidance and mental support.

REFERENCES

AFRY Finland Oy. (2020). Tuulivoima Suomessa 2019 [Wind power in Finland]. Retrieved on 1.1.2023 from https://www.tuulivoimayhdistys.fi/media/tuulivoimatilastot_afry_200227-1.pdf

AFRY Finland Oy. (2020). Toiminnassa olevat & puretut voimalat [Operating & dismantled wind turbines]. Retrieved on 1.1.2023 from https://tuulivoimayhdistys.fi/tuulivoima-suomessa/toiminnassa-olevat-puretut

Alexandrov, G. (2008). Climate Change 1: Short-Term Dynamics. In S. E. Jørgensen & B. D. Fath (Eds.), Encyclopedia of Ecology (pp. 588–592). Academic Press. https://doi.org/10.1016/B978-008045405-4.00724-2

Arzoumanidis, I., D'Eusanio, M., Raggi, A. & Petti, L. (2020). Functional unit definition criteria in life cycle assessment and social life cycle assessment: A discussion. Teoksessa M. Traverso, L. Petti & A. Zamagni (toim.), Perspectives on social LCA: Contributions from the 6th international conference (s. 1-10). Cham: Springer International Publishing. doi:10.1007/978-3-030-01508-4_1

Arvesen, A., & Hertwich, E. G. (2012). Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. *Renewable and Sustainable Energy Reviews*, *16*(8), 5994–6006. https://doi.org/10.1016/j.rser.2012.06.023

Baumann, H. & Tillman, A. (2004). *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application* (1:10). Sweden: Studentlitteratur.

Bārdule, A., Liepiņš, J., Liepiņš, K., Stola, J., Butlers, A., & Lazdiņš, A. (2021). Variation in Carbon Content among the Major Tree Species in Hemiboreal Forests in Latvia. Forests, 12(9). https://doi.org/10.3390/f12091292

Bartlett, J., Rusch, G. M., Kyrkjeeide, M. O., Sandvik, H., & Nordén, J. (2020). *Carbon storage in Norwegian ecosystems (revised edition)* (No. 1774b). Norwegian Institute for Nature Research. Retrieved on 27.05.2022 from https://media.wwf.no/assets/article_images/rapport_karbonlagring.pdf

Beig, A. R., & Muyeen, S. M. (2016). 4 - wind energy. In M. H. Rashid (Ed.), *Electric renewable energy systems* (pp. 60-77). Academic Press. https://https://doi.org/10.1016/B978-0-12-804448-3.00004-9

Beuckelaers, W. (2017). Numerical modelling of laterally loaded piles for offshore wind turbines.

Bernal, B., Murray, L. T., & Pearson, T. R. H. (2018). Global carbon dioxide removal rates from forest landscape restoration activities. *Carbon Balance and Management*, *13*(1), 22. https://doi.org/10.1186/s13021-018-0110-8

Besseau, R., Sacchi, R., Blanc, I., & Pérez-López, P. (2019). Past, present and future environmental footprint of the Danish wind turbine fleet with LCA_WIND_DK, an online interactive platform. Renewable and Sustainable Energy Reviews, 108, 274–288. https://doi.org/10.1016/j.rser.2019.03.030

Bhandari, R., Kumar, B. & Mayer, F. (2020). Life cycle greenhouse gas emission from wind farms in reference to turbine sizes and capacity factors. *Journal of Cleaner Production, 277*, 123385. doi:https://doi.org/10.1016/j.jclepro.2020.123385

Bhandari, K. P., Collier, J. M., Ellingson, R. J., & Apul, D. S. (2015). Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis. Renewable and Sustainable Energy Reviews, 47, 133–141. https://doi.org/10.1016/j.rser.2015.02.057

Bhattacharyya, S. S., Ros, G. H., Furtak, K., Iqbal, H. M. N., & Parra-Saldívar, R. (2022). Soil carbon sequestration – An interplay between soil microbial community and soil organic matter dynamics. *Science of The Total Environment*, *815*, 152928. https://doi.org/10.1016/j.scitotenv.2022.152928

Bonou, A., Laurent, A. & Olsen, S. I. (2016). Life cycle assessment of onshore and offshore wind energy-from theory to application. *Applied Energy, 180*, 327-337. doi:https://doi.org/10.1016/j.apenergy.2016.07.058

Britannica, T. Editors of Encyclopaedia. *Lithosphere*. *Encyclopedia Britannica*. Retrieved on 17.4.2022 from https://www.britannica.com/science/lithosphere

Carlson, C. A., Bates, N. R., Hansell, D. A., & Steinberg, D. K. (2001). Carbon cycle. In J. H. Steele (Ed.), *Encyclopedia of ocean sciences (second edition)* (pp. 477-486). Academic Press. https://doi.org/10.1016/B978-012374473-9.00272-1

Contreras, S. (2015). Complementing the circular economy with LCA. Retrieved on 4.4.2021 from https://pre-sustainability.com/articles/complementing-the-circular-economy-with-lca/

Chipindula, J., Botlaguduru, V., Du, H., Kommalapati, R. & Huque, Z. (2018). Life cycle environmental impact of onshore and offshore wind farms in texas. Sustainability (Basel, Switzerland), 10(6), 2022. doi:10.3390/su10062022

Curran, M. A. (2012). *Life cycle assessment handbook : A guide for environmentally sustainable products*. Somerset, UNITED STATES: John Wiley & Sons, Incorporated.

Demir, N. & Taşkın, A. (2013). Life cycle assessment of wind turbines in pınarbaşı-kayseri. *Journal of Cleaner Production, 54*, 253-263. doi:https://doi.org/10.1016/j.jclepro.2013.04.016

de Wit, H., Austnes, K., Hylen, G., & Dalsgaard, L. (2015). A carbon balance of Norway: Terrestrial and aquatic carbon fluxes. *Biogeochemistry*, *123*. https://doi.org/10.1007/s10533-014-0060-5

DNV GL. (2018). Project certification of wind farms according to IEC 61400-22 (DNVGL-SE-0073). Retrieved on 9.9.2021 from https://www.dnv.com/energy/standards-guidelines/dnv-se-0073-project-certification-of-wind-farms-according-to-iec61400-22.html

Dormann, C. F., Bagnara, M., Boch, S., Hinderling, J., Janeiro-Otero, A., Schäfer, D., Schall, P., & Hartig, F. (2020). Plant species richness increases with light availability, but not variability, in temperate forests understorey. BMC Ecology, 20(1), 43. https://doi.org/10.1186/s12898-020-00311-9

Edelen, A., Ingwersen, W. W., Rodríguez, C., Alvarenga, R. A. F., de Almeida, A. R., & Wernet, G. (2017). Critical review of elementary flows in LCA data. The International Journal of Life Cycle Assessment, 2017, 1. doi:10.1007/s11367-017-1354-3

ENERCON GmbH. (2019). Life cycle assessment E 138 EP3.

ENERCON GmbH. (2020). Life cycle assessment E 92.

Environmental Administration (Ympäristöhallinto). (2020). Tuulivoimarakentaminen. Retrieved on 5.5.2021 from https://www.ymparisto.fi/fi-fi/elinymparisto_ja_kaavoitus/elinymparisto/tuulivoimarakentaminen

Environmental Administration (Ympäristöhallinto). (2021). Usein kysytyt kysymykset tuulivoimasta. Retreived on 5.5.2021 from https://www.ymparisto.fi/fi-FI/Elinymparisto_ja_kaavoitus/Elinymparisto/Tuulivoimarakentaminen/Tuulivoimaneuvonta/Usein_kysytyt_kysymykset_tuulivoimasta(39060)#Onko%20tuulivoimalan%20melusta%20tai%20v%C3%A4lkkeest%C3%A4%20koettua%20rasitusta%20mahdollistaa%20v%C3%A4hent%C3%A4%C3%A4?

European Commission. (2010). Variations in topsoil organic carbon content across Europe. Retrieved on 5.10.2022 from https://www.eea.europa.eu/data-and-maps/figures/variations-in-topsoil-organic-carbon

European Environment Agency. (2021). Forest: growing stock, increment and fellings. Retrieved on 5.5.2022 from https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3/assessment

Eurostat. (2021). Glossary: Biomass. Retrieved on 5.5.2022 from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Biomass

Fingrid Oyj. (n.d.a). Real-time CO_2 emissions estimate. Retrieved September 26, 2022 from https://www.fingrid.fi/en/electricity-market-information/real-time-co2-emissions-estimate/

Fingrid Oyj. (n.d.b). Download datasets. Retrieved on 20.9.2022 from https://data.fingrid.fi/open-data-forms/search/en/index.html?selected_datasets=266

Fingrid Oyj. (n.d.c). Net import/export of electricity - real time data. Retrieved on 31.12.2022 from https://data.fingrid.fi/en/dataset/net-import-export-of-electricity-real-time-data

Fingrid Oyj. (n.d.d). Emission factor for electricity consumed in Finland - real time data. Retrieved on 30.12.2022 from https://data.fingrid.fi/en/dataset/suomessa-kulutetun-sahkon-paastokerroin-reaaliaikatieto

Finnish Biodiversity Info Facility. (n.d.). Hieskoivu – Betula pubescens. Retrieved on 16.3.2023 from https://laji.fi/taxon/MX.37999?showTree=true

Frühwald , A. (2020). Wood and climate. Retrieved on 25.10.2022 from https://www.wooddays.eu/en/woodclimate/index.html

FCG Finnish Consulting Group Oy. (2021). Lasorin tuulivoimapuisto, Vöyri: Ympäristövaikutusten arviointiohjelma. Retrieved on February 8, 2022 from https://www.ymparisto.fi/fiFI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/Lasorin_tuulivoimapuisto_Voyri

FCG Finnish Consulting Group Oy. (2022). Tornimäen tuulivoimahanke, Padasjoki: Ympäristövaikutusten arviointiohjelma. Retrieved on 22.06.2022 from https://www.ymparisto.fi/fi FI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/ABO_Wind_Oy_Tornimaen_tuulivoimahanke_Padasjoki

FCG Suunnittelu ja tekniikka Oy. (2016). TuuliWatti Oy: Palokankaan Tuulivoimapuisto. Retrieved on 15.6.2022 from https://www.ymparisto.fi/fi-FI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/Palokankaan_tuulivoimapuisto_Ii

FCG Suunnittelu ja tekniikka Oy. (2018). Palokankaan tuulivoimapuiston yleiskaava. Retrieved on June 20, 2022 from https://www.ii.fi/sites/ii.fi/files/TIEDOSTOT/ASUMINEN_YMPARISTO/Kaavoitus/Palokangas_YK_10122018_10000.pdf

Finnish Wind Power Association (FWPA). (n.d.a). Tuulivoimasanastoa. Retrieved on 29.1.2023 from https://tuulivoimayhdistys.fi/tietoa-tuulivoimasta-2/tuulivoimasanastoa

Finnish Wind Power Association (FWPA) (n.d.b). How much wind power to Finland? Retreived on 29.1.2023 from https://tuulivoimayhdistys.fi/en/wind-power-in-finland-2/wind-power-in-finland/how-much-wind-power-to-finland

Finnish Wind Power Association (FWPA). (n.d.c). About wind power in Finland. Retrieved on 29.1.2023 from https://tuulivoimayhdistys.fi/en/wind-power-in-finland-2/wind-power-in-finland/about-wind-power-in-finland

Finnish Wind Power Association (FWPA). (n.d.d). List of constructed wind farms 1999 - 2022. Retrieved on 11.2.2023 from https://tuulivoimayhdistys.fi/en/wind-power-in-finland/wind-power-in-production-and-dismantled

Finnish Wind Power Association (FWPA). (2021). Windpower in Finland 2020. Retrieved on 2.1.2023 from https://tuulivoimayhdistys.fi/media/tuulivoima_vuositilastot_2020_eng-public-10.2.pdf

Finnish Wind Power Association (FWPA). (2022a). Wind power in Finland 2021. Retrieved on 29.1.2023 from https://tuulivoimayhdistys.fi/media/tuulivoima_vuositilastot_2021_in_english-2.pdf

Finnish Wind Power Association (FWPA). (2022b). Tuulivoima Suomessa 2021. Retrieved on 28.2.2022 from https://tuulivoimayhdistys.fi/media/tuulivoima_vuositilastot_2021.pdf

Finnish Wind Power Association (FWPA). (2022c). Rakenteilla olevat hankkeet. Retrieved on 11.8.2022 from https://tuulivoimayhdistys.fi/tuulivoima-suomessa/rakenteilla-olevat-hankkeet

Finnish Wind Power Association (FWPA). (2022d). Toiminnassa olevat & puretut voimalat. Retrieved on 12.2.2023, from https://tuulivoimayhdistys.fi/tuulivoima-suomessa/toiminnassa-olevat-puretut

Finnish Wind Power Association (FWPA). (2023). Wind power in Finland 2022. Retrieved on 29.1.2023 from https://tuulivoimayhdistys.fi/media/finnish-wind-power-stats_2022-12.1.2023-.pdf

Food and Agriculture Organization (2019). GLOSIS - GSOCmap (v1.5.0): Global Soil Organic Carbon Map. Contributing Countries. Retrieved on 6.6.2022 from http://54.229.242.119/GSOCmap/

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Galloway, J. N. (2003). 8.12 - the global nitrogen cycle. In H. D. Holland, & K. K. Turekian (Eds.), *Treatise on geochemistry* (pp. 557-583). Pergamon. https://https://doi.org/10.1016/B0-08-043751-6/08160-3

Gareiou, Z., Drimili, E. & Zervas, E. (2021). 12 - public acceptance of renewable energy sources. Teoksessa G. L. Kyriakopoulos (toim.), *Low carbon energy technologies in sustainable energy systems* (s. 309-327) Academic Press. doi:https://doi.org/10.1016/B978-0-12-822897-5.00012-2

GEMET. (2021). Dead organic matter. Retrieved on 21.6.2022 from https://www.eionet.europa.eu/gemet/en/concept/15112

Ghenai, C. (2012). Life cycle analysis of wind turbine. () doi:10.5772/29184

Grant, N., Hawkes, A., Mittal, S. & Gambhir, A. (2021). The policy implications of an uncertain carbon dioxide removal potential. *Joule, 5*(10), 2593-2605. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.joule.2021.09.004

Guezuraga, B., Zauner, R. & Pölz, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy, 37*(1), 37-44. doi:https://doi.org/10.1016/j.renene.2011.05.008

Hannah, L. (2015). Chapter 19 - carbon sinks and sources. In L. Hannah (Ed.), *Climate change biology (second edition)* (pp. 403-422). Academic Press. https://https://doi-org.ezproxy.jyu.fi/10.1016/B978-0-12-420218-4.00019-6

Harding, A., & Moreno-Cruz, J. B. (2019). 25 - the economics of geoengineering. In T. M. Letcher (Ed.), *Managing global warming* (pp. 729-750). Academic Press. https://https://doi.org/10.1016/B978-0-12-814104-5.00025-9

Holtsmark, B. (2015). Quantifying the global warming potential of CO2 emissions from wood fuels. *GCB Bioenergy, 7*(2), 195-206. doi:https://doi.org/10.1111/gcbb.12110

Horne, R., Verghese, K. & Grant, T. (2009). *Life cycle assessment : Principles, practice, and prospects*. Collingwood, Vic: CSIRO Publishing.

Huotari, J. (2020). *Wind power generation efficiency and seasonality*. (). http://www.jussihuotari.com/randstan/demo_wind/wind_seasonality_report.html

International Organization for Standardization. (2006a). Environmental management — life cycle assessment — principles and framework. (ISO Standard No. 4040:2006)

International Organization for Standardization. (2006b). Environmental management — life cycle assessment — requirements and guidelines. (ISO Standard No. 14044:2006)

Kadiyala, A., Kommalapati, R. & Huque, Z. (2017). Characterization of the life cycle greenhouse gas emissions from wind electricity generation systems. *International Journal of Energy and Environmental Engineering, 8*(1), 55-64. https://doi:10.1007/s40095-016-0221-5

Kaldellis, J. K. & Apostolou, D. (2017). Life cycle energy and carbon footprint of offshore wind energy. comparison with onshore counterpart. *Renewable Energy, 108*, 72-84. doi:https://doi.org/10.1016/j.renene.2017.02.039

Kauppi, P. E. ; P., Maximilian; Hänninen, Pekka; Henttonen, Helena M; Ihalainen, Antti; Lappalainen, Eino; Starr, Michael; Tamminen, Pekka. (1997). *Carbon reservoirs in peatlands and forests in the boreal regions of Finland.* http://hdl.handle.net/1975/8507

Khoie, R., Bose, A., & Saltsman, J. (2021). A study of carbon emissions and energy consumption of wind power generation in the Panhandle of Texas. Clean Technologies and Environmental Policy, 23(2), 653–667. https://doi.org/10.1007/s10098-020-01994-w

Kinnunen, T., & Engström, A. (2019). Päätös Ympäristövaikutusten Arviointimenettelyn (YVA-menettely) Soveltamisesta Yksittäistapauksessa Ilmatar Loviisa Oy:n Tuulivoimapuisto, Loviisa. Elinkeino-, liikenne- ja ympäristökeskus (ELY-keskus). https://www.ymparisto.fi/download/noname/%7BA9A6E331-84B6-464A-B689-4D47BDA11CB3%7D/151515

Klöpffer, W., Grahl, B. & Klöpffer, W. (2014). *Life cycle assessment (LCA) : A guide to best practice*. Weinheim: John Wiley & Sons, Incorporated.

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Environmental Change Issues*, *15*, 79–86. https://doi.org/10.1016/j.cosust.2015.09.002

Lambers, H. and Bassham, . James Alan (2021, June 11). *photosynthesis*. *Encyclopedia Britannica*. https://www.britannica.com/science/photosynthesis

Laybourn-Parry, J. E.M. and Diaz, Julia M. (2019, February 7). protozoan. Encyclopedia Britannica. https://www.britannica.com/science/protozoan

Leino, L., & Joensuu, K. (2021). *Summary Of The Wind Power Development Process In Finland*. Finnish Wind Power Association.

Lehmann, J., Hansel, C. M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J. P., Torn, M. S., Wieder, W. R., & Kögel-Knabner, I. (2020). Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience*, *13*(8), 529–534. https://doi.org/10.1038/s41561-020-0612-3 as cited in Cano Bernal, J. E., Rankinen, K., & Thielking, S. (2022). Concentration of organic carbon in Finnish catchments and variables involved in its variations. *Journal of Environmental Management*, *302*, 113981. https://doi.org/10.1016/j.jenvman.2021.113981

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., & Liski, J. (2004). Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management, 188(1), 211–224. https://doi.org/10.1016/j.foreco.2003.07.008

Lehtonen, A., Heikkinen, J. (2015). Uncertainty of upland soil carbon sink estimate for Finland. *Canadian Journal of Forest Research.* 46(3): 310-322. https://doi.org/10.1139/cjfr-2015-0171

Lindroos, A.-J., Mäkipää, R., & Merilä, P. (2022). Soil carbon stock changes over 21 years in intensively monitored boreal forest stands in Finland. *Ecological Indicators*, *144*, 109551. https://doi.org/10.1016/j.ecolind.2022.109551

Lundell, T. K., Mäkelä, M. R., de Vries, R. P., & Hildén, K. S. (2014). Chapter Eleven—Genomics, Lifestyles and Future Prospects of Wood-Decay and Litter-Decomposing Basidiomycota. In F. M. Martin (Ed.), *Advances in Botanical Research* (Vol. 70, pp. 329–370). Academic Press. https://doi.org/10.1016/B978-0-12-397940-7.00011-2

Maiti, S. K. & Ghosh, D. (2020). Chapter 24 - plant–soil interactions as a restoration tool. Teoksessa M. N. V. Prasad & M. Pietrzykowski (toim.), Climate change and soil interactions (s. 689-730) Elsevier. doi:https://doi-org.ezproxy.jyu.fi/10.1016/B978-0-12-818032-7.00024-2

Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E. & Blanco, J. (2009). Life cycle assessment of a multi-megawatt wind turbine. Renewable Energy, 34(3), 667-673. doi:https://doi.org/10.1016/j.renene.2008.05.020

Mendecka, B. & Lombardi, L. (2019). Life cycle environmental impacts of wind energy technologies: A review of simplified models and harmonization of the results. Renewable and Sustainable Energy Reviews, 111, 462-480. doi:https://doi.org/10.1016/j.rser.2019.05.019

Metsiensuojelualue- ja METSO-tilastointi -työryhmä, 2014. (2015). Suunnitelma metsien suojelualue- ja METSO-tilastoinnin kehittämiseksi: METI-työryhmä.

Metsä Group. (n.d.). Every wooden building is a carbon storage. Retrieved on 5.5.2022 from https://www.metsagroup.com/en/Campaigns/IntelligentMetsa/urbancarbon/every-wooden-building-is-a-carbon-storage/Pages/default.aspx

Metsä Wood (2022a). Carbon Storage. Retrieved on 5.5.2022 from https://www.metsawood.com/global/Products/plywood/Pages/Plywood.aspx

Metsä Wood (2022b). Plywood. Retrieved on 5.5.2022 from https://www.metsawood.com/global/Products/plywood/Pages/Plywood.aspx

Mikkonen, A. (2021). Pohjois-Pohjanmaa pysyy suomen tuulivoimakeskittymänä – kiinteistöverotulot lähes 6 miljoonaa. Retrieved on 2.1.2022 from https://tuulivoimayhdistys.fi/ajankohtaista/tiedotteet/pohjois-pohjanmaa-pysyy-suomen-tuulivoimakeskittymana-kiinteistoverotulot-lahes-6-miljoonaa

Ministry of Agriculture and Forestry. (n.d.). Kasvupaikkatyypin tunnistaminen. Retrieved on 16.2.2023 from https://metsanhoidonsuositukset.fi/fi/toimenpiteet/kasvupaikkatyypin-tunnistaminen

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., Geden, O., Ghosh, A., Low, S., Njamnshi, A., Noël, J., Táíwò, O. O., Talati, S., & Wilcox, J. (2020). Principles for thinking about carbon dioxide removal in just climate policy. One Earth, 3(2), 150-153. https://https://doi.org/10.1016/j.oneear.2020.07.015

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang (2013). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nautiyal, H., & Goel, V. (2020). Sustainability assessment of hydropower projects. Journal of Cleaner Production, 265, 121661. https://doi.org/10.1016/j.jclepro.2020.121661

Navin kumar, B., Rajendran, S., Vasudevan, A., & Balaji, G. (2020). Aerodynamic braking system analysis of horizontal axis wind turbine using slotted airfoil. *International Conference on Nanotechnology: Ideas, Innovation and Industries, 33, 3970–3979. https://doi.org/10.1016/j.matpr.2020.06.334*

National Land Survey. (2023). Pinta-ala kunnittain 1.1.2023 (Excel). Retrieved on 10.5.2023 from https://www.maanmittauslaitos.fi/sites/maanmittauslaitos.fi/files/attachments/2023/02/Vuoden_2023_pinta-alatilasto_kunnat_maakunnat.xlsx

Natural Resources Institute Finland (Luke). (2019). Forest protection 1.1.2019. Retrieved from https://stat.luke.fi/en/forest-protection-112019_en

Natural Resources Institute Finland (Luke). (n.d.a). File service for publicly available data. Retrieved on 15.12.2022 from https://kartta.luke.fi/index-en.html

Natural Resources Institute Finland (Luke). (n.d.b). Mean growing stock volume on forest land (m^3/ha). Retrieved on 4.1.2023 from http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__04%20Metsa__06%20Metsavarat/1.22_Puuston_keskitilavuus_metsamaalla.px/

Natural Resources Institute Finland (Luke). (n.d.c). Annual increment of growing stock on forest land and on poorly productive forest land. Retrieved on 5.5.2023 from https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__04%20Metsa__06%20Metsavarat/1.24_Puuston_vuotuinen_kasvu_metsa_ja_kitu.px/

Natural Resources Institute Finland. (n.d.d). Total roundwood removals by forest ownership category and region (maakunta) 2015-. Retrieved on 10.5.2023 from https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__04%20Metsa__02%20Rakenne%20ja%20tuotanto__10%20Hakkuukertyma%20ja%20puuston%20poistuma/02b_Puuston_poistuma_maak.px/

Natural Resources Institute Finland (Luke). (n.d.e). Age of forest stands on forest land (1000 ha). Retrieved on 17.4.2023 from https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__04%20Metsa__06%20Metsavarat/1.13_Metsikoiden_ikaluokat_metsamaalla.px/

Natural Resources Institute Finland (Luke). (n.d.f). Total drain by forest ownership category and region (maakunta), 2015-. Retrieved on 5.5.2023 from https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__04%20Metsa__02%20Rakenne%20ja%20tuotanto__10%20Hakkuukertyma%20ja%20puuston%20poistuma/02b_Puuston_poistuma_maak.px/

Nordex SE. (2021). The N149/5.X even more flexibility. even more power. Retrieved on 5.6.2022 from https://www.nordex-online.com/en/product/n149-5-x/

Nordex SE. (2021b). Customization. Retrieved on 1.11.2021 from https://www.nordex-online.com/en/product/customization/#coldclimatesolution

Nordex SE. (2022). *ABOUT THE NORDEX GROUP*. Nordex-Online. Retrieved on 31.3.2022 from https://www.nordex-online.com/en/company/

Nordex SE. (2023). The N163/6.x entering the 6MW+ class. Retrieved on 21.1.2023 from https://www.nordex-online.com/en/product/n163-6-x/

Nunes, L. J. R., Meireles, C. I. R., Pinto Gomes, C. J., & Almeida Ribeiro, N. M. C. (2020). Forest Contribution to Climate Change Mitigation: Management Oriented to Carbon Capture and Storage. Climate, 8(2). https://doi.org/10.3390/cli8020021

Oberle, B. (2016). Carbon Relations, the Role in Plant Diversification of. In R. M. Kliman (Ed.), *Encyclopedia of Evolutionary Biology* (pp. 260–266). Academic Press. https://doi.org/10.1016/B978-0-12-800049-6.00261-4

Official Statistics of Finland (OSF) (n.d.). Concepts: Renewable energy sources [e-publication]. Helsinki: Advisory Board of Official Statistics of Finland. Retrieved on 18.11.2021 from https://www.stat.fi/meta/kas/uusiutuvat_ener_en.html

Official Statistics of Finland (OSF). (2020). Production of electricity and heat [e-publication]. ISSN=1798-5099. 2020. Helsinki: Statistics Finland. Retrieved on 8.8.2022 from http://www.stat.fi/til/salatuo/2020/salatuo_2020_2021-11-02_tie_001_en.html

Official Statistics of Finland (OSF) (2021a). Production of electricity and heat [e-publication]. ISSN=1798-5099. Helsinki: Statistics Finland. Retrieved on 14.1.2021 from http://www.stat.fi/til/salatuo/index_en.html

Official Statistics of Finland (OSF) (2021b). Energy supply and consumption [e-publication].
ISSN=1799-7976. Helsinki: Statistics Finland. Retrieved on 3.1.2022 from http://www.stat.fi/til/ehk/index_en.html

Jolliet, O., Myriam Saade-Sbeih, Shaked, S., Jolliet, A., & Crettaz, P. (2016). *Environmental life cycle assessment*. Boca Raton: CRC Press. Retrieved from https://search-ebscohost-com.ezproxy.jyu.fi/login.aspx?direct=true&db=nlebk&AN=1099097&site=ehost-live

Paikkatietoikkuna (n.d.a). Topographic database: Wind power generator - National Land Survey. Retrieved on 7.6.2022 from https://kartta.paikkatietoikkuna.fi/#

Paikkatietoikkuna (n.d.b). Topographic Map - National Land Survey. Retrieved on 27.6.2022 from https://kartta.paikkatietoikkuna.fi/?lang=en#

Paikkatietoikkuna (n.d.c). Orthophotos - National Land Survey. Retrieved on 29.06.2022 from https://kartta.paikkatietoikkuna.fi/?lang=en#

PE (2013). Life Cycle Assessment of the Musselroe Wind Farm for Hydro Tasmania. Version 7. PE Australasia, October 2013 as cited in Vestas. (2017c). Life Cycle Assessment of Electricity Production from an onshore V136-3.45 MW Wind Plant – 31st July 2017, Version 1.0. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Peltoniemi, M., Mäkipää, R., Liski, J., & Tamminen, P. (2004). Changes in soil carbon with stand age – an evaluation of a modelling method with empirical data. *Global Change Biology*, *10*(12), 2078–2091. https://doi.org/10.1111/j.1365-2486.2004.00881.x

Plug in India. (2019). What is wind energy? Retrieved on 20.1.2021 from https://www.pluginindia.com/whatiswindenergy.html

Pöyry Finland Oy. (2018). Vaalan Turkkiselkä tuulivoimahanke YVA-ohjelma [Vaala Turkkiselkä's wind farm projects' environmental impact assessment's programme]. Retrieved on 10.5.2022 from https://www.ymparisto.fi/turkkiselkatuulivoimayva

Pukkala, T. (2020). Calculating the Additional Carbon Sequestration of Finnish Forestry. *Journal of Sustainable Forestry*, 1–18. https://doi.org/10.1080/10549811.2020.1792935

QGIS project (2022). QGIS documentation. Retrieved on 22.12.2022 from https://docs.qgis.org/3.22/en/docs/user_manual/processing_algs/qgis/rasteranalysis.html?highlight=zonal%20statistics#zonal-statistics

Ramboll Finland Oy. (2014). Piiparinmäen tuulivoimapuiston osayleiskaava: osayleiskaavaluonnos 27.10.2014 [Piiparinmäki wind farm's partial disposition plan: draft of the partial disposition plan]. Retrieved on 1.6.2022 from https://www.metsa.fi/wp-content/uploads/2020/06/Piiparinmaki-Pyhanta-14604-kaavakartta.pdf

Ramboll Finland Oy. (2019). Yli-Olhavan tuulivoimapuiston osayleiskaava: osallistumis- ja arviointisuunnitelma [Yli-Olhava wind farm project's partial disposition plan: participation and assessment plan]. Retrieved June 10, 2022 from https://www.ymparisto.fi/fi-FI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/YliOlhavan_tuulivoimahanke_Ii

Ramboll Finland Oy. (2020). *Yli-Olhavan tuulivoimahanke, Ii* [Yli-Olhava wind farm project, Ii]. Retrieved February 8, 2022 from https://www.ymparisto.fi/fi-fi/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/YliOlhavan_tuulivoimahanke_Ii

Räike, A., Kortelainen, P., Mattsson, T., & Thomas, D. N. (2012). 36year trends in dissolved organic carbon export from Finnish rivers to the Baltic Sea. Science of The Total Environment, 435–436, 188–201. https://doi.org/10.1016/j.scitotenv.2012.06.111

Royal Academy of Engineering (2010) Wind Turbine Power Calculations. RWE Npower Renewables, Mechanical and Electrical Engineering Power Industry. Retrieved from https://www.raeng.org.uk/publications/other/23-wind-turbine

Russ, M. & Reid-McConnell, L. (2020). LCA of a Nordex Windfarm with Delta4000 turbines. Retrieved on 1.5.2021 from https://www.nordex-online.com/wp-content/uploads/sites/2/2020/03/30032020-LCA-of-Nordex-Windfarm-with-Delta4000-turbines-without-Annex-B_Update.pdf

Saffour, H. & Omar, A. (2010). Wind turbine wireless communication network & Heading measurement system (Feasibility study).

Salminen, H. (2023). Miten hiilensidontaa ja varastointia lasketaan? [How do we calculate carbon sequestration and storage?]. Retrieved on 11.5.2023 from https://www.oamk.fi/images/Hankkeet/Canemure/Hiilensidonta_Salminen.pdf

Selin, Noelle Eckley. "Carbon Sequestration". Encyclopedia Britannica, 16 Jan. 2019. Retrieved on 26.5.2022 from https://www.britannica.com/technology/carbon-sequestration

Seppälä, J., Grönroos, Koskela, Holma, Leskinen, Liski, Tuovinen, Laurila, Turunen, Lind, Maljanen, Matikainen & Kilpeläinen (2010). Climate impacts of peat fuel utilization chains – a critical review of the Finnish and Swedish life cycle assessments. Finnish Environment Institute. The Finnish Environment 16/2010. Retrieved on 10.11.2022 from http://hdl.handle.net/10138/37984

Seppälä, J., Kanninen, M., Vesala, T., Uusivuori, J., Kalliokoski, T., Lintunen, J., Saikku, L., Korhonen, R., & Repo, A. (2015). *Ilmastopaneeli: Metsien hyödyntämisen ilmastovaikutukset ja hiilinielujen kehittyminen*. Suomen ympäristökeskus SYKE; Helsingin yliopisto, HY; Luonnonvarakeskus, Luke. https://www.ilmastopaneeli.fi/wp-content/uploads/2018/10/Metsien-hyodyntamisen-ilmastovaikutukset-ja-hiilinielujen-kehittyminen.pdf

Šerešová, M., Štefanica, J., Vitvarová, M., Zakuciová, K., Wolf, P., & Kočí, V. (2020). Life Cycle Performance of Various Energy Sources Used in the Czech Republic. *Energies*, *13*(21). https://doi.org/10.3390/en13215833

Schreiber, A., Marx, J. & Zapp, P. (2019). Comparative life cycle assessment of electricity generation by different wind turbine types. *Journal of Cleaner Production, 233*, 561-572. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.jclepro.2019.06.058

Siemens Gamesa Renewable Energy. (2020). Electricity from a European onshore wind farm using SG 5.0-145 wind turbines. Retrieved on 10.10.2021 from https://portal.environdec.com/api/api/v1/EPDLibrary/Files/cbde865c-fdea-43ef-a49d-8efe701d6842/Data

Siemens, A. G. (n.d.). A clean energy solution - from cradle to grave.

Soimakallio, S. (2017). *Sampo Soimakallio: Avaimia metsien käytön ilmastovaikutusten ymmärtämiseen*. Suomen Ympäristökeskus. https://www.syke.fi/fi-FI/Ajankohtaista/Ratkaisujablogi/Sampo_Soimakallio_Avaimia_metsien_kayton(42331)

Soimakallio, S., Kalliokoski, T., Lehtonen, A., & Salminen, O. (2021). On the trade-offs and synergies between forest carbon sequestration and substitution. *Mitigation and Adaptation Strategies for Global Change*, *26*(1), 4. https://doi.org/10.1007/s11027-021-09942-9

Sitowise Oy. Hanhinevan tuulivoimahanke - Ympäristövaikutusten arviointiohjelma. Retrieved on 10.11.2022 from https://www.ymparisto.fi/HanhinevantuulivoimahankeYVA.

Sokka, L., Sinkko, T., Holma, A., Manninen, K., Pasanen, K., Rantala, M. & Leskinen, P. (2016). Environmental impacts of the national renewable energy targets – A case study from finland. *Renewable and Sustainable Energy Reviews, 59*, 1599-1610. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.rser.2015.12.005

Sparks, D. L. (2003). 3 - chemistry of soil organic matter. Teoksessa D. L. Sparks (toim.), *Environmental soil chemistry (second edition)* (s. 75-113). Burlington: Academic Press. doi:https://doi.org/10.1016/B978-012656446-4/50003-7

Sumnall, M., Fox, T. R., Wynne, R. H., & Thomas, V. A. (2017). Mapping the height and spatial cover of features beneath the forest canopy at small-scales using airborne scanning discrete return Lidar. *ISPRS Journal of Photogrammetry and Remote Sensing*, *133*, 186–200. https://doi.org/10.1016/j.isprsjprs.2017.10.002

Stora Enso Metsä. (2023). Männyn kasvu ratkaistaan edellisenä kesänä. Retrieved on 16.2.2023 from https://www.storaensometsa.fi/mannyn-kasvu/

Thompson, Michael B., Gates, D. M. & Thompson, John N. (2022, October 6). biosphere. Encyclopedia Britannica. https://www.britannica.com/science/biosphere

Treyer, K. & Bauer, C. (2016). Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: Electricity generation. *The International Journal of Life Cycle Assessment,* 21(9), 1236-1254. doi:10.1007/s11367-013-0665-

United Nations Economic Commission for Europe (UNECE). (n.d.). Carbon Storage in Harvested Wood Products (HWP). Retrieved on 18.4.2023 from https://unece.org/forests/carbon-storage-harvested-wood-products-hwp

UNEP/SETAC Life Cycle Initiative. (2012). Greening the economy through life cycle thinking: Ten years of the UNEP/SETAC life cycle initiative.

UPM. (2023). Milloin on ensiharvennuksen aika? Milloin päätehakkuun? Retrieved on 28.5.2023 from https://www.upmmetsa.fi/tietoa-ja-tapahtumia/artikkelit/hakkuun-aika/

Vaahtera, E., Niinistö, T., Peltola, A., Räty, M., Sauvula-Seppälä, T., Torvelainen, J., Uotila, E. (2021). METSÄTILASTOLLINEN VUOSIKIRJA: Finnish Statistical Yearbook of Forestry 2021. Luonnonvarakeskus (Luke). Helsinki 2021. Retrieved on 13.1.2022 from https://stat.luke.fi/sites/default/files/suomen_metsatilastot_2021_verkko.pdf

Uri, V., Varik, M., Aosaar, J., Kanal, A., Kukumägi, M., & Lõhmus, K. (2012). Biomass production and carbon sequestration in a fertile silver birch (Betula pendula Roth) forest chronosequence. *Forest Ecology and Management*, *267*, 117–126. https://doi.org/10.1016/j.foreco.2011.11.033

Vargas, A. V., Zenón, E., Oswald, U., Islas, J. M., Güereca, L. P. & Manzini, F. L. (2015). Life cycle assessment: A case study of two wind turbines used in mexico. *Applied Thermal Engineering, 75*, 1210-1216. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.applthermaleng.2014.10.056

Vattenfall Oy. (2021). Energiatekniikka. Retrieved on 8.7.2022 from https://energyplaza.vattenfall.fi/fi-fi/energiatekniikka

Vestas. (2011a). Life Cycle Assessment of Electricity Production from a V80-2.0MW Gridstreamer Wind Plant - December 2011. Vestas Wind Systems A/S, Alsvej 21, 8900 Randers, Denmark.

Vestas, (2011b). Life Cycle Assessment of Electricity Production from a V90-2.0 MW Gridstreamer Wind PlantDecember 2011. Vestas Wind Systems A/S, Alsvej 21, 8900 Randers, Denmark

Vestas. (2012). Life Cycle Assessment of Electricity Production from an onshore V100-2.6 MW Wind Plant - 31 October 2013, Version 1.1. Vestas Wind Systems A/S, Hedeager 44, Aarhus N, 8200, Denmark. Retrieved on 12.8.2022 from https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload

Vestas. (2015). Life Cycle Assessment of Electricity Production from an onshore V110-2.0 MW Wind Plant – 18th December 2015, Version 1.0. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2017a). Life Cycle Assessment of Electricity Production from an onshore V105-3.45 MW Wind Plant – 31st July 2017, Version 1.1. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2017b). Life Cycle Assessment of Electricity Production from an onshore V126-3.45 MW Wind Plant – 31st July 2017, Version 1.1. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2017c). Life Cycle Assessment of Electricity Production from an onshore V136-3.45 MW Wind Plant – 31st July 2017, Version 1.0. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2018a, February 2). *Anti-icing system™*. [Video]. YouTube. Vestas. https://www.youtube.com/watch?v=eO-1tBwS_sY

Vestas. (2018b). Life Cycle Assessment of Electricity Production from an onshore V116-2.0 MW Wind Plant – 12th July 2018, Version 1.1. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. Retrieved on 12.8.2022 from https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload

Vestas. (2019). Life Cycle Assessment of Electricity Production from an onshore V150-4.2 MW Wind Plant – 1st November 2019. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2020). *Vestas develops highly customised power plant solution to secure 42 MW order in Finland*. Press Release. https://www.vestas.com/en/media/company-news/2020/vestas-develops-highly-customised-power-plant-solution--c3249491

Vestas. (2021). *This is Vestas*. Vestas. Retrieved on 31.3.2021 from https://www.vestas.com/en/about/this-is-vestas/who-we-are

Vestas. (2022a). Life Cycle Assessment of Electricity Production from an onshore V150-4.2 MW Wind Plant – 22nd March 2022. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2022b). V150-6.0 MW™ at a glance. Retrieved on 30.6.2022 from https://www.vestas.com/en/products/enventus-platform/v150-6-0

Vestas. (2022c). V162-6.2 MW™ at a glance. Retrieved on 30.6.2022 from https://www.vestas.com/en/products/enventus-platform/v162-6-2-mw

Vestas. (2022d). V172-7.2 MW™ at a glance. Retrieved on 30.6.2022 from https://www.vestas.com/en/products/enventus-platform/V172-7-2-MW

Vestas. (2022e). V150-4.2 MW™. Retrieved on 15.8.2022 from https://www.vestas.com/en/products/4-mw-platform/V150-4-2-MW

Vestas. (2022f). Life Cycle Assessment of Electricity Production from an onshore Enventus V150-6.0 MW Wind Plant – 31st January 2023. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas. (2023). Life Cycle Assessment of Electricity Production from an onshore Enventus V162-6.2 MW Wind Plant – 31st January 2023. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Vestas Wind Systems A/S. (2019, November 25). GlobeNewswire. Retrieved on 16.5.2022 from https://www.globenewswire.com/news-release/2019/11/25/1951745/0/en/Vestas-secures-118-MW-EnVentus-order-with-30-year-service-agreement-in-Finland.html

VTT Technical Research Centre of Finland. (2020). Capacity factors of wind power 2019. Retrieved on February 2, 2022, from https://tuulivoimayhdistys.fi/media/finland-capacity-factors-2019.pdf

Wang, S. & Wang, S. (2015). Impacts of wind energy on environment: A review. *Renewable and Sustainable Energy Reviews, 49*, 437-443. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.rser.2015.04.137

Weidema, B. P., Thrane, M., Christensen, P., Schmidt, J. & Løkke, S. (2008). Carbon footprint. *Journal of Industrial Ecology, 12*(1), 3-6. doi:https://doi.org/10.1111/j.1530-9290.2008.00005.x

Weinzettel, J., Reenaas, M., Solli, C. & Hertwich, E. G. (2009). Life cycle assessment of a floating offshore wind turbine. *Renewable Energy, 34*(3), 742-747. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.renene.2008.04.004

Wheeler, I. (2011, August 30). *TEDxDubbo - Ichsani Wheeler - The Good Carbon Story.* [Video]. YouTube. TEDx Talks.https://www.youtube.com/watch?v=AhSggAFw7TU

Wiedmann, T. & Minx, J. (2008). A definition of carbon footprint. *CC Pertsova, Ecological Economics Research Trends, 2*, 55-65.

Wright, L. A., Kemp, S. & Williams, I. (2011). 'Carbon footprinting': Towards a universally accepted definition. *Null, 2*(1), 61-72. doi:10.4155/cmt.10.39

Xu, K., Larsen, K., Shao, Y., Zhang, M., Gao, Z. & Moan, T. (2021). Design and comparative analysis of alternative mooring systems for floating wind turbines in shallow water with emphasis on ultimate limit state design. *Ocean*

Engineering, 219, 108377. doi:https://doi-org.ezproxy.jyu.fi/10.1016/j.oceaneng.2020.108377

APPENDICES

To retrieve the average amount of m^3 of roundwood on the typical Finnish wind farm's area, open source GIS software - QGIS (version 3.26.0-Buenos Aires) - was used as the analysis tool. The following existing wind farms in North Ostrobothnia were selected for the GIS analysis. The year of electricity production commencement and their position in the TM35 sheet line system was mentioned in brackets:

1) Haapajärvi, Välikangas (2021, Q4)
2) Kajaani, Piiparinmäki-Murtomäki (Pyhäntä, Kajaani, Vieremä) (2021, Q4)
3) Sievi, Jakoistenkallio (2021, Q4)
4) Pyhäjoki, Paltusmäki (2020, R4)
5) Ii, Viinamäki (2019, S4)
6) Liminka, Hirvineva (2020, R4)
7) Siikalatva, Kokkoneva (2022, Q4)
8) Posio, Saukkovaara-Mäkiaho (only turbines in North Ostrobothnia) (2016, S5)
9) Keso, Haapavesi (2022, Q4)
10) Vaala, Metsälamminkangas (2022, Q4)

As shown in Figure 11 below, coordinate marker was placed in between or (in some cases) among wind turbines.

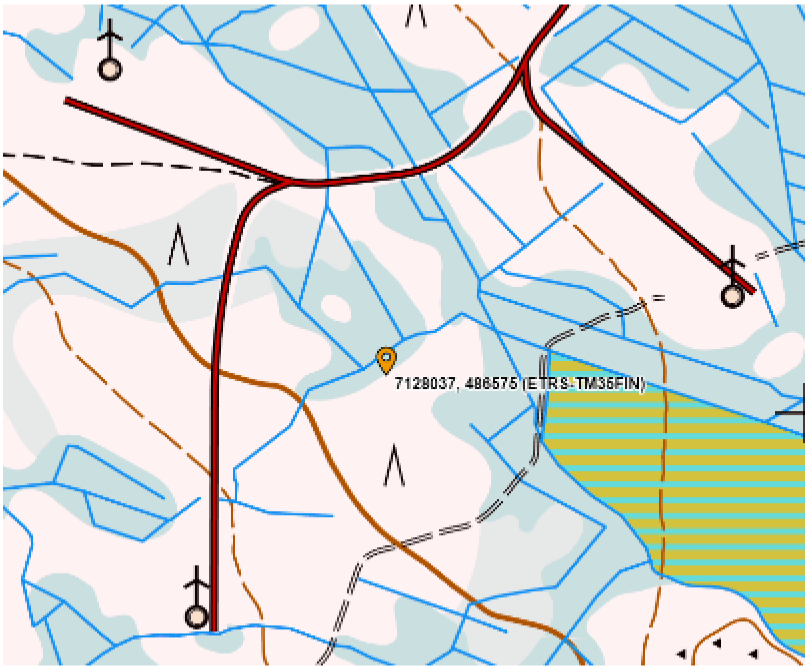
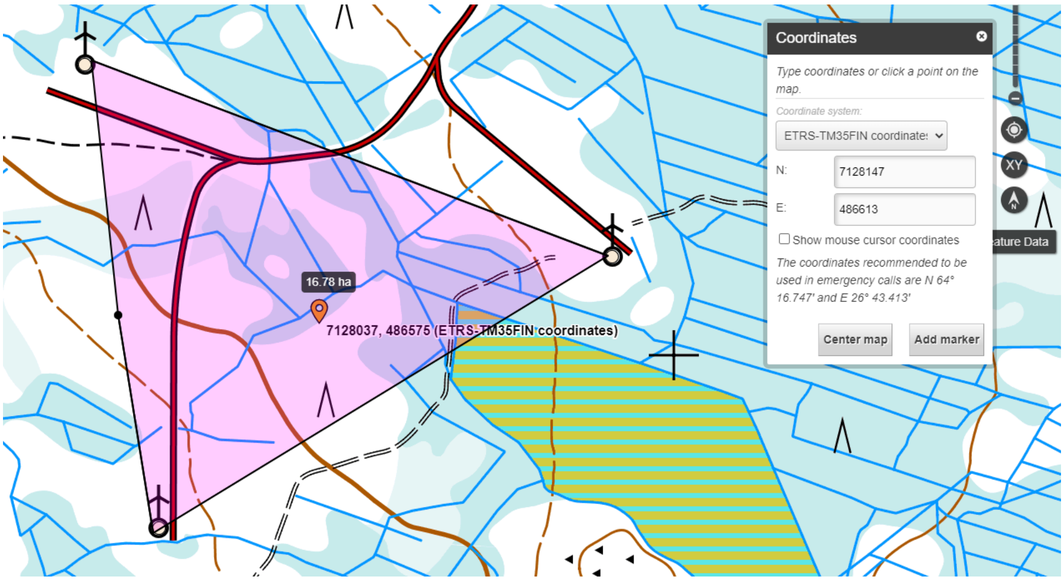


FIGURE 11 Placement of coordinate in WMS Paikkatietoikkuna (n.d.b) using ETRS TM35 coordinates.

From the place the coordinate was placed, an area around the coordinate was measured to ensure the wind turbines were included in the 20 hectare area size. In general, the coordinate was placed to ensure the maximum possible amount of wind turbines to be included in the 20 hectare area, while places with the highest concentration of wind turbines around in the wind farm area were also chosen. The following Figure 12 depicts the rough measurement process (screen snapshot from Vaala, Metsälamminkangas wind farm). The signs in the corners of the area measured were signs for wind turbines.



Type coordinates or click a point on the map.

Coordinate system: ETRS-TM35FIN coordinate:

N: 7128147

E: 486613

☐ Show mouse cursor coordinates

The coordinates recommended to be used in emergency calls are N 64° 16.747' and E 26° 43.413'

FIGURE 12 Approximate measurement of 20 hectare area in Metsälämminkangas wind farm in Vaala municipality located in North Ostrobothnia region. WMS Paikkatietoikkuna (n.d.a,b) was used in the measurement.

The coordinates (N,E) were put into Microsoft Excel sheet file and saved as CSV document to ensure readability by the open-source geoinformatics software QGIS (version 3.26.0-Buenos Aires). Then, the CSV file was read by QGIS and labels next to the points showing the exact location of the wind farms were set to be displayed. The result was depicted in the following Figure 13:

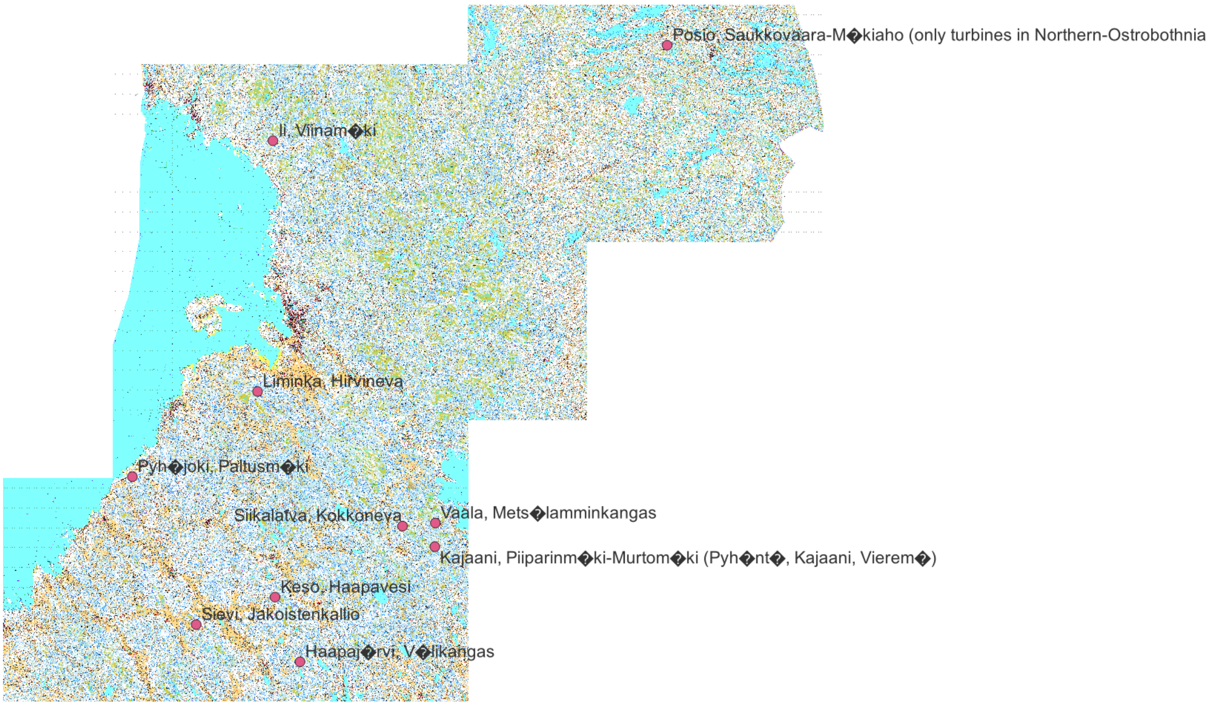


FIGURE 13 Names and exact location of the wind farms selected for the analysis in QGIS.

The imported CSV file was exported in the programme to a shapefile to prevent modifications of the original CSV file. Then, a vector spatial analysis called "buffer" was applied to the points. As a result, a circle shaped object covering the area of 20 hectares around the established points was created. A mathematical formula ($A = \pi r^2$) was used to find out the size of the circle's (buffers) radius (in metres). The radius was found to be 252,3 metres. The following Figure 14 illustrated the analysis:

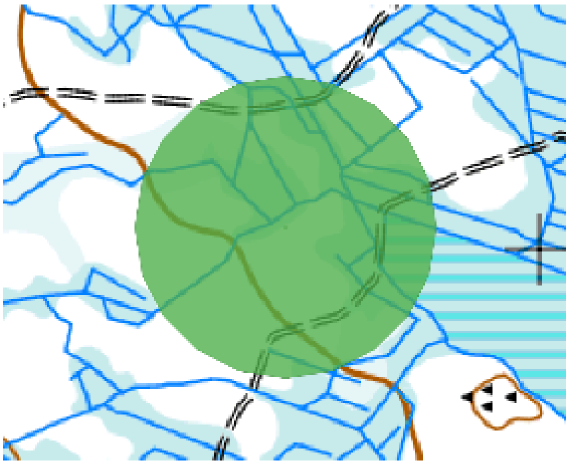


FIGURE 14 An extraction from the vector analysis function (buffer) covering area of 20 hectares around the points was set. The points represented the above presented wind farms. (Paikkatietoikkuna, n.d.b.)

Data on volume of the growing stock of roundwood given in (m3/ha) was retrieved from the Natural Resources Institute Finland website (Luke, n.d.). The data on volume of the growing stock included the following tree types: spruce, pine and birch.

In order to ensure credibility of the results regarding the amount of forest that grew before any of the abovementioned (EXCEL) wind farm construction works' began, three (3) year timeframe between the data on the growing stock volume and the wind farm's official operation year was established. As a result, depending on the year a wind farm project transformed into electricity production, whenever possible, wind farm specific data from the Natural Resources Institute Finland website was downloaded. To clarify this, volume of the roundwood's growing stock from 2019 was applied to a wind farm that began electricity production in 2022 while roundwood volume data from 2017 was applied to a wind farm that began electricity production in 2021 (minimum of three year time window). However, in case more than one wind farms were situated on the same TM35 sheet line system, the older farm determined the year of the volume of the roundwood's growing stock.

The Luke's raster data recorded in 2013, 2015 and 2017 were inserted to the QGIS project. The data was retrieved to fit the wind farm's location in the TM35 sheet line system presented above. The result of this was depicted in Figure 15 below:

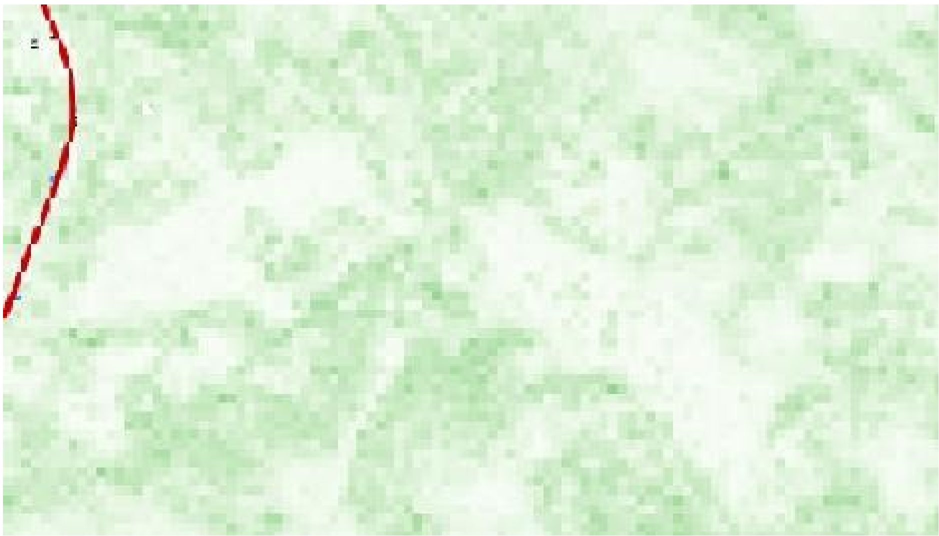
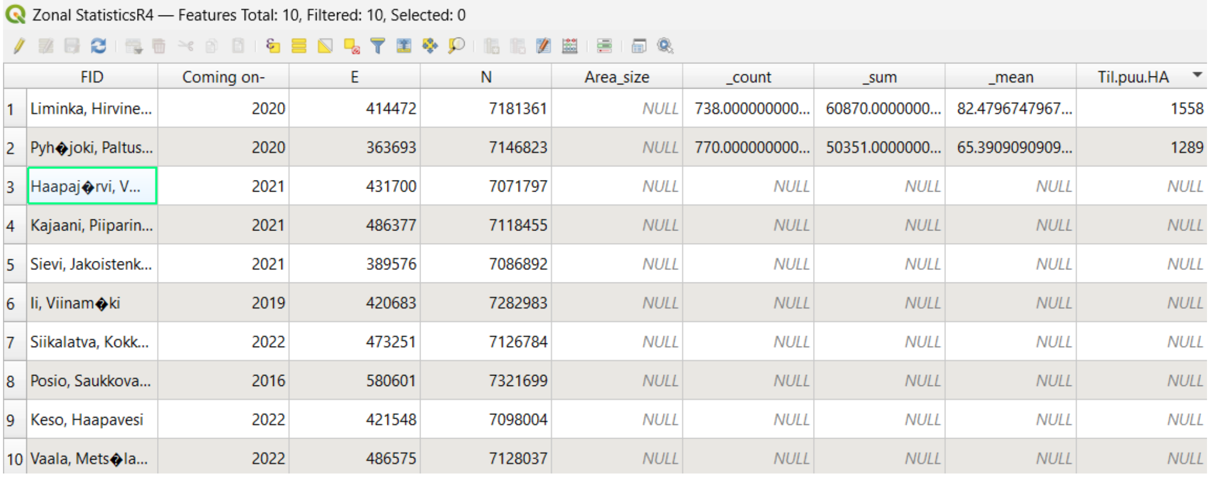


FIGURE 15 Luke's raster data (volume of the growing stock of roundwood (m^3/ha)). The darker the green pixels were, the greater amount of roundwood was presented (pixel size 16 x 16 meters). Red line on the left represented a road.

A geoprocessing analysis of Luke's raster data named "Zonal statistics" was applied. According to QGIS project (2022), the analysis *"calculates statistics of a raster layer for each feature of an overlapping polygon vector layer."*. The analysis was conducted in the area of the established buffers representing the 20 hectare area. All the pixels (Luke's data) presented in that 20 hectare area were analysed. The result was the following table 3 (note this table represented statistic only for the R4 TM35 sheet line system). Table 3 illustrated the Zonal statistics-analysis for wind farms presented in the R4 TM35 sheet line system (Liminka and Pyhäjoki wind farms). "Til.puu.HA column" showed the amount of roundwood on 20 hectares of land. The Values for other wind farms were found in attribute tables of zonal statistics analysis conducted individually for the Q4, S4 and S5 sheet lines in TM35 sheet line system.

TABLE 3 Zonal statistics analysis conducted in QGIS



Zonal StatisticsR4 — Features Total: 10, Filtered: 10, Selected: 0

	FID	Coming on-	E	N	Area_size	_count	_sum	_mean	Til.puu.HA
1	Liminka, Hirvine...	2020	414472	7181361	NULL	738.000000000...	60870.0000000...	82.4796747967...	1558
2	Pyh�joki, Paltus...	2020	363693	7146823	NULL	770.000000000...	50351.0000000...	65.3909090909...	1289
3	Haapaj�rvi, V...	2021	431700	7071797	NULL	NULL	NULL	NULL	NULL
4	Kajaani, Piiparin...	2021	486377	7118455	NULL	NULL	NULL	NULL	NULL
5	Sievi, Jakoistenk...	2021	389576	7086892	NULL	NULL	NULL	NULL	NULL
6	Ii, Viinam�ki	2019	420683	7282983	NULL	NULL	NULL	NULL	NULL
7	Siikalatva, Kokk...	2022	473251	7126784	NULL	NULL	NULL	NULL	NULL
8	Posio, Saukkova...	2016	580601	7321699	NULL	NULL	NULL	NULL	NULL
9	Keso, Haapavesi	2022	421548	7098004	NULL	NULL	NULL	NULL	NULL
10	Vaala, Mets�la...	2022	486575	7128037	NULL	NULL	NULL	NULL	NULL

In order to acquire the amount of roundwood (m^3) per 20 ha of land, the fields *_count* and *_mean* were multiplied together and then multiplied by 0,0256 because the size of the pixels retrieved from Luke was 16x16 metres. Therefore, the resulting values in “Til.puu.HA” column represented the actual amount of growing stock on 20 hectares land.

After this, the average value retrieved and presented in the “Til.puu.HA” column of all the analysed wind turbine areas was calculated using Microsoft Excel. The average amount of roundwood considering all the analysed wind farms in North Ostrobothnia on a 20 hectare land-area was found to be 1493,4 m^3.