Dissertation thesis
Czech University of Life Sciences, Faculty of Environmental Science

Doktorská práce
Česká zemědělská univerzita v Praze, Fakulta životního prostředí

Adverse Impacts of Wind Farm Installations that are Impeding the Development of Wind Energy and Mitigation Pathways thereof

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Prague 2023

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This thesis is submitted in fulfilment of the requirements for the Ph.D. degree in Applied Landscape Ecology at the Czech University of Life Sciences Prague, Faculty of Environmental Sciences

Acknowledgements

I would like to thank the following people, without whom I would not have been able to complete this research.

First and foremost, I would like to thank my supervisor, Assoc. Prof. Peter Kumble, for his tireless efforts and amazing level of dedication throughout my research.

I am expressing my gratitude to all professors and staff of the Department of Landscape and Urban Planning, and Faculty of Environmental Sciences. Special thanks to Ing. Jana Stýblová and Dr. Petra Kadlecová for their seamless work and support.

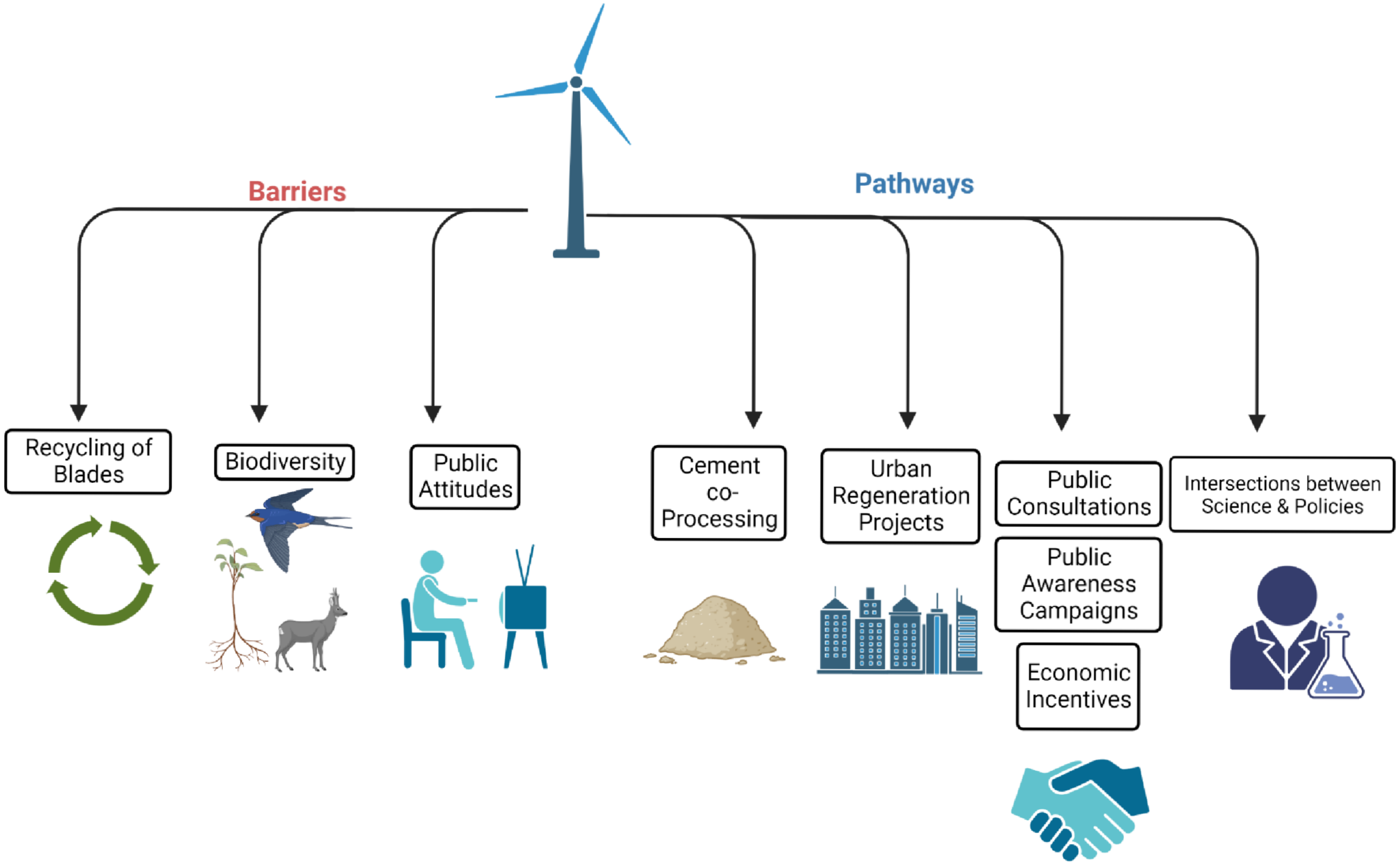
My profound gratitude to Jules Portier for instilling in me the can-do and problem-solving attitude, that was the catalyst for completing this thesis. I would like to say a special thank you to my fellow researcher Chinkei Pebam for all the times we shared in Prague analysing and talking about our respective research.

I would also like to thank all the people who participated in the study’s surveys, answered my questions and gave me some real insight on the social perception of wind turbines.

I would like to express my great appreciation to Alexandros Koutentakis, Jonas Pagh Jensen, and Rafael Gonzalez, for sharing their knowledge and expertise with me during the interviews.

Finally, from the bottom of my heart thank you, Angeliki Peponi, for your in-depth knowledge, scientific advice, and constant moral support. It is thanks to your positive attitude and encouragement, that this thesis is completed.

Graphical Abstract



Abstract

Decarbonising our economies and societies has become a challenging and intricate issue, involving complex socioeconomic interrelations that hinder a smooth and fair transition. In addition to costs and infrastructure, long-established beliefs, scepticism, and public attitudes impede the progress that technology can deliver in the energy sector.

This thesis aims to identify the main environmental, ecological, aesthetic, and societal factors that delay the public acceptance of the wind energy and impedes its development, attempting to identify pathways that will mitigate those barriers. Regarding the environmental barriers, the recycling capacity of the wind turbines was deemed the most important one. Wind turbine blades constitute a big challenge in the end-of-life stage, with their composite material being difficult to recycle or reuse. To this direction, the concept of urban regeneration coupled with the circularity of the blades was examined.

The mitigation pathway that is proposed is a circular economy model where the emphasis is placed on the recovery, reuse, and recycling of natural resources while simultaneously enabling the application of transformational processes to create social, cultural, and economic progress.

The green-green dilemma of wind energy was also explored in this thesis, as windfarms in addition to posing a threat to avian wildlife, harm the local biodiversity by reducing, fragmenting, and degrading natural habitats for flora and fauna. The proposed mitigation pathways are drawn from the recent scientific literature, and they include suggestions that span from predictive models for avoiding avian collisions, to technical characteristics of the windfarm siting, construction, and operation in order to prevent wildlife avoidance, loss of wildlife density and acoustic disturbance.

In order to explore the public acceptance of the wind energy, interviews and questionnaires were employed to two groups of population: experts in the wind energy field, and permanent populations of areas that have been identified of interest for wind energy projects. Responses were analysed using descriptive statistics and the structural equation modelling, in order to identify the interrelations between the behaviours and the perceptions, awareness, perceived behavioural control and social norms on the subject of wind energy. This model was intended to examine the cause-and-effect relationships between those constructs, which define the basis of the Theory of Planned Behaviour (TPB). The questionnaires were designed and analysed using TPB simulated in the Structural Equation Modelling using R, with each variable of the theory being investigated in multiple questions.

The results show that the acceptance of wind energy is directly linked to the value set and awareness of the individual regarding climate change and energy security, as well as the perceptions that the individual has on the use of wind energy.

On this basis, social behaviour theories should be considered, when designing large- scale wind projects and local communities should be involved and participate in the decision making.

Keywords: wind turbines, end-of-life solutions, societal acceptance, wildlife, noise disturbance, aesthetic impact

Abstrakt

Dekarbonizace našich ekonomik a společností se stala náročným a složitým problémem, který zahrnuje složité socioekonomické vzájemné vztahy, které brání hladkému a spravedlivému přechodu. Kromě nákladů a infrastruktury brání pokroku této technologie dlouhodobá přesvědčení, skepse a postoje veřejnosti. Tato práce si klade za cíl identifikovat hlavní environmentální, ekologické, estetické a společenské faktory, které oddalují přijetí větrné energie veřejností a brání jejímu rozvoji, a snaží se nalézt cesty, které tyto bariéry zmírní. Z hlediska environmentálních bariér byla za nejdůležitější považována recyklační kapacita větrných turbín. Lopatky větrných turbín představují velkou výzvu ve fázi konce životnosti, protože jejich kompozitní materiál je obtížné recyklovat nebo znovu použít. V tomto směru byl zkoumán koncept městské regenerace spojený s kruhovitostí lopatek. Navrhovaná cesta zmírňování je model oběhového hospodářství, kde je kladen důraz na obnovu, opětovné použití a recyklaci přírodních zdrojů a současně umožňuje aplikaci transformačních procesů k vytvoření sociálního, kulturního a ekonomického pokroku.

V této práci bylo také zkoumáno ‘green green’ dilema větrné energie, protože větrné farmy kromě toho, že představují hrozbu pro volně žijící ptáky, poškozují místní biodiverzitu tím, že snižují, fragmentují a degradují přírodní stanoviště pro flóru a faunu. Navrhované cesty zmírnění jsou čerpány z nejnovější vědecké literatury a zahrnují návrhy od prediktivních modelů pro zabránění srážkám ptáků až po technické charakteristiky umístění, konstrukce a provozu větrné farmy, aby se zabránilo vyhýbání se zvěři, ztrátě hustoty a akustickému rušení. Aby bylo možné prozkoumat, jak veřejnost přijímá větrnou energii, byly použity rozhovory a dotazníky pro dvě skupiny populace: odborníky v oblasti větrné energie a stálé populace oblastí, které byly identifikovány jako zajímavé pro projekty větrné energie. Odpovědi byly analyzovány pomocí deskriptivní statistiky a modelu strukturální rovnice, aby se identifikovaly vzájemné vztahy mezi chováním a vnímáním, povědomím, vnímanou kontrolou chování a společenskými normami na téma větrná energie. Tento model byl určen ke zkoumání vztahů příčiny a následku mezi těmito konstrukty, které definují základ teorie plánovaného chování (TPB). Dotazníky byly navrženy a analyzovány pomocí TPB simulované v modelu strukturních rovnic s využitím R, přičemž každá proměnná teorie byla zkoumána ve více otázkách.

Výsledky ukazují, že přijetí větrné energie je přímo spojeno se souborem hodnot a povědomím jednotlivce o změně klimatu a energetické bezpečnosti, stejně jako s vnímanou kontrolou chování, kterou má jednotlivec při využívání větrné energie. Na tomto základě by při navrhování velkých větrných projektů měly být brány v úvahu teorie sociálního chování a místní komunity by měly být zapojeny a podílet se na rozhodování.

Klíčová slova: větrné turbíny, řešení na konci životnosti, společenská akceptace, divoká příroda, rušení hlukem, estetický dopad

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List of Abbreviations

AHP: Analytic Hierarchy Process

dB: decibel

dB re 1 μPa: dB referenced to a pressure of 1 microPascal

CV: Coefficient of Variation

CE: Circular Economy

EoL: End-of-Life

EU: European Union

FRP: Fibre Reinforced Polymer

GFRP: Glass Fibre Reinforced Polymer

GHG: Greenhouse Gases

IPCC: Intergovernmental Panel on Climate Change

ML: Maximum Likelihood

MW: Megawatt

NIMBY: Not in My Backyard

OWF: Offshore Wind Turbine

RES: Renewable Energy Sources

SDG: Sustainable Development Goals

SEL: Sound Exposure Level

SEM: Structural Equation Modelling

SRF: Solid Recovered Fuel

SWT: Small Wind Turbine

TPB: Theory of Planned Behaviour

TWh: Terawatt Hour

UK: United Kingdom

USA: United States of America

UN: United Nations

UNFCCC: United Nations Framework Convention on Climate Change

WT: Wind Turbine

Mathematical Terms and Constants

A: Attitude toward behaviour

B: Behaviour

b: the strength of each belief concerning an outcome or attribute

BI: Behavioural Intention

c: the strength of each control belief

e: the evaluation of the outcome or attribute

m: the motivation to comply with the referent

n: the strength of each normative belief of each referent

p: the perceived power of the control factor

PBC: Perceived Behavioural Control

SN: Subjective Norm

w: empirically derived weight/coefficient

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1 Introduction

The Framework Convention on Climate Change (UNFCCC) defines climate change, in its article 1, as: '*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*.' (UN Climate Change, 1992). Climate change is defined thereof as a change in the condition of the climate that may be detected (e.g., by statistical tests) by changes in the mean and/or variability of its properties over time, generally decades or more. Climate change can be caused by natural internal processes or external forcings such as solar cycle modulation, volcanic eruptions, and long-term anthropogenic changes in atmospheric composition or land use (IPCC, 2018).

One of the many facets of climate change is global warming, which is defined as an increase in combined surface air and sea surface temperatures averaged over the globe and over a 30-year period(Pachauri et al., 2014). 2011-2020 is the warmest decade on record, with global average temperatures 1.1°C above pre-industrial levels in 2019. Anthropogenic global warming is currently increasing at a rate of 0.2°C per decade. A 2°C increase in temperature compared to pre-industrial temperatures has serious adverse effects on the natural environment and human health and well-being, including a much higher risk of dangerous and catastrophic changes in the global environment. For this reason, the international community recognizes the need to make efforts to keep warming below 2°C and limit it to 1.5°C (European Commission, 2022). Temperature rise to date has already resulted in profound alterations to human and natural systems, including increases in droughts, floods, and some other types of extreme weather, sea level rise, and biodiversity loss – these changes are causing unprecedented risks to vulnerable populations (Hoegh-Guldberg et al., 2018). Global warming is however one of the many alterations that climate change is causing across the globe, all of which will worsen as the planet warms. Changes in the hydrological cycle, warmer land and air, warming oceans, melting sea ice and glaciers, rising sea levels, ocean acidification, changes in ocean currents and more extreme weather are all examples of the changes to the climate system.

Those changes will undoubtedly have severe impacts to our systems such as risk to water supplies, flooding of coastal regions, conflict and climate migrants, damage to marine ecosystems, fisheries failing, loss of biodiversity, localized flooding, change in seasonality, heat stress, pests, forest mortality and increased risk of fires, damage to infrastructure and food insecurity. As all systems on earth are interrelated, climate change will have a domino effect in the entire ecosystem.

Since 1950, there have been changes in weather and climatic phenomena. A decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels, and an increase in the number of heavy precipitation events have all been connected to human activities (Castellani, 2018). Already in Europe we see that heat waves, forest fires, and droughts are becoming more common in southern and central countries. Drought and wildfires are growing increasingly common in the Mediterranean region, which is becoming drier. Northern Europe is also becoming drier, and winter floods have become more prevalent.

Heat waves, flooding, and rising sea levels are all threats to urban areas, which now house four out of every five Europeans, but they are typically ill-equipped to adapt to climate change (European Commission, 2022).

The anthropogenic greenhouse effect that occurs in addition to the natural greenhouse effect is the cause of climate change. The Intergovernmental Panel on Climate Change (IPCC) concluded in its Fifth Assessment Report that human activities are responsible for global warming with a probability of more than 95% (Pachauri et al., 2014).
Natural causes, such as changes in solar radiation or volcanic activity are estimated to have contributed less than plus or minus 0.1°C to total warming between 1890 and 2010 (European Commission, 2022).
Humans cause climate change by releasing greenhouse gases (GHG) like carbon dioxide, methane, nitrous oxide, and fluorinated gases, into the air. The main ways through which we emit GHG are burning fossil fuels, agriculture, deforestation, and cement production.

Carbon dioxide has been in the ground for thousands of years in fossil fuels like oil, gas, and coal. By burning those substances, we release the stored carbon dioxide into the air. The main sectors that emit GHG are the energy production and consumption, transport, agriculture, industry, and waste. In 2018, the energy producing industries had the largest share (28.0 %) of total GHG emissions, followed by fuel combustion by users (25.5 %) and the transport sector (24.6 %) (Eurostat, 2018).

In 2019, the energy mix in the EU originated in five different sources: Petroleum products (including crude oil) (36 %), natural gas (22 %), renewable energy (15 %), nuclear energy and solid fossil fuels (both 13 %) (Eurostat, 2019).
Around 21 % of the final energy we consume is electricity and it comes from various sources. In the EU in 2019, 39 % of the electricity consumed came from power stations burning fossil fuels and 35 % from renewable energy sources, while 26 % came from nuclear power plants. Among the renewable energy sources, the highest share of electricity consumed came from wind turbines (13 %), hydropower plants (12 %), biofuels (6 %) and solar power (4 %) (Eurostat, 2019).

With increasing human population, the consumption and need for resources and energy grows as well. Using renewable sources is a way to satisfy the needs for energy and simultaneously decrease the use of finite natural resources like fossil fuels. Currently wind energy is the most used renewable energy source. Europe (EU-27 and UK) installed 17.4 GW of new wind energy capacity in 2021 and generated 437 TWh of electricity which covered 15% of the electricity demand in the EU-27+UK (Komusanac et al., 2022).

Climate change is shifting the world out of the relatively stable Holocene period into a new geological era, often termed the Anthropocene. Responding to climate change in the Anthropocene will require approaches that integrate multiple levels of interconnectivity across the global community (Biermann et al., 2016).

The strive to stay within the threshold of 1.5°C temperature rise above pre-industrial levels, necessitates a complete paradigm shift of our current way of living. It is scientifically proven that anthropogenic activities are the sole offenders for climate change and the only way to mitigate its adverse effects is to achieve net-zero carbon emissions by 2050. If we want to attain energy and food security, while providing a decent future for the next generations, energy transition is the only way forward.

From sailboats to windmills, humanity has known for millennia how essential wind power can be in our daily lives. The use of wind power can significantly reduce the impact of the energy sector on climate change, but it comes with some inherent disadvantages that must be mitigated in order to achieve the goals of the Paris Agreement and the Sustainable Development Goals (SDG) for clean and affordable energy. The global installed capacity of wind energy has increased from 216.346MW in 2011 to 769.196MW in 2021 (IRENA, 2021). However, it is not increasing to an optimal pace in order to tackle climate change and decarbonise the electricity sector, even though it is technologically feasible. According to the Global Wind Energy Council, the growth of global wind capacity needs to quadruple by the end of the decade if the world is to stay on-course for a 1.5C pathway and net zero by 2050 (Global Wind Energy Council, 2022). The transition to a sustainable energy system as a response to big global concerns such as climate change and energy security involves multiple factors such as technology, policy, and social institution innovation. Energy transition therefore requires large socioeconomic, political, and economic changes.

As a result, even though the technological aspect may not be an issue, social acceptance levels can have a substantial impact on the wind industry's nature, perhaps limiting the sector's ultimate development and contribution to national energy systems.

Social phenomena such the Not in My Backyard (NIMBY) try to explain why individuals with a positive attitude towards wind energy, might not be open in living in close proximity to wind farm. In addition, behavioural theories endeavour to explain how the individuals and societies react in a perceived paradigm shift.

Until today the design and materials choices are centred around two key factors: energy output and cost. The renewable energy sector's expanding need for industrial materials may put the industry against other sectors of the economy. Steel, cement, aluminium, and plastics are estimated to triple in demand by 2050 across the economy, while mineral needs (including metals for renewable energy infrastructure) are expected to increase fivefold. This could result in both supply and price difficulties. Prices are expected to grow and remain high as a result of possible shortages, fuelled by the transformation to a carbon-neutral economy. Increased geopolitical and environmental issues and limits may also limit availability and disrupt supply systems (Robertson-Fall, 2022).

Research Objectives

This thesis aims to use a multi-criteria approach to explore, analyse, and provide solutions to the environmental problems related to the life cycle of wind turbines, the ecological concerns that arise from their use and the societal barriers for the acceptance of the wind energy. Problems that lie in the aesthetic impact on the landscape, auditory annoyance, wildlife disturbances and the difficulty in recycling end-of-life blades, will be investigated and discussed. In addition, it will explore the public perception of inhabitants in areas that could be on the proximity of wind farms and will suggest different schemas in order to mitigate eventual negative experiences from the public. Lastly, the Theory of Planned Behaviour is employed in order to investigate how the eventual behaviour of the public is influenced by variables such as perceptions, awareness, subjective norms and perceived behavioural control. The results are analysed using the Structural Equation Modelling (SEM) in an R environment, which intends to examine the cause-and-effect relationships between the above constructs and the behaviour of the public. The purpose is to suggest viable and feasible mitigation pathways.

Specifically, the following research questions will be investigated: What are the main environmental, ecological, aesthetic, and societal factors that delay the public acceptance of the wind energy, and how to mitigate them? What is the societal perception of the wind turbines and how do they affect the attitudes and behaviours of local populations towards wind farm installations? What are the challenges with end-of-life solutions of the wind turbines and what opportunities arise thence?

The thesis is structured in five chapters; with the first being the introduction. The second chapter is the literature review, where scientific knowledge and understanding on the field of wind energy were examined. The main topics that were explored in the literature review were the recycling of the blades, the main threats that wind parks and/or wind turbines are posing for the wildlife and the issue of public acceptance for wind energy and/or wind parks. The purpose of the literature review was to examine the studied issues, to find additional barriers than the ones that had been identified by personal observation and identify mitigation measures other researchers had proposed. During the literature review, the main literature gaps were identified and through that process the need of conducting a survey and interviews for collecting primary data was born. Those are explored in the third chapter, where the methodology and the research design are presented. In chapter 3.3, the theoretical framework of this thesis is presented. In the fourth chapter, the main body of the thesis, the results, is organised in three sub-chapters:
4.1: environmental barriers for the development and acceptance of wind turbines and proposed mitigation pathways. In this chapter the article 'Wind Turbine Blade Waste Circularity Coupled with Urban Regeneration: A Conceptual Framework' that was written in the framework of this thesis is included.
4.2: ecological barriers, where the main threats that wind parks and/or wind turbines pose for wildlife and nature; mitigation pathways that are considered in the scientific literature are proposed.
4.3: the barrier of public acceptance of wind parks and/or wind turbines; the population survey and the coupling of results with the Theory of Planned Behaviour and the Structural Equation Modelling is presented here. Mitigation pathways are proposed based both on the scientific literature and the results.
The fifth and last chapter includes the discussion and conclusions of this thesis.

2 Literature Review

Wind energy has been utilised by the mankind for millennia. As early as 5,000 BC, people used wind energy to drive boats along the Nile River. Simple wind-powered water pumps were employed in China by 200 BC, and windmills with woven-reed blades were utilized in Persia and the Middle East to grind grain. Wind energy was finally used in new ways all around the world. Wind pumps and windmills were widely used for food production in the Middle East by the 11th century. Wind technology was brought to Europe by merchants and Crusaders. The Dutch invented huge windpumps to drain the Rhine River Delta's lakes and marshes. Windmills were used by American colonists to grind grain, pump water, and cut wood at sawmills. Thousands of wind pumps were erected by homesteaders and ranchers when they populated the western United States. Small wind-electric generators were also popular in the late 1800s and early 1900s (Kaldellis & Zafirakis, 2011; Shepherd, 2010).

Scotland is home to the world's first wind turbine, which was developed to generate power. Prof James Blyth of Anderson's College in Glasgow designed the wind turbine (now known as Strathclyde University). "Blyth's ten-meter-high cloth-sailed wind turbine was put in the garden of his holiday cottage in Marykirk, Kincardineshire, and was used to charge accumulators designed by the Frenchman Camille Alphonse Faure to power the cottage's illumination, making it the world's first wind-powered house." Blyth offered the surplus power to the residents of Marykirk for the purpose of lighting the main street, but they declined because they considered electricity to be "the work of the devil" (Shahan, 2014).

Oil shortages of the 1970s altered the energy landscape in the United States and around the world. Oil constraints sparked interest in finding new ways to generate electricity using other energy sources like wind. The federal government of the United States backed massive wind turbine research and development. Thousands of wind turbines were installed in California in the early 1980s, partly as a result of federal and state regulations encouraging the use of renewable energy sources.
As rural electrification projects in the 1930s stretched electricity connections to most farms and ranches across the country, the number of wind pumps and turbines decreased. After 1990, the majority of market activity shifted to Europe, with the last two decades propelling wind energy to the forefront of the global scene, attracting large participants from every continent (Kaldellis & Zafirakis, 2011).

Wind power has the potential to greatly reduce the energy sector's influence on climate change, but it has several inherent drawbacks that must be addressed if the Paris Agreement and the Sustainable Development Goals (SDG) for clean and affordable energy are to be met. Wind energy's global installed capacity climbed from 216.346MW in 2011 to 769.196MW in 2021 (IRENA, 2021). Even while it is technologically feasible, it is not rising at an ideal rate to combat climate change and decarbonize the electrical sector. According to the Worldwide Wind Energy Council, if the world is to stay on track for a 1.5C pathway and net zero by 2050, global wind capacity must treble by the end of the decade. Multiple variables, such as technology, policy, and social institution innovation, are involved in the transition to a sustainable energy system as a response to major global challenges such as climate change and energy security. As a result, energy transition necessitates significant societal, political, and economic reforms (Global Wind Energy Council, 2022).

The literature review shows that the adverse impacts of the wind farms are as much studied as their benefits. There is a plethora of books and scientific articles available in the literature that examine their documented or potential impacts. The main problems analysed in the literature, as shown by the bibliometric analysis in section 3.2.1 below, are end-of-life solutions, bird and bat fatalities from avian collisions, wildlife displacement or avoidance due to habitat fragmentation, and the societal acceptance of the wind farms and their impacts on the landscape.

The first topic that I tackled during my literature review was the recycling issue of the blades and their potential circularity.
Previous research showed that the amount of waste from wind turbines in the next decades will be up to 200.000 tonnes. Paulsen and Enevoldsen argue that Europe is expecting 160,000 tonnes of composite waste annually from the year 2030 and investigated the current recycling methods for end-of-life wind turbine blades. They compared the processing capacity, cost, environmental impact, technological maturity, and the usability of the output product of each method and concluded that at present the only economical option is the recycling of blades through co-processing in the production of cement. Additionally, co-processing is able to handle large amounts of waste materials and could reduce up to 16% of the CO2 footprint of end-of-life wind turbine blades (Paulsen & Enevoldsen, 2021). In other studies, the amount of waste has been calculated from 100.000 to 200.000 tonnes, depending on the methods used (Deeney et al., 2021; Lichtenegger et al., 2020).

This has also been explored in prior studies by researchers in Ireland that developed a method integrating eleven different metrics to measure the relative sustainability of ways to deal with the upcoming estimate of 200.000 tonnes of decommissioned wind turbine blades per year. Because wind turbine blades are made of glass fibre reinforced polymer or carbon fibre reinforced polymer composites, they are not easily recyclable in contrast to the rest of a wind turbine's components. Focusing on reuse, this investigation has found that bridge fabrication and furniture making are the most sustainable waste management options for wind turbine blades. The sustainability index uses a multi-layered weighting system, integrating economic, social, and environmental perspectives and thus offers researchers and policymakers a practical and robust decision-making guide. This assessment method facilitates the evaluation of the sustainability of different end-of-life choices, not only for wind turbine blades, but is expandable to a variety of challenges in the waste management industry (Deeney et al., 2021).

In 2020 Lichtenegger et al. conducted a study to estimate the tonnage and country by country location of wind turbine blades that are expected to be decommissioned in Europe until 2050. Because there are currently few viable sustainable solutions to recycle blade waste, the estimated 100,000 tons that will be generated per year in Europe by 2034 is a crucial waste management concern. The study, which distinguishes between offshore and onshore sites, can support researchers, processors, suppliers, and policy makers across multiple geographical contexts, considering the high logistical cost of transporting waste material for long distances and between countries. It quantifies the security and continuity of blade waste supply over time and identifies local hotspots at a high level of geographical granularity, which will facilitate the development and investigation of cross-sectoral circular economy pathways (Lichtenegger et al., 2020).

A large number of existing studies in the broader literature have examined the environmental drawbacks of wind energy. Researchers in Denmark with expertise in renewable energy and composites examine the sustainability challenges of wind turbine blades, which are composed of glass fibre reinforced thermoset polymer composite. Estimations of current and future kiloton amounts of end-of-life wind turbine blades along with information including lifespans, geographic location, and material specifications are highlighted as important in driving research and legislative and industrial decision-making. Waste legislation in Europe, the USA, and China is covered, pointing to a lack of harmonized regulations regarding continuing operations and the decommissioning of wind turbines. Waste management solutions for wind turbine blades are outlined, revealing at present very few viable recycling solutions considering utility, cost, technical feasibility, and environmental impact. A holistic approach is called for, one that encompasses all processes in the life cycle of wind turbine blades, key to a circular economy and life cycle engineering. Strategies include using fewer resources with accompanying reductions in cost and environmental burden, designing longer-lasting goods and extending product life via repair, as well as recycling. A concluding list is provided of research, industry, and policy recommendations, requiring global standards and long-term vision in the wind energy sector (Beauson et al., 2022).

Sommer et al. calculate the upcoming mass and geographical specificity of end-of-life wind turbine blades within the European Union. Between 2020 and 2030, the estimate is 18 megatons of carbon fibre reinforced plastic waste and 552 megatons of glass fibre reinforced plastic waste. The distribution function also includes national behaviour influenced by parameters such as decreasing economic efficiency due to the phasing out of subsidies, national electricity markets, and lifetime extension measures. This data of upcoming material flows serves to bridge knowledge gaps in directing research, including designing waste stream infrastructures, and forecasting achievable recycling and energy recovery targets to assist in the EU's aims to increase resource efficiency and establish a circular economy (Sommer et al., 2020).

There exists a considerable body of literature on recycling methods of blades and their environmental impacts. Fonte and Xydis examine the recycling methods available for decommissioned wind turbine blades and estimate the economic values of recovered materials. As composite recycling is relevant to a variety of industries including construction, aviation, shipping, and automotive, the identification of economically viable solutions for recycled blades will have an extensive positive impact on the handling of the tonnes of end-of-life blades expected in the coming decades in Europe. Compared to thermal and chemical recycling, mechanical grinding has captured the most interest from private industries because its process costs are 3.4 times lower at 90€ per tonne. The materials additionally find applications in large markets, such as cement clinker. To support and secure the commercial viability of recycling methods, Fonte and Xydis recommend establishing a stable supply chain so that recovered materials sustain the operations of recycling companies as well as create value for new products in other industries. The authors also advise the EU to introduce policies to promote recycling strategies in companies of all sizes, which will create jobs alongside minimizing the environmental impact across a range of manufacturing sectors (Fonte & Xydis, 2021).

Korniejenko et al. analysed and compared the methods available to recover material from multilateral composites used in tyres, wind turbine blades, and solar panels. The analysis was carried out in the context of aims to transform the global economy into a circular system to reduce environmental harm while also considering economic and social effects. Although composite materials offer high performance in use, the current range of technologies to recycle them are not efficient, with advantages offset by disadvantages. The increased use and accompanying volume of end-of-life composite materials involved in wind and solar energy especially have garnered attention from government, industry, and academia. In order to align research and policy focus with circular economy thinking, we must foster the design of future products with sustainable end-of-life recycling processes in mind (Korniejenko et al., 2021).

Liu et al. evaluated and compared costs of recycling options for decommissioned wind turbine blades. They determined that for glass fibre composite waste, mechanical recycling is the only profitable industrial-scale option. For carbon fibre composite waste, the net cost of thermal recycling was assessed to be favourable. Of lab-scale technologies, chemical recycling was found to be the most profitable. The authors noted that where landfill costs are cheaper than recycling, the development and promotion of recycling technologies would need to be driven by government support. Investment in research to increase process efficiency and to reduce energy consumption and costs would additionally make recycling options more attractive. Liu et al. conclude that end of life composite waste treatment is a cross-sector challenge. In addition to refining recycling technologies, parties from across sectors need to identify suitable markets for the recycled material. Both are important objectives in addressing the environmental challenges of wind energy and other composite-using sectors (Liu et al., 2022).

Mello et al. apply life cycle assessment to wind energy to evaluate the sector's environmental and economic sustainability. Although cleaner than other energy sources, when the entire life cycle of wind turbines is considered, there remain negative environmental impacts with greenhouse gas emissions produced in the manufacturing and decommissioning of blades. The authors highlight important issues including waste management, applied technology, legislation, environmental protection, and human health regulations, as well as the benefits and drawbacks of wind farm investment. They suggest improvements in logistics, more efficient equipment production, and research in new materials and innovative building techniques. Regarding decommissioned blades, they advise reuse and recycling to reduce both the extraction of raw materials and the total consumption of resources. Mello et al. cast a wide net in research focus to tackle the challenge of matching growing energy demands with the preservation of the environment and the reduction of emissions in the wind energy sector.(Mello et al., 2020).

Some authors have driven the further development of scenarios concerning the environmental impacts and best practices for blades' EoL solutions. Nagle et al. compared the environmental impacts of three ways to manage wind turbine blade waste in Ireland using life cycle assessment, considering all resulting effects on the natural world. The three methods quantified using life cycle assessment were co-processing in cement kilns in Germany, co-processing in cement kilns in Ireland, and disposal in landfills in Ireland. Co-processing uses shredded blade waste incorporated with other waste to replace fuel and raw materials in the production of clinker in cement kilns. Although estimated to be more costly than landfilling, projected co-processing in Ireland was determined to have the least negative impact on the environment of the three options, due to material substitution and reduced transport. At present, however, co-processing is not available in Ireland. Nagle et al. conclude that the challenge will be to develop solutions and to inform policy changes to encourage repurposing, which is further up the waste hierarchy than co-processing, as a more sustainable second life option to manage the forecasted tonnes of blade waste (Nagle et al., 2020).

A recent study by the same author, developed three scenarios for the maximal utilization of an estimated 53,000 tonnes of decommissioned wind turbine blades that will be generated in Ireland by 2040. They examined blade repurposing concepts using life cycle assessment to determine their environmental impacts focusing on greenhouse gas emissions. Approximately 342kg of CO2 could be saved for every tonne of blade waste used in these scenarios. Blade substitution of steel products was determined to be the most environmentally beneficial—as long as blade material did not travel more than 370km—followed by the substitution of concrete products. Although repurposing would not be possible for all Irish blade waste, the use of 20% annually could divert 315 tonnes of blade waste from landfill, creating resiliency in supply chains, as well as avoiding emissions of around 30,780kg of CO2. Nagle et al. also recommend government support to encourage second life solutions and markets, which in turn could boost rural job creation (Nagle et al., 2022).

With the growth of the wind energy sector comes the continued challenge of finding materials and methods so that wind turbine blades can enter closed-loop recycling processes. Wu et al. explored effective chemical treatments for recycling epoxy composites conducted by mild acid digestion under moderate atmospheric pressure and temperatures between 80C and 110C. This separation process affords the opportunity to recover glass fibres retaining near-virgin surface quality and matrix residue with high strength retention suitable for blending with virgin epoxy for re-use in second-life applications. Despite promising results, the digestive solution is presently both costly and not safe to deploy on an industrial scale. Future efforts must focus on developing more cost-effective and safer recycling routes for both reclaimed resin and recycled fibres—as well as the development of markets and applications for the recovered products. The recyclability of end-of-life wind turbine blades remains an important research objective tied to increasing the sustainability of wind energy (Wu et al., 2019).

Several methods are reported in the literature to address this issue of wind farms threatening the local wildlife, the second issue tackled in this dissertation. Schöll and Nopp-Mayr explored the effects of wind farms on wildlife in shrubland and woodland areas in Europe and North America. A systematic literature review determined that the construction, operation, and maintenance of wind power plants affect wildlife in terms of collision mortality, seasonal migration patterns, changed anti-predator behaviour, habitat use, abundance or absence of species, as well as biodiversity. With the wind energy sector growing and encroaching beyond open landscapes into shrublands and woodlands, the increased levels of noise emission, vibration, shadowing, presence of flickering warning lights, and enhanced human presence will have as yet unmeasured impacts in these landscapes. The authors advise additional studies in order to fill knowledge gaps and better support conservation needs, management options, and planning decisions including the effectiveness of mitigation measures and the micro-siting of wind farms (Schöll & Nopp-Mayr, 2021).

Environmental science researchers surveyed wind farms across two districts in Karnataka, India for over two years to gauge the impact of wind turbines on wildlife. India is currently fourth in global wind harvesting capacity, and with the ongoing expansion of wind energy, Kumara et al. raise conservation concerns with the aid of the collection of data regarding biodiversity, habitat loss, and fatalities due to direct collision.

It was found that the collision of birds and bats to wind turbine blades is negligible at 0.26 animals per year. However, the disappearance of birds and mammals on the wind farms is clear. While recognised as an alternative and clean energy source, wind farms transform their locality with an as yet unknown range of environmental consequences. Continued study is vital to inform early decision-making and to manage and mitigate the potential harm of wind turbines on animals (Kumara et al., 2022).

Huso et al. investigated the effect of upgrading wind farms on wildlife mortality rates in a study location in California. As the wind energy sector grows, so has the concern for reducing wildlife deaths caused by collisions with rotating turbine blades. Repowering involves replacing smaller, lower capacity, and closely spaced turbines with larger, higher capacity, and more widely spaced ones. The authors found that avian and bat mortality rates were constant per unit of energy produced. Rather than the size, spacing, or rated capacity of turbines, the determining factor on wildlife mortality was the relative amount of energy produced. Consequently, in a given location, newer turbines would be expected to be less harmful to wildlife only if they produced less energy than the older models, they replaced (Huso et al., 2021).

With this study based on telemetry data, Peschko et al explored the effects of OWFs situated 23–35 kilometers north of the colony on Helgoland in the southern North Sea on breeding gannets. Over the course of two years, GPS tags were placed on 28 adult gannets mating on Helgoland for several weeks. In both years, the majority of gannets (89%) avoided the OWFs, while 11 percent frequented them when foraging or travelling between the colony and foraging regions. Inside the OWFs, flight heights were near to the rotor-blade zone, especially for those who avoided the OWFs. When inside the OWF, gannets preferred a distance of 250–450 meters from the turbines. According to a point process modelling technique, gannet resource selection in the OWF area was reduced by 21% in 2015 and 37% in 2016 when compared to the surrounding area (Peschko et al., 2021).

The differences in magpie nest density factors and character characteristics were examined across quadrats inside and outside a wind farm on Chongming Island, China by Song et al. The purpose was to assess the effect of wind farms on the nest distribution of magpie (Pica pica), a frequent bird species in agroforestry systems. In each quadrat, the link between magpie nest character characteristics and density variables was investigated, as well as the effects of landscape variables on magpie nest density variables. Nest density data (including total and in-use nest density) were measured in quadrats inside and outside a wind farm in an agroforestry system on Chongming Island, Shanghai, from March to December 2019. In each quadrat, three nest character characteristics and five landscape variables were also recorded, located in agroforestry systems on Chongming Island, China (Song et al., 2021).

In their study Hartmann et al., evaluated the worst-case scenarios for bat avian collision with small wind turbines (SWT). Using a specially developed high-spatial-resolution 3D camera, bat flight patterns around the SWT were captured at each station for five consecutive nights. The recordings revealed substantial amounts of bat activity around the SWT (7, 065 flight trajectories within a 10-m radius). Each trajectory's minimum distance to the rotor ranged from 0 to 18 meters, with an average of 4.6 meters across all sites. Bats flew 0.4 meters closer to the rotor (95 percent CI 0.3-0.6 meters) if it was out of function and 0.3 meters closer (95 percent CI 0.1-0.4 meters) if it was moving slowly, according to linear mixed models designed to account for site differences. Many bats deviated from their original flight path to approach the rotor, which was seen as exploratory behaviour. The rotor was crossed by 176 of the 7,850 reported trajectories, including 65 when it was in motion. During the experiment, one P. pygmaeus individual collided with another. These findings show that, despite bats' generally great ability to avoid moving rotor blades, bat casualties at SWTs located in high bat activity areas can reach or exceed the current threshold levels specified for large wind turbines. Because SWTs produce less energy than huge turbines, their detrimental impact on bats should be reduced by mitigation techniques like as site selection that is bat-friendly or curtailment algorithms (Hartmann et al., 2021).

Finally, Madsen et al. 2008, demonstrated that pink-footed geese have become accustomed to small-scale wind farm; in one case, the area of displacement was significantly reduced due to geese grazing within the wind farm. The amount of acclimatization appears to be proportional to the height of the wind turbines. This is the first instance of a bird species becoming accustomed to wind farms over time, highlighting the necessity for longer-term impact assessment studies to adequately analyse the disruption impacts of wind farms. Because this species has developed a habit, it's conceivable that other species may follow suit (J. Madsen & Boertmann, 2008).

Although there are many studies for onshore wind farm environmental impacts, the research for offshore wind farms remains more limited. A previous study by Russell et al., concluded that vibration and sound from pile driving has the potential to inflict auditory harm. Using data from GPS/GSM tags on 24 harbour seals, they report on a behaviour study conducted during the construction of a wind farm. With the help of pile driving data and acoustic propagation models, as well as seal movement and diving data, auditory damage in each seal could be predicted. To estimate transitory auditory threshold alterations in each seal, growth and recovery functions for auditory injury were coupled. When compared to the exposure criterion, it appears that half of the seals have persistent auditory damage. Predicting hearing injury in marine mammals is a rapidly developing topic with a lot of significant difficulties. As a result, the predictions should be interpreted in the context of how sound propagates in shallow water habitats and the impact of pulsed noises on seal hearing. Implications for policy. They estimated that half of the tagged seals were exposed to sound levels from pile driving that were higher than pinniped auditory damage thresholds. These findings have ramifications for the offshore business and will be critical for legislators drafting pile drive recommendations. They conclude suggesting that engineering solutions to minimize sound levels at the source, or strategies to keep animals out of damage risk zones or altering piling temporal patterns could all help to reduce the danger of auditory harm (Russell et al., 2014).

The same author, in 2016, proved that seal abundance was dramatically reduced up to 25 kilometres away from the piling operation; within 25 kilometres of the wind farm's centre, utilization was reduced by 19 to 83 percent (95 percent confidence intervals), equal to a mean estimated relocation of 440 individuals. Starting from expected received levels of between 166 and 178 dB re 1 Pa, this represents a considerable shift. Displacement was limited to piling activities; seals were dispersed according to the non-piling scenario within 2 hours of pile drive ceasing (Russell et al., 2016).

Previous studies from Dahne et al., found out that piling causes acoustic disturbances and as a result avoidance for the common porpoises in the German North Sea. From 2008 to 2010, 15 aerial lines transect distance sampling studies were used to visually monitor harbour porpoises before, as well as during, construction and operation. From 2008 to 2011, static acoustic monitoring (SAM) with echolocation click loggers at 12 locations was also done. SAM devices were placed between 1 and 50 kilometres from the wind farm's centre. Aerial surveys encompassed 18 600 km of transect lines in two survey areas (10 934 and 11 824 km2), yielding 1392 harbour porpoise sightings. During the building period in 2009, the lowest concentrations were recorded. Within 20 kilometres of the noise source, the spatial distribution pattern observed on two aerial surveys three weeks before and exactly during pile-driving testifies to a strong avoidance response. Pile-driving had a negative impact on relative porpoise detection rates at eight locations with distances less than 10.8 km, according to generalized additive modelling using SAM data. Increased detection rates were discovered at two locations, 25 and 50 kilometres apart, indicating that porpoises had been moved to these locations. SAM might thus detect a pile-driving-related behavioural reaction at a considerably greater distance than a pure avoidance radius would predict (Dähne et al., 2013).

A closer look to the literature on wind farms' negative impacts on wildlife, however, reveals a number of gaps and shortcomings. Even though the majority of the studies provide well documented risks and adverse impacts, they are not so many those that offer concrete solutions or mitigation measures.

There have been numerous studies to investigate the impact of wind farms in human health and their general perception by the public. This is the last, but not least, issue tackled in this research. Researchers in Finland conducted an epidemiological survey of the influence of wind turbine and road traffic noise exposure on self-reported health effects, with a case group near wind turbine areas and a control group farther away from wind turbines. Because wind turbines are built near existing infrastructure so that large transport vehicles have access to install and maintain them, it is important to consider in aggregate all potential environmental stressors and their health effects on the public. The wind turbine areas met with modern tightened regulations where sound levels did not exceed 40 dB. They were associated with increased noise annoyance, but no other health effects. On the other hand, increased road traffic noise levels were associated with self-reported health effects including migraines, dizziness, impaired hearing, heart palpitations, and heart disease. The study found that when wind turbine sound levels meet with regulations, it is more important to control road traffic noise in these residential areas. The results provide significant contextual data for wind energy policy developers since noise is among the top objections affecting the social acceptability of wind turbines (Radun et al., 2022).

Research from Roddis et al, 2018, argue that variables related to community acceptance are statistically significant when it comes to planning outcomes for onshore wind and solar farms, according to their research. Across both technologies, more variables in thematerial arguments' category were significant than those in the 'attitudinal/social impacts' category, especially aesthetic variables. Aesthetic, environmental, economic, project details, demographic, chronological, and geographical considerations proved to be significant. However, for neither of the technologies, no political variables were found to be relevant. The visual impact of the project installed capacity, the social deprivation of the local area, and the year of the planning application are all important in terms of planning outcome for both onshore wind and solar farms, according to common significant variables, namely visibility of modern artefacts and structures, installed capacity, and the year of the planning application (Roddis et al., 2018). This suggests that aesthetics and visual impacts are substantially linked to onshore wind and solar farm planning outcomes, which is consistent with much of the previous work on public acceptability of these technologies (Wolsink, 2000). This study's findings have a variety of consequences for community acceptability and energy justice. To begin with, the findings on social deprivation indicate that solar farm projects are more likely to be located in disadvantaged areas, whereas onshore wind farms are more likely to be located in wealthy areas. Although it is debatable whether these technologies are a cost or a benefit, their unequal distribution across the country has implications for distributive, procedural, and recognition justice. Second, the findings suggest that aesthetic variables are particularly important in explaining planning outcomes, highlighting the need for greater public awareness of the range of options and trade-offs involved in future energy pathways so that visual preferences can be formulated and balanced in the context of broader energy system change. Finally, the authors raise the question of whether public acceptance of energy justice should be a key value. While acceptance is difficult to quantify, its inclusion in energy decision-making should be taken into account more closely in order to accomplish a low-carbon transition that is based on fairness and equity. Within the field of energy justice scholarship, the authors urge that this vital subject be given more critical and ethical scrutiny (Roddis et al., 2018).

Hofer et al, in 2016 suggest that the site assessment can be improved by providing a holistic multi-criteria decision-making strategy that integrates techno-economic, socio-political, and environmental factors that are formulated in such a way that societal acceptance-related issues are especially stressed. They use a GIS-based Analytic Hierarchy Process technique, in which a group of local experts and stakeholders are requested to pairwise assess the included criteria in order to determine their relative relevance. According to the findings, 9.4 percent of the research area is still open for wind energy development, while just 1.74 percent of the territory has high appropriateness. The northern half of the region, in particular, has a lot of untapped wind energy potential. The model's accuracy and dependability are confirmed by a comparison to the location of current wind farms (Höfer et al., 2016).

According to a study published in 2021,1,000–1,200 m zoning limits only have minimal externalities on the surrounding settlements (Peri & Tal, 2021).
This study created a scientific basis for choosing the ideal setback distance from populated areas. It starts by describing the trade-off between the environmental externalities of turbines and their potential for energy in Israel's northern region, where prospective wind farms are currently being taken into consideration. Using GIS software, the analysis can quantify the energy potential as well as the effects of noise and shadow flickering. They analyzed six different regulatory approaches to setback distance for limiting wind turbines based on geographic data and assess how they might be implemented in northern Israel. The findings show that annoyance levels depend on site-specific variables, which in certain places are marginal, at setbacks of 700–800 m.

3 Research Design & Methodology

For the substantiation of this thesis, the use of a mixed-methods design that integrates aspects of both qualitative and quantitative approaches was chosen. Combining both insights, a more complete picture of the problem is gained, and the credibility of the conclusions are strengthened.

Quantitative research is a type of research that uses natural science approaches to generate numerical data and hard facts. It uses mathematical, computational, and statistical tools to demonstrate a cause-and-effect link between two variables. The study is also known as empirical research because it can be measured correctly and precisely. The information gathered by the researcher can be organized into categories, ranked, or measured in terms of units of measurement.

Quantitative research can be used to create raw data graphs and tables, making it easier for the researcher to analyse the results (Streefkerk, 2019).
Qualitative research entails gathering information and understanding about a topic. It's an unstructured, exploratory research strategy for studying extremely complicated phenomena that quantitative research can't explain. It does, however, produce concepts or hypotheses for future quantitative research.
On the basis of observation and interpretation, qualitative research is used to get an in-depth understanding of human behaviour, experience, attitudes, intentions, and motives in order to discover how people think and feel. It's a type of research in which the researcher gives the participants' opinions more weight. Qualitative research includes case studies, grounded theory, ethnography, history, and phenomenology (Ograjenšek & Thyregod, 2004; Streefkerk, 2019).

Having chosen a mixed methods design the type of the design has to be identified. Descriptive research from the quantitative and case study for the qualitive design will be employed in this research.

Descriptive research is to make careful observations and detailed recording of interesting phenomena. These observations must follow the scientific method (i.e., they must be consistent, accurate, etc.) and are thus more reliable than casual observations made by untrained persons. Descriptive research may not cleanly fit into either the quantitative or qualitative research methodology definitions, although it can incorporate components of both, often within the same study and is therefore the ideal approach for this thesis, as methods for both types will be utilized. The word descriptive research refers to the type of research question, design, and data analysis that will be used to investigate a certain issue. Inferential statistics attempt to determine cause and effect, whereas descriptive statistics describe what is. The type of inquiry posed by the researcher will ultimately define the approach required to conduct a thorough examination of the subject at hand (Sahin & Mete, 2021).

The **case study** enables for in-depth, multi-faceted examinations of difficult subjects in their natural environments. *A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."*(Yin, 2009). In a case study the examination of the data is usually done in the context of the situation in which the activity takes place. Differences in intrinsic, organic, and collective approaches to case studies allow for both quantitative and qualitative data analysis.

The detailed quality accounts often produced in case studies not only help to investigate or describe data in the real-life environment, but also help to explain the complexities of real-world situations that may not be recorded through experimental research. A case can be about a phenomenon or a group of people. Cases in the first scenario are illustrative of a phenomenon and are chosen based on empirical evidence. According to the study design, the procedure reveals certain characteristics of instances while obscuring others, allowing the complexity, specificity, and context of the phenomena to be investigated. The selection of instances comes before the research in the alternative, population-focused scenario. In order to investigate a phenomenon, both positive and negative cases are studied, with the definition of the collection of cases being determined by theory and the essential goal being to create generalizations (Ragin, 1992). It's worth noting here that a study of many examples necessitates an a priori determination of the unit of analysis. It will be impossible to do cross-case comparisons otherwise.

The case study's purported lack of "generalizability" stems from a misunderstanding of case and population selection (for testing) from a domain on the one hand, and population sampling on the other, as well as a misunderstanding of what it is generalized to (the study, its outcome, or a proposition) (Dul & Hak, 2007; cited in Ebneyamini & Sadeghi Moghadam, 2018).

For the purposes of this research, a multiple case studies approach has been chosen. According to Stake (2003), this approach used to search for evidence in a variety of settings; direct comparisons aren't always necessary. Rather, there is an ongoing search for patterns of convergence and divergence that run through all of the cases, as the same challenges are addressed in each. The researcher then progressively increases cases until theoretical saturation is reached (R. E. Stake, 2003). He also highlights four defining characteristics of qualitative research which are valid for qualitative case studies as well: *"holistic," "empirical," "interpretive," and "emphatic"*(R. Stake, 1995).

For this research, one case study was analysed: the case study of the attitude of the inhabitants of the Argolis plains in Greece, regarding the possible installation of wind turbines on the hills and mountains surrounding the plain.

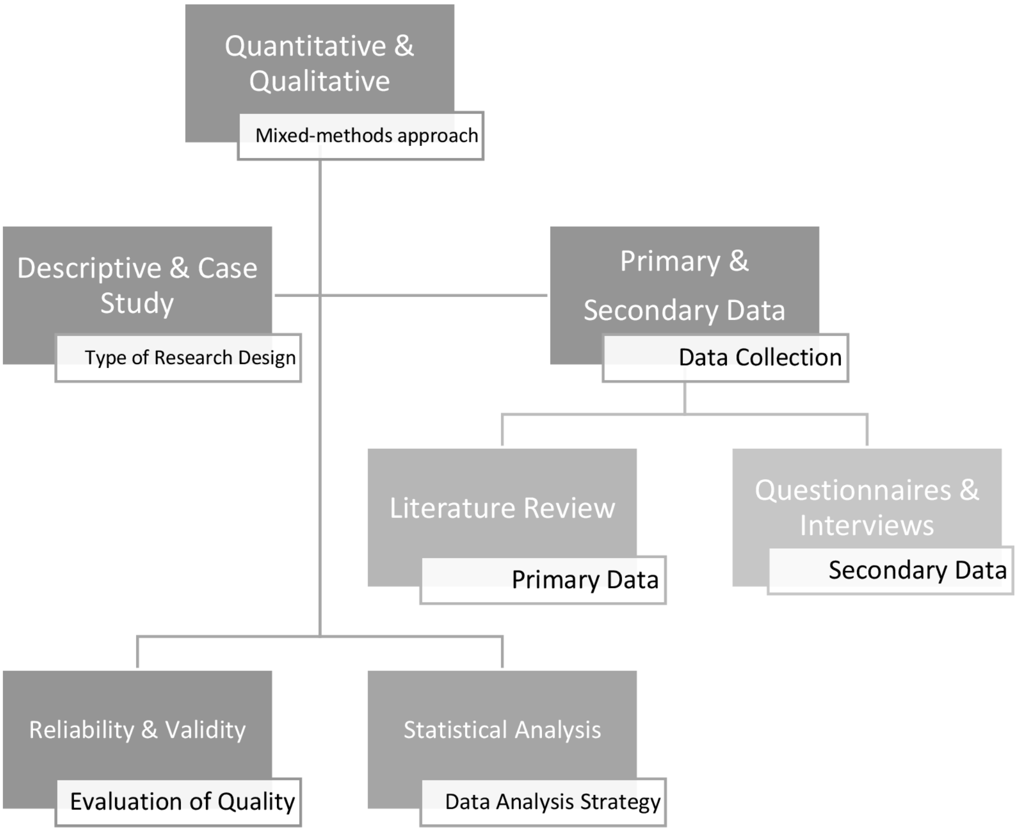

Figure 1: Research Design of Current Dissertation

3.1 Research Questions

1. What are the main environmental, ecological, aesthetic, and societal factors that delay the public acceptance of the wind energy, and how to mitigate them?
2. What is the societal perception of the wind turbines and how do they affect the attitudes and behaviours of local populations towards wind farm installations?
3. What are the challenges with end-of-life solutions of the wind turbines and what opportunities arise thence?

3.2 Research Methods for Data Collection and Analysis

The research methods that have been utilised for collecting and analysing data are both qualitative and quantitative and were chosen taking into consideration the above research questions. Therefore, it was chosen to conduct a thorough literature review for the acquisition of secondary data and surveys in the form of questionnaires and interviews with the purpose of filling the knowledge gap in the literature and acquire primary data.

3.2.1 Secondary Data

Having established that the best approach for my design is a mixed-methods approach, i.e., both quantitative and qualitative, the data collection for the research started. The first step was to conduct a thorough literature review in scholarly books, dissertations, scientific journals, conference proceedings, technical and commercial documentation, market research reports, and the web. The purpose of the review was to establish familiarity and understanding of current research, detect areas of controversy, identify knowledge gaps and open questions left from previous studies, and develop my own theoretical framework and methodology.

The review started broadly, continued with topics that overlapped with mine, to culminate to studies that were directly relevant to my research. My literature review started in 2018 and it was updated regularly with an astounding number of new articles added every month in the literature. The databases used were mainly Scopus, and then Web of Science, SAGE Journals, ScienceDirect, IEEE Xplore, SpringerLink, PubMed and last but not least library catalogues. Throughout the literature review, the aim was to use the most recent publications, that do not pass the 4 years. However, certain exceptions arose if the studied areas had not seen important developments over the last few years.

The review started by creating a list of keywords related to my research topic. The key concepts initially used were wind turbines, blades, aesthetic impact, end-of-life, waste management. Then those key concepts and variables were included in a list and my search began in Scopus with the method of 'pearl growing' with below searches: wind turbines AND blades, environmental problems AND wind turbines, aesthetic impact AND wind turbines, end-of-life AND wind turbines, wind turbines AND noise annoyance, wind turbines AND waste management. As I became more familiar to the topic and the research became more specific, the 'snowballing technique' was used, tracking down references and citations in documents and reading those initial documents(Wohlin, 2014).

In order to choose the most relevant literature for my research and identify the literature gaps, some principles of a bibliometric literature review were examined. The analysis was done to the searches that were conducted in Scopus and specifically to the articles that appeared for below searches: blades AND recycling, wind AND turbines AND recycling, wind AND farms AND public AND perception, circular AND economy AND wind AND turbines, industrial AND symbiosis AND wind AND farms, wildlife AND wind AND farms, biodiversity AND wind AND farms, wind AND turbines AND aesthetic AND impact, wind AND turbines AND visual AND pollution, wind AND turbines AND landscape, wind AND turbines AND seascape, wind AND farms AND noise AND pollution, wind AND farms AND flicker.

The analysis was made using VOSviewer version 1.6.18 software and was pertinent to the keywords used by authors (VOSViewer Team, 2022). From those searches combined a cumulative of 12 different thematic clusters occurred. Below each network for each one of the above searches is visualised on the basis of keyword co-occurrence by association strength using VOSviewer.

Each node represents a keyword, the size of the node indicates the number of times that the keyword occurs, the line between the nodes represents the co-occurrence between keywords, the thickness of the lines shows the number of times that the keywords co-occur. Each colour represents a thematic cluster, where the nodes and links in that cluster can be used to explain the coverage of topics and the relationships between them manifesting under that theme. I did not attempt to conduct a bibliometric analysis, but rather to identify the main scientific articles using this method.

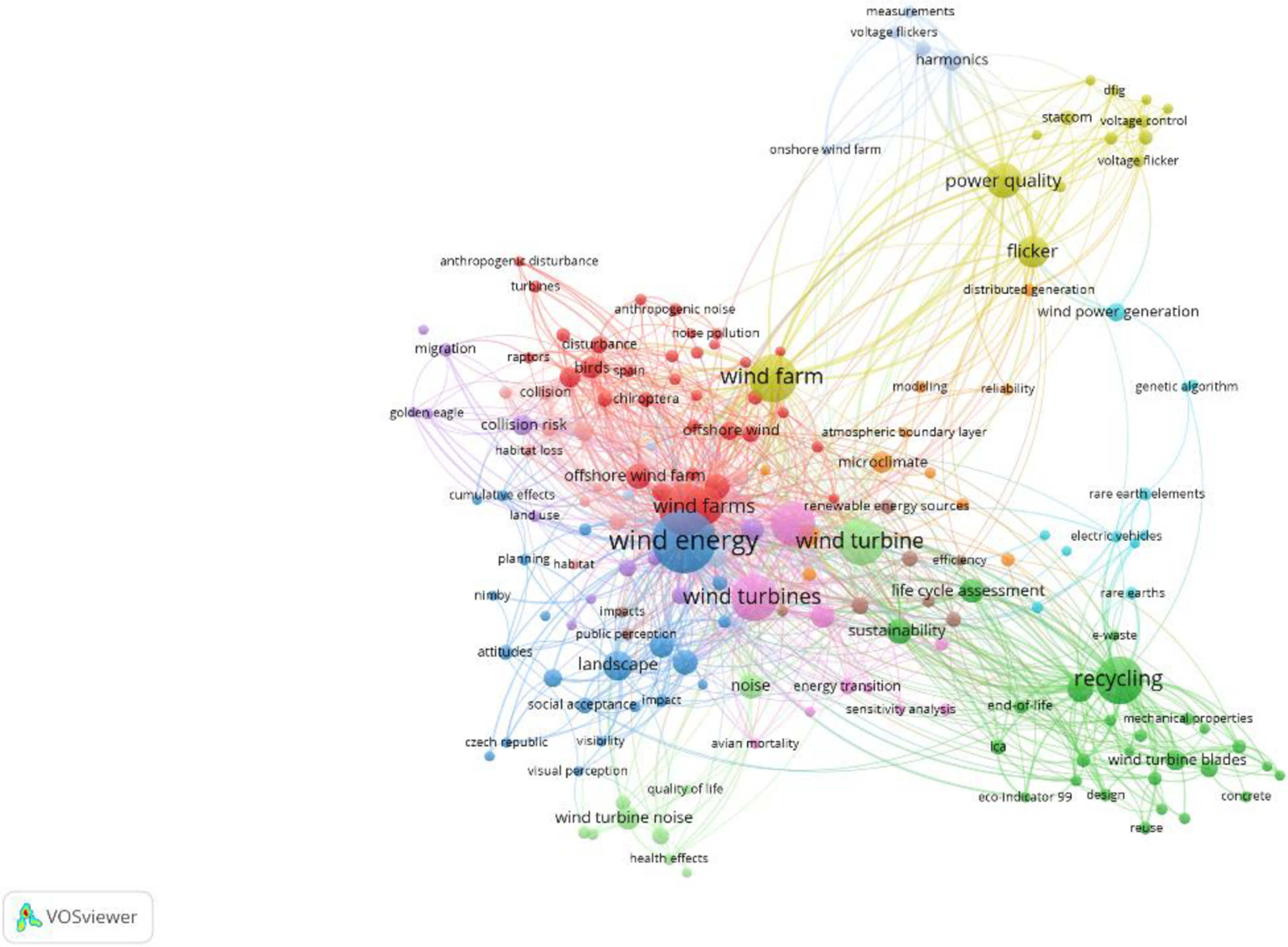

Figure 2: Keyword Network Visualisation of Cumulative Searches

3.2.2 Primary Data

Covering the literature review and identifying the main gaps, it was clear that more data were needed. It was therefore deemed necessary to acquire primary data in order to add novelty in the existing literature. It was then that the methods chosen to fill this gap were surveys- in the form of questionnaires and interviews- to gain information and insights on the main topics of the research.

The questionnaire

Firstly, the goal of the questionnaire was to explore the impacts that wind turbines may have upon the open space, environmental and community services, on rural areas that have permanent agricultural populations. It was intended to explore if this impact has a negative, positive, or neutral consequence for the behaviour of the locals towards wind energy or whether it creates discomfort to the local populations.
Thereafter the target population was defined in the case study. Nonprobability sampling was preferred, as for the case study a certain profile of respondents was required. However, the random selection within the chosen population was followed and it allowed me to make strong statistical inferences about the whole group.
Later the proper questions were formed, based on the goal of the survey. The last step, in order to improve the quality, was to conduct pilot surveys among ten people. During this process inconsistences, biases and weaknesses of the questions were identified and eventually modified to render them more impartial and comprehensible. The questionnaire was prepared in English and Greek, to be able to reach multiple inhabitants. The questionnaires can be found on Appendix A.

Regarding the case study in the Argolis Plain in Greece, the survey was contacted over 10 visits in different periods of the year, at random time slots and it happened door-to-door in the first visits and then online. The main obstacle was the unwillingness of the respondents to share income and education information, fact that has been taken into consideration in the data validation. In addition, the global pandemic of Covid 19, was a great obstacle to the substantiation of this survey.

The questions were designed to be simple and brief, and they always included a field 'other', with the choice to fill up manually the answer, in order to gather attitudes that would otherwise be lost in a strict closed-ended questionnaire. They also included answers as 'I do not know' or 'I do not want to answer'. Before handing out the questionnaire, confidentiality was discussed and questions with sensitive personal data have the choice to be left unanswered.
All analyses were undertaken using R version 4.2.0 (R Team, 2022).

Individual respondents' comments about their preferences are used in a family of approaches called stated preference valuation to assess the change in utility associated with a proposed improvement in the quality or quantity of an ecosystem function or bundle of services. Techniques of preference analysis include revealed (observed) and declared methods (hypothetical). As opposed to stated preference analysis methods, which build a fictitious case to which the responder must relate, revealed preference analysis methods are based on real case transactions. There are several issues with stated preference methodologies since they examine hypothetical behaviour in which respondents do not feel the repercussions of their decisions, unlike in a real life.

The questionnaires consist of approximately 30 questions and have the following structure: background characteristics and questions about wind energy and attitudes to renewables. The contents of the questionnaire have been prepared based on a number of prior studies: 1. A review of the existing literature on social attitudes on wind energy 2. Dialogue with selected stakeholders in the wind energy 3. In-depth interviews with eight respondents to validate the final draft of the survey and a pilot test with 10 respondents. The prior analyses have been necessary for a number of reasons, including to ensure that the focus is on attributes that are relevant to inhabitants of the studied area, measurable and adjustable for the me to analyse the results.

The questionnaire begins with general demographic questions about gender, age, and place of residence. These questions are used in an assessment of whether the respondents constitute a representative selection of the inhabitants of the Argolis plain.

The interviews

There are various styles of interviews, ranging from the unstructured to the highly structured. The type of interview is determined by the amount of control the interviewer has over the dialogue. For the current research semi-structured and structed interviews were conducted.

In semi-structured interviews, there is an interview guide that is followed including questions and topics that have to be discussed. It resembles to a conversation with the difference that there is a general direction in the discussion. It is used when the researcher wants to investigate thoroughly the topic and to understand deeply the answers that the interviewee provides (Harrell & Bradley, 2009).

In structured interviews, there are very specific questions that are asked, they follow a strict order, and they resemble to a survey. Structured interviews have the advantage that their results can be generalized to a large population. However, they have the disadvantage that the interviewer is very limited in explaining the interviewees the questions that they do not understand (Harrell & Bradley, 2009). The interviews are qualitative due to the issue of information, which leads to wider and clearer understanding of this specific case (Seidman, 2006).

Initially all interviews were prepared as semi structured, so it would lead to a continuous and unbiased dialogue, but some the interviewees preferred a structured approach, so for them a structured interview was conducted. The interviews were contacted through an online communication platform, due to geographical proximity issues. Three interviews were conducted with two of the interviewees based in Denmark and one in. All of the interviews are transcribed and can be found on Appendix B. The purpose of the interviews was again to acquire data missing from the literature, but this time from experts in the field of wind energy. The interviewees were chosen because of their affiliation to leading wind turbine manufacturers and their personal level of expertise in the field.

3.2.3 Data Analysis

In the data analysis a mixed-methods approach has also been used. For the objectives of this research, it was deemed necessary to conduct a statistical analysis to analyse the data collected form the questionnaires, and a thematic analysis in order to analyse data collected from the interviews and textual sources and to comprehend general themes and how they are communicated.

I applied thematic analysis to identify patterns from the literature and to describe the various aspects of the research questions. The analysis was deemed suitable in order to give the current state of the art on the topic and the knowledge acquired from the interviews. A deductive approach was used as I handled the data with some preconceived themes that I expect to find reflected -mainly in the literature review- based on theory or existing knowledge.

For the statistical analysis, descriptive statistics are employed. With the descriptive statistics we can summarize or describe the characteristics of a data set using measures of either central tendency or variability. Descriptive statistics include its minimum, maximum, range, percentile, mean, median, mode, mean deviation, standard deviation, variance, skewness, and kurtosis. Descriptive statistics represent information that can be used as the basis for comparing how data series differ (Lee, 2020).

The sum of all the observations of the sample is symbolised with n. If $x_1, x_2, \dots, x_k$ are the values of a variable x, of a sample size n, the natural number v_i, which indicates how many times the value x_i is displayed in the sample, is called the frequency of x_i. That is:

$$v_1 + v_2 + \cdots + v_k = n$$

If we divide the frequency v_i, by the sample size n, we get the relative frequency f_i of the value x_i. That is:

$$f_i = \frac{v_i}{n} \qquad i = 1, \dots, n$$

It applies:

i. $0 \leq f_i \leq 1$
ii. $f_1 + f_2 + \cdots + f_k = 1$

The mean, $\bar{x}$, is the most used measure of statistics and is defined as the sum of the observations by the number of remarks. That is:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Except for the mean, which is the sum of a variable's values divided by the total number of values, we also meet the median, which is the middle value of a variable; and the mode which is the value that occurs most often. Those were the measures of central tendency and are the most basic and, often, the most informative description of a population's characteristics (Ali & Bhaskar, 2016).

In descriptive statics we have also the measures of dispersion which are the range (the difference between the smallest and largest values in the data), the variance (which is calculated by taking the average of the squared differences between each value and the mean), the standard deviation (the square root of the variance) and the skewness and kurtosis (a measures of whether some values of a variable are extremely different from the majority of the values) (Ali & Bhaskar, 2016).

In addition to descriptive statistics, Structural Equation Modelling (SEM) was used in order to identify the causal relationships between the hypothesized reasons behind the acceptability of wind energy and the behaviour of the local populations towards it.
A SEM is defined as having continuous-valued latent variables, continuous-valued observable (or manifest) variables, and linear relationships between the latent variables.

The linear SEM has the form:

$$y_i = \Lambda_y \eta_i + \varepsilon_i$$

where εi, δi, and υi are mutually independent error terms with zero means and constant covariance matrices (Jöreskog, 1973, as cited in (O'Malley & Neelon, 2014)).

Model specification, identification, parameter estimation, model assessment, and model change are the five logical phases in SEM. Based on one's understanding, model specification describes the assumed relationships between the variables in a SEM. Model identification involves determining if a model is over-, just-, or under-identified. Only the just-identified or over-identified model allows for the estimation of model coefficients.
In SEM the Cronbach A is utilised, which is a statistical metric that calculates the internal consistency or reliability of a group of items or variables. In other words, it can be described as a function of the test's item number, the average item-to-item covariance, and the variance of the entire score. The following formula is used to calculate the alpha:

$$\alpha = \frac{N\bar{c}}{\bar{v} + (N-1)\bar{c}}$$

Where N is the number of items, $\bar{c}$ is the average inter-item covariance among the items and $\bar{v}$ is the average variance.

The theoretical range of alpha is $0 \leq \alpha \leq 1$. However, in some cases, the value might be negative. This indicates that something was wrong with the data. In general, the acceptable alpha values are $\alpha \geq 0.7$. When $\alpha = 0$, it means that the scaled items are not correlated and when alpha approaches 1, it means all items have high covariance. When the alpha coefficient is less than 0.5, it means that it is generally unacceptable, especially for scales purporting to be unidimensional (Weston & Gore, 2006).

3.3 Theoretical Framework

In order to substantiate the current research and strengthen its scientific value, theoretical framework is included in this thesis. In order to create a strong liaison between the existing knowledge and the research questions, multiple behavioural theories were studied, analysed, and evaluated for their relevance to the research topic and questions. So as to conclude on the most relevant theory for this dissertation, an elaborate conceptual diagram was developed. The objectives were to link different ideas together and identify the scope through which they would be examined.

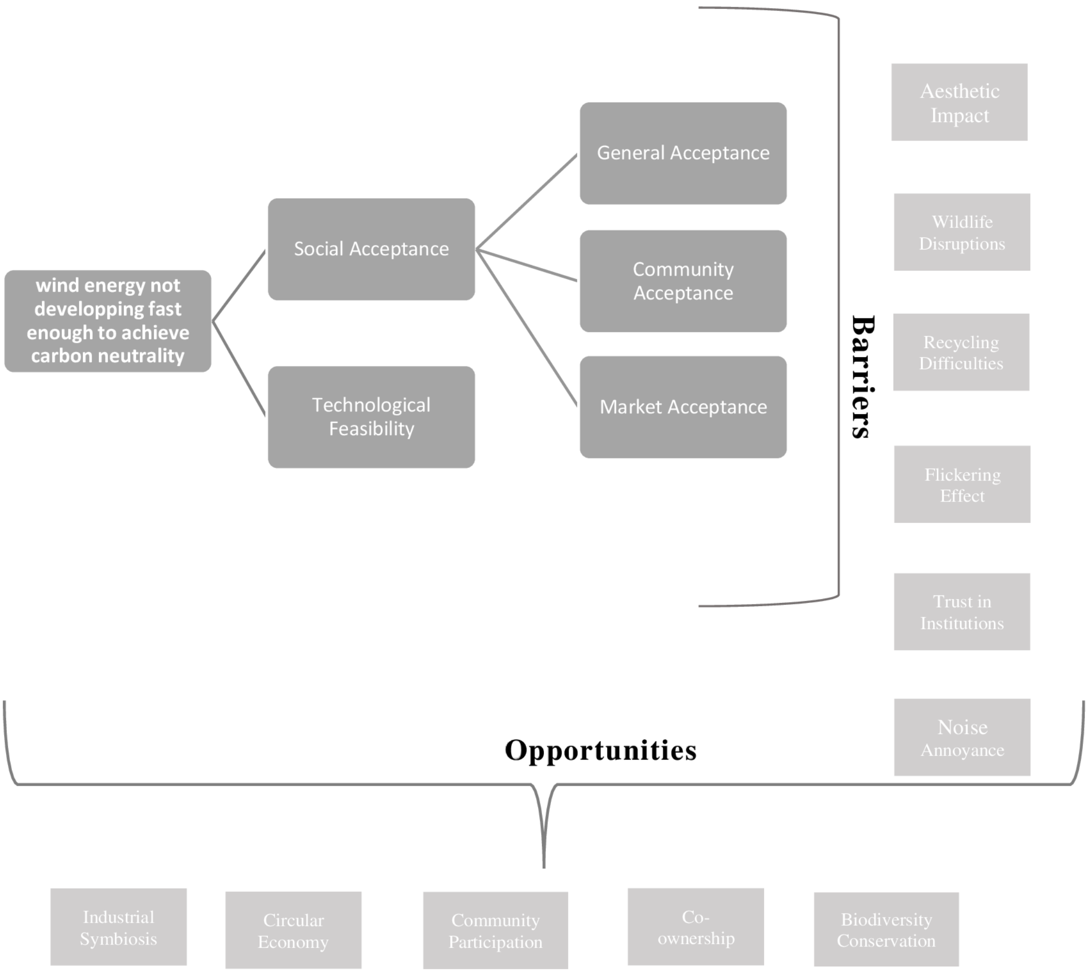

Figure 3: Conceptual Framework of Current Research

Having created and analysed the conceptual framework and reviewed the most relevant behavioural theories, the Theory of Planned Behaviour was chosen.

The Theory of Planned Behaviour (TPB) was elaborated by Icek Ajzen in 1985 and relates beliefs to behaviour. According to Ajzen, the central components that shape an individual’s behavioural intentions are the subjective norms, the attitude, and the perceived behavioural control (Ajzen, 1991).

By normative beliefs it is denoted the perception that an individual holds regarding the social normative pressures, or the beliefs of other individuals assuming what behaviours should be performed. By subjective norm it is meant perception of an individual about the specific behaviour, which is influenced by the judgment of relevant others.

Perceived behavioural control is defined as an individual's perceived comfort or difficulty of performing the particular behaviour and it is conceptually related to self-efficacy. It is assumed that perceived behavioural control is contingent to the total set of accessible control beliefs. Each one of those predictors is weighed regarding its significance in connection to the behaviour and population under consideration.

In simple terms, one’s attitude towards a behaviour will affect how likely one is to perform that behaviour; what others in one’s social circle think about a behaviour, has an impact on your behaviour; and whether one believes they have the capacity and means required to exhibit the behaviour, affects one’s behaviour.

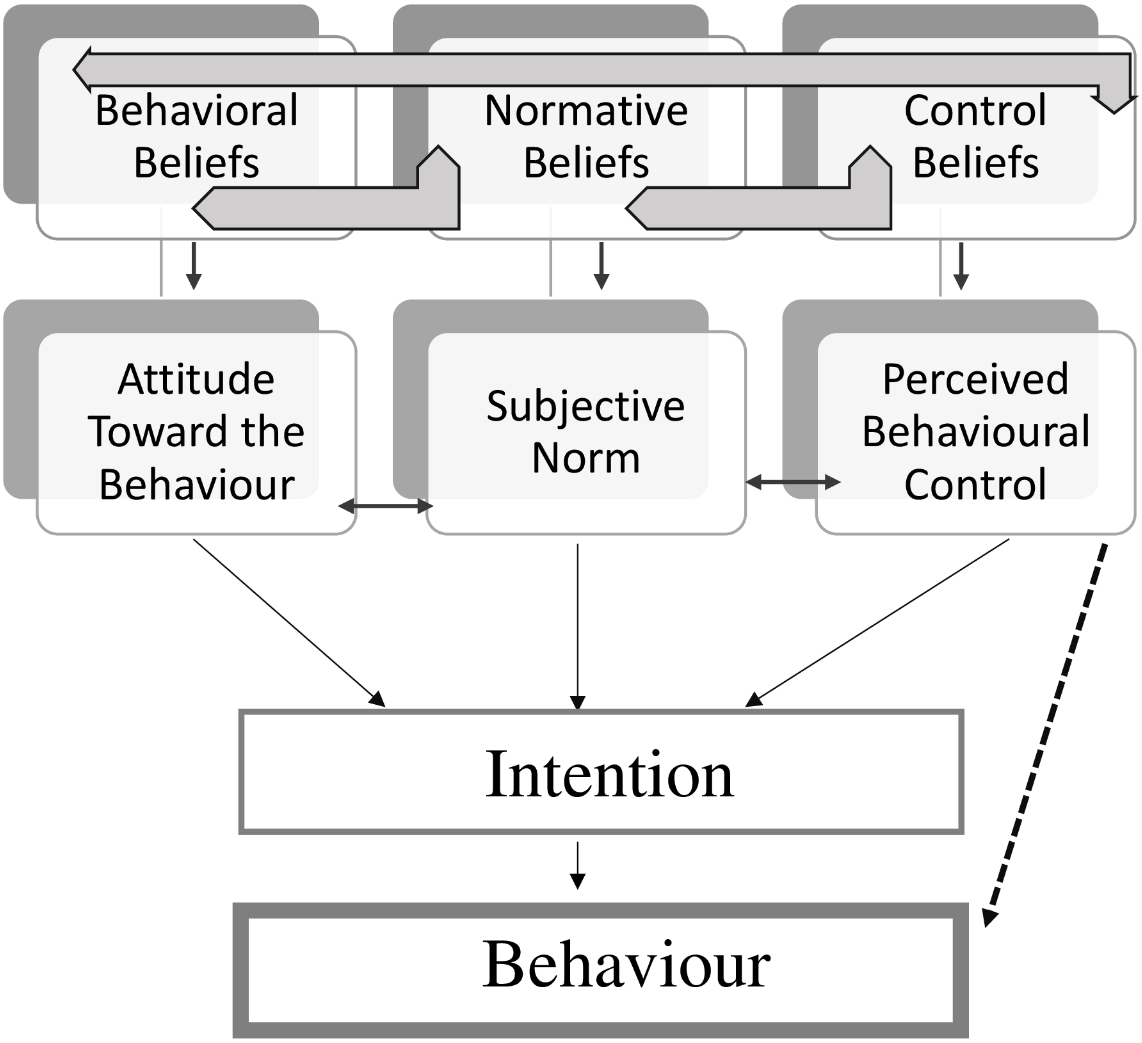

Figure 4: Schematic representation of the Theory of Planned Behaviour

Behavioural intention for the theory of planned behaviour can be expressed as the following mathematical function:

$$BI = w_A A + w_{sN} SN + w_{PBC} PBC$$

The three factors being proportional to their underlying beliefs:

$$\mathrm{A} \propto \sum_{i-1}^{n} b_i e_i$$

$$SN \propto \sum_{i-1}^{n} n_i m_i$$

$$PBC \propto \sum_{i-1}^{n} c_i p_i$$

where

BI: Behavioural intention

A: Attitude toward behaviour

b: the strength of each belief concerning an outcome or attribute

e: the evaluation of the outcome or attribute

SN: Subjective norm

n: the strength of each normative belief of each referent

m: the motivation to comply with the referent

PBC: Perceived Behavioural Control

c: the strength of each control belief

p: the perceived power of the control factor

w: empirically derived weight/coefficient

$$B = w_{BI}BI + w_{PBC}PBC$$

where

B: Behaviour

BI: Behavioural intention

PBC: Perceived Behavioural Control

c: the strength of each control belief

p: the perceived power of the control factor

w: empirically derived weight/coefficient

3.4 Validity and Reliability

Qualitative designs do not typically take samples from large-scale data sets due to the time and costs involved, which is a key critique is the lack of acceptable validity or reliability. It's challenging to apply traditional reliability and validity requirements to qualitative data because of its subjective character and single-context origins (Guba & Lincoln, 1994).

Validity is defined as *"the extent to which the instrument measures what it implicates to measure"* (Messick, 1987). In other words, it is a measure of success of the used tools. In a relation to the current research, validity represents a measurement of the survey's success, in which the survey is the main tool. The survey served its purpose of finding out about attitude and knowledge towards wind turbines of the target group.
The data and results used in the project are identified as valid for this purpose.
Hypothetical bias occurs when the respondents overestimate their acceptance towards wind energy. Protest and strategic behaviour mean that, for various reasons, the respondents do not reveal their actual attitudes. Finally, problems may arise if the respondents misunderstand or if the descriptions of the individual attributes are not sufficiently accurate. This may result in an insensitivity to the scope of the individual improvements (Laitila, 2004). In the design of the questionnaire and the subsequent analysis, commonly used methods have been used to test for these sources of error and minimise their impact on the results. In addition, a number of analyses have been done to ensure the validity of the survey results. All invalid data that was encountered has been excluded from the analysis and any interpretations on the basis of proving unnecessary and invaluable to the project. For instance, a few of the survey forms were dismissed from the analysis because they were considered as invalid because they were filled incorrectly. During the design and the pilot trial of the questionnaire, the potential biases were eliminated, and questions were rephrased in order to ensure that the wording does not favour one perspective over another.

"Reliability applies to a measure when similar results are obtained over time and across situations" (Seymour, 2012). In other words, a reliable sample would give the same result even if it were done several times. For instance, the questionnaire that was conducted gave similar results across the different locations that the method was performed. This experiment shows that if someone wants to conduct the same survey under the same circumstances the result will not change significantly. This applies for the rest of the research methods used in the project as well, including interviews.
During the collection of secondary data, it was assured that the sources were credible, with the intention to have high reliability. Thus, the chosen data was checked and compared to other related sources and the literature was reviewed in an iterative fashion every month. Furthermore, all the information sources are included as references in the project and can be verified.
During the surveys, convenience sampling, which was used to gather the data, might have led to researcher bias. To gain a deeper knowledge of attitude and behavioural intentions, more factors and dimensions could be added to the research model, which focuses on only a few key variables. To increase representativeness, additional communities could be included in future research.

4 Results

4.1 Environmental Barriers

4.1.1 The recycling problem of the blades

The designed life of a wind turbine is 20 to 25 years, but in actuality, their lifespan is uncertain. Technical, economic, and regulatory factors drive the decision-making process about whether to extend the lifetime, repower, or decommission a turbine("Albers et al., 2009). The foundation, tower, components of the gear box and generator (i.e., parts that are made of steel, concrete, iron or cast iron, copper, and aluminium) can be easily recycled or reused. However, blades constitute a great challenge for end-of-life (EoL) management and compromise the sustainability of the life cycle of a wind turbine.

It is forecasted that the total waste blade material in 2050 will reach 325.000 t, where 247.000t (76%) will originate from onshore installations while 78.000t (24%) from offshore (Lichtenegger et al., 2020), while the estimation for 2034 is 100.000t (Lichtenegger et al., 2020). It is therefore apparent that the blades constitute a crucial waste management concern.

Figure 5: Aerial view of a turbine blade landfill site in the USA (Pinna, 2021)

The main parts of a wind turbine are the rotor, the blades, the blade pitch system, the main shaft and bearing, the magnet or the gearbox, the generator, the mechanical brake, and the yaw system. The rotor usually contains three blades on horizontal axis made of reinforcement fibres, with an aerodynamic design. It has the ability for pitch regulation with variable speed in order to generate the optimal power. The blades have no openings in the joints, a fact that constitutes them resistible to water and lightning. The rotor central part, the hub, is cast in nodular cast iron and has enough space for two technicians during repair and maintenance. The blade pitch system is activated when wind surpasses a certain speed, and the blades are feathered for safety reasons. The gearbox is a three-stage spur planetary one and ensures low noise levels; it also includes fail-safe a mechanical brake. The yaw system is used to keep the rotor facing into the wind and to unwind the cables that are sprawled to the base of the tower. The generator converts mechanical energy to electrical energy; it is equipped with advanced ventilation systems. The tower of the turbine is a steel tube. Nacelles are made out of glass fibre composites or steel and protect the components, that are enclosing, from the environment. The blades are made of laminated materials like balsa wood, epoxy, carbon fibre, and fibreglass. The main shaft is made out of iron cast and the cables consist of aluminium, copper, and plastic. The foundation made of concrete and steel represent nearly 80% of the structure total weight.

Wind turbine blades are composite structures, made up of a variety of materials with varying qualities. Blades vary depending on the type of blade and the manufacturer but generally they are manufactured with reinforcement fibres (glass, carbon, aramid, or basalt), polymer matrix (thermosets such as epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics), sandwich core (balsa wood or foams such as polyvinyl chloride, polyethylene terephthalate, coatings (polyethylene, polyurethane) and metals (copper wiring, steel bolts) (Wind Europe, 2017).
This combination of fibres and polymers is known as fibre reinforced polymer (FRP) composites and represents the majority of the blades' material composition by weight — 60-70% reinforcing fibres and 30-40% resin (Wind Europe, 2017).

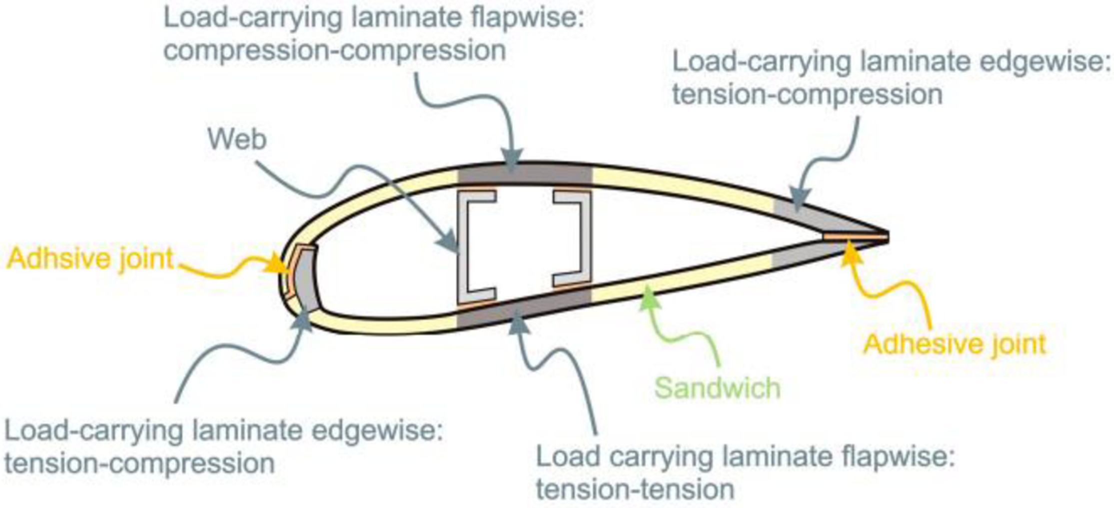

Figure 6: Schema of the section of the blade, including a description of the main elements (Mishnaevsky et al., 2017)

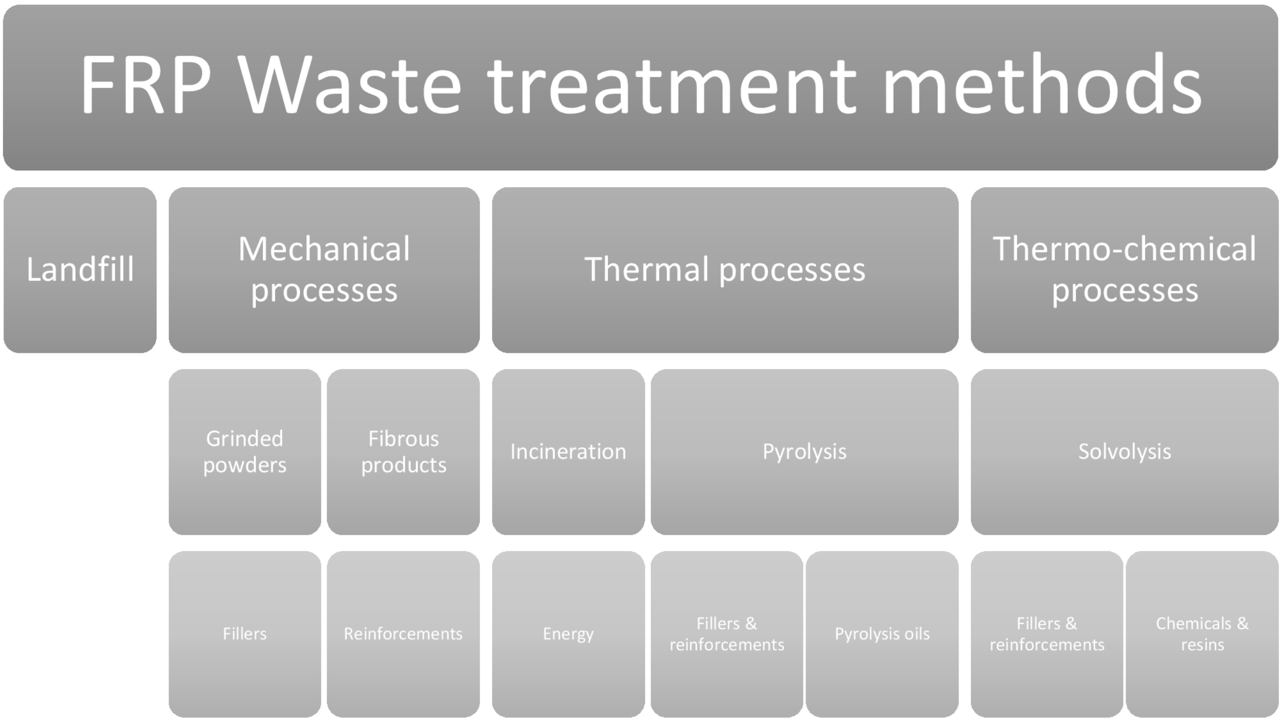

Figure 7: Fibre Reinforced Polymer (FRP) composite waste treatment methods adapted from (Gharde & Kandasubramanian, 2019)

The blades must be detached from the rest of the wind turbine as a first step in decommissioning and cut into smaller sections before being transported for waste treatment. In the waste treatment facility, they are treated depending on their intended EoL application. Currently, the most typical method of dealing with wind blade waste is to discard it in landfills cut in various sizes, depending on the landfill rules; however, landfills are saturated and, in some countries, like Germany, the method has been banned (Lichtenegger et al., 2020). In addition, material recovery is not possible with this method. Biotechnological methods have been also tested where microorganisms are used to degrade matrix, but the availability of this method is limited even at laboratory scale (Purohit et al., 2020). The same applies to electrochemical solutions, where electrical current is applied through an electrolyte solution to degrade the composite matrix.

Another option is to incinerate the blades in 800°C for energy recovery, although this has a number of disadvantages, as the non-flammability of the glass fibres and the large volume of non-combustible by-products.
Alternatively, the blades can be burnt in cement kilns and a few businesses in Germany have lately inserted mechanically recycled fibres into concrete, boosting the material's structural integrity (Gu & Ozbakkaloglu, 2016). Other newly proposed solutions include using the blades as thermal insulation or noise cancelling screens. Even while mechanical and thermal treatment technologies exist, there is currently no connection to end users, and the low cost of virgin material and landfilling reduces the incentive for recycling (Lichtenegger et al., 2020).

Finally, the process of pyrolysis is utilised, where the blades are cut into suitable dimensions and decomposed using conventional heating in an inert atmosphere (450-700°C). With this way, material recovery is achieved - in the form of fibres which can be used as reinforcements (glues, paints, concrete) and the by-products syngas and char can be combusted for electricity and heat recovery and recycled as fertilizer-respectively (Wind Europe, 2017). The life cycle of a wind turbine consists of raw material extraction, production/manufacturing, transportation and installation, operation and maintenance, and end-of-life disposal and their environmental impact depends in a great extent on the EoL method that is used (Nagle et al., 2022).

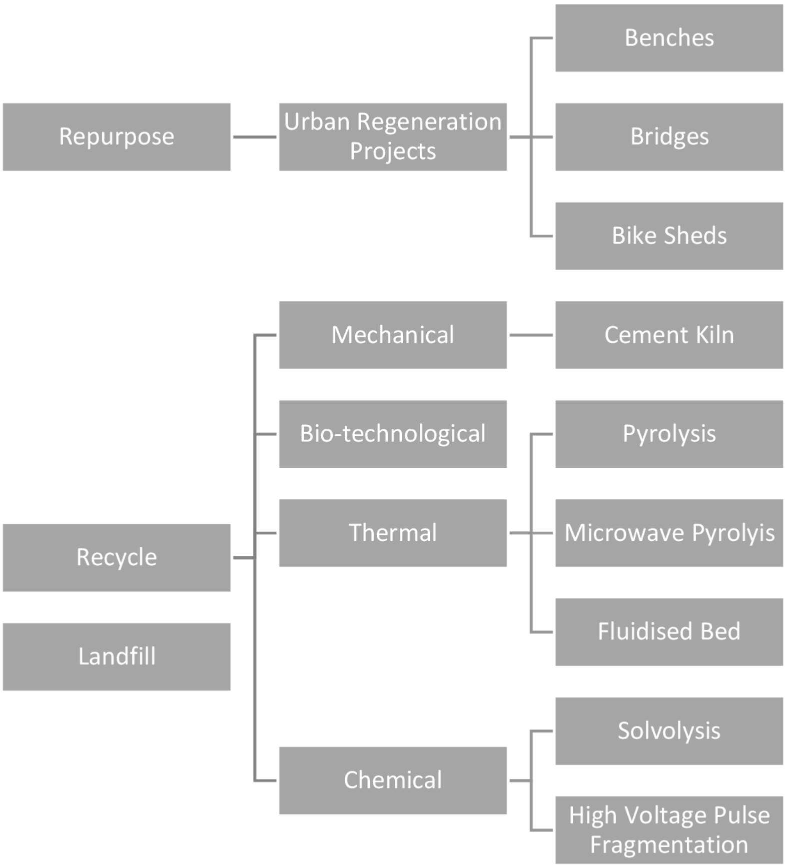

Figure 8: Current EoL solutions for WT blades adapted from Andersen et al., 2016

Mechanical Recycling

Mechanical grinding of composites is the process of reducing composite waste to a few centimetres. The shredded composite mixture that results is then employed in new applications. It has been proved to be an efficient waste management process but has important disadvantages as it does not take advantage of the initial structural properties of the composite and the value of the material is reduces considerably, since the blades downcycled (Beauson & Brøndsted, 2016). The resulting fibres are significantly reduced, unstructured, coarse and they lack consistency. In addition, the end product has still contaminants, coatings, and paint, and as a result its tensile force is limited (Beauson & Brøndsted, 2016; Ierides & Reiland, 2022). The most difficult aspect of this recycling process is finding uses for the shredded composite material. Aside from cement manufacture, concrete reinforcing and polymer composites have also been studied. The cement production has shown the most promising results, and it will be examined in detail below as an important mitigation pathway.

Thermal Recycling

Pyrolysis is a process that uses heat to breakdown a composite's polymer matrix in an inert environment. Because the absence of oxygen precludes burning, pyrolysis has a lower air pollution impact than incineration. The resin is flammable at temperatures around 1000°C. During the degradation of the resin, gases and viscous oily liquids are produced. The fibrous and char-based solid product is left in the reactor.(Oliveux et al., 2015) Pyrolysis gas and oil can then be used as energy source, wax recyclate can be used as fuel or intermediate for chemicals production. However, the fibre product may retain oxidation residue or char, leading to important degradation of glass fibres and bringing about changes in their chemical structure. Pyrolysis is not currently economically viable and there is the danger of combustible gases leaking from waste treatment chambers (Beauson et al., 2022; Ierides & Reiland, 2022).
Fluidisised bed is a highly flexible and simple process where gases are recovered with the added opportunity to recover precursor chemicals. However, the resulted fibres have very low tensile strength and has the capacity to economically viable if it reaches capacities of more than 10,000 tonnes per year (Ierides & Reiland, 2022).

Figure 9: Recovered fibre after separation, using pyrolysis (Cunliffe & Williams, 2003)

Chemical Recycling

The method of solvolysis and high Voltage Pulse Fragmentation allow the recovery of clean fibres in their full length and the recovery of resin which can be re-used. However, it demands high energy due to the high-temperature and high-pressure involved and the use of large quantities of solvents. In addition, the method has adverse impacts on human health and ecotoxicity(Ierides & Reiland, 2022; Paulsen & Enevoldsen, 2021). The methods are able to treat industrial quantities and has sufficient scalability of the process to treat larger capacities but are considered dangerous for human safety and environmentally unfriendly (Paulsen & Enevoldsen, 2021).

Wu et al. explored effective chemical treatments for recycling epoxy composites conducted by mild acid digestion under moderate atmospheric pressure and temperatures between 80C and 110C. This separation process affords the opportunity to recover glass fibres retaining near-virgin surface quality and matrix residue with high strength retention suitable for blending with virgin epoxy for re-use in second-life applications. Despite promising results, the digestive solution is presently both costly and not safe to deploy on an industrial scale (Wu et al., 2019).

Even though it is technologically feasible to recycle composites, it is not happening in large scale because of legislative, economic and market related barriers.
Currently, just a few commercially viable recycling systems exist. From the ones mentioned above, only pyrolysis and mechanical grinding for cement kiln are more mature technologies. Especially pyrolysis absorbs large capacities of the current Glass Fibre Reinforced Polymer (CFRP) waste supply (Ierides & Reiland, 2022). As a result, innovative technologies that are now approaching market maturity need sufficient waste supply to scale up to commercially feasible levels. Currently recyclate quantities and qualities are insufficient to constitute a sufficient business case (J. Pagh Jensen, personal communication, May 16, 2022). In addition, the low cost of raw glass fibres is a key obstacle to technological commercialization, as recycled glass fibres must compete with the low market price while exhibiting diminished qualities (Ierides & Reiland, 2022; Paulsen & Enevoldsen, 2021).

There have been a series of successful collaborations, but still the market cannot support large scale solutions. A collaboration between Holcim, a German cement company, and Fiberline, a Danish fiber composite company, has reported that 1000 tonnes of Fiberline composite waste may replace 150 tonnes of alumina, 200 tonnes of sand, 200 tonnes of limestone, and 450 tonnes of coal in the cement manufacturing process(Paulsen & Enevoldsen, 2021).
A collaboration between Vestas Wind Systems and industrial and academic stakeholders including Olin, a leading producer of Epoxy, the Danish Technological Institute (DTI), Aarhus University and partly funded by the Innovation Fund Denmark (IFD) has developed an epoxy that can dissolve and be processed back into the original chemical compounds, making blades recyclable. Firstly, thermoset composites are disassembled into fibre and epoxy. Then, through a chem-cycling process, the epoxy is further broken up into base components similar to raw materials. These materials can then be reintroduced into the manufacturing of new turbine blades (Frølich, 2021).
Another collaboration between Veolia and General Electric is managing to recover more than 90% of the weight of the blades. 65% in the form of raw materials that can replace sand and clay, and 28% as an alternative fuel, replacing coal to provide the energy needed for the chemical reaction in the cement kiln. The cement produced in this way has exactly the same properties as traditional cement (Veolia, 2019).

The challenge will be to develop solutions and to inform policy changes to encourage repurposing, which is further up the waste hierarchy than co-processing, as a more sustainable second life option to manage the forecasted tonnes of blade waste (Nagle et al., 2020). Blade pieces can be reused directly, for example, blade FRP panels as building facades, albeit this is currently more of a display solution. To make this a realistic solution, more effort is required through design considerations (Ierides & Reiland, 2022).

Mello et al. apply life cycle assessment to wind energy to evaluate the sector's environmental and economic sustainability. Although cleaner than other energy sources, when the entire life cycle of wind turbines is considered, there remain negative environmental impacts with greenhouse gas emissions produced in the manufacturing and decommissioning of blades. The authors highlight important issues including waste management, applied technology, legislation, environmental protection, and human health regulations, as well as the benefits and drawbacks of wind farm investment. They suggest improvements in logistics, more efficient equipment production, and research in new materials and innovative building techniques. Regarding decommissioned blades, they advise reuse and recycling to reduce both the extraction of raw materials and the total consumption of resources (Mello et al., 2020).

4.1.2 Possible Mitigation Pathways

Improving the sustainability of waste management is a key policy priority for the European Union (EU), which has established a legal framework for waste treatment with the Directive 2008/98/EC and with its 2018 amendment, the principles of circular economy were introduced.

The framework is designed to protect the environment and human health by emphasising the importance of proper waste management, recycling, and resource recovery. Its main key areas are support sustainable production and consumption models; to encourage the design, manufacturing and use of products that are resource efficient, durable, reparable, reusable and capable of being upgraded; to target products containing critical raw materials to prevent those materials becoming waste; to encourage the availability of spare parts, instruction manuals, technical information, or other means enabling the repair and re-use of products without compromising their quality and safety; to reduce food-waste generation; to promote the reduction of the content of hazardous substances in materials and products; and to stop the generation of marine litter (European Commission, 2018).

In addition, the Directive endorses the waste hierarchy, where preventing waste is the preferred option, and disposing waste of in landfills should be the last choice, as illustrated in Figure 10 below.

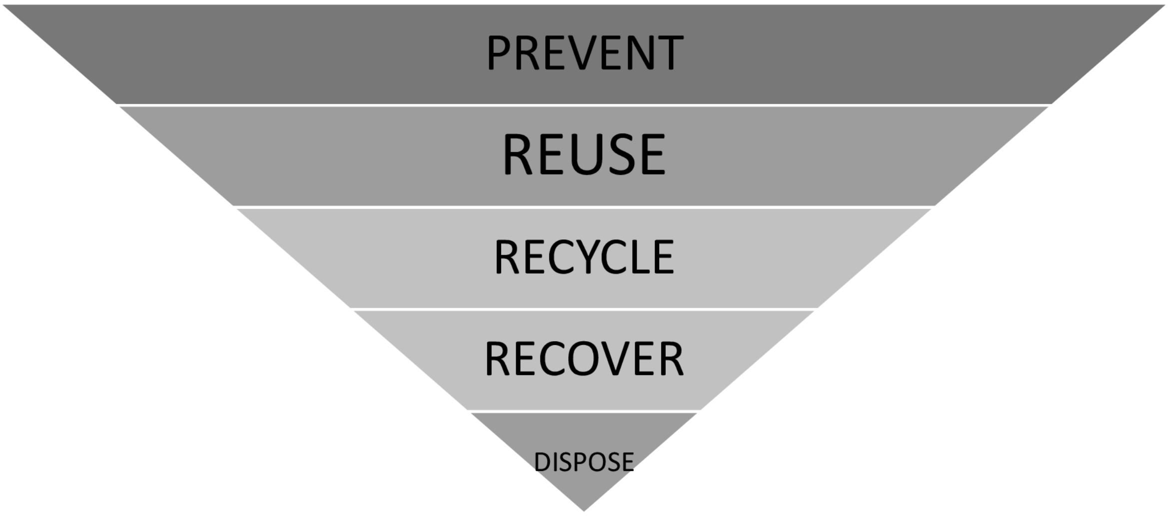

Figure 10: Waste Hierarchy in the Waste Framework Directive

Analysing the existing scientific literature, it become apparent that are multiple solutions for tackling the problem of EoL related waste. Most of them have not reached market maturity but they have exhibited the potential to improve circularity. In order to align research and policy focus with circular economy thinking, we must foster the design of future products with sustainable end-of-life recycling processes in mind (Korniejenko et al., 2021). A holistic approach is called for, one that encompasses all processes in the life cycle of wind turbine blades, key to a circular economy and life cycle engineering. Strategies include using fewer resources with accompanying reductions in cost and environmental burden, designing longer-lasting goods and extending product life via repair, as well as recycling (Beauson et al., 2022).

Below a set of mitigation pathways are presented, all looked through the lens of circular economy.

The Circular Economy (CE) model is a systematic approach to economic development that can benefit business, society, and the environment. CE can be explained as an economic model with the main aim of resource efficiency through long-term value creation, waste minimization, and reduction of closed-loop products considering environmental protection (Morseletto, 2020). According to Ellen MacArthur Foundation, the circular economy is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. A move to renewable energy and materials underpins the CE, while economic activity is decoupled from the consumption of finite resources. We are talking therefore for a resilient system that benefits businesses, people, and the environment (Ellen MacArthur Foundation, 2021).

The model of circular economy includes the elimination of waste and careful design of the products, the differentiation of the consumable from the durable parts of a product, the replacement of the term consumer with that of user, and the use of renewable energy. Elimination of waste is succeeding by disassembling or reusing. Methods like disposal of waste or recycling are considered energy and labour consuming. Durable parts of a product are designed to be used again or be upgraded. Consumable parts are made of organic, non-polluting material and they can safely be returned to nature. The products will be leased, rented, or be given to the users. In case they are sold, the user will be responsible for their return after their end-of-life. The energy used for this economic model is always renewable (Ellen MacArthur Foundation, 2021).

Implementing material efficiency in the life cycle of a wind turbine can help the transition towards sustainable wind energy under the circular economy model. Material efficiency describes the ratio between material input and output, and due to production losses, inputs are usually larger than outputs. Meaning in our case, that to produce a 300-tonnes turbine requires more than 300 tonnes of materials. Achieving material efficiency helps reduce the need for materials and waste quantities due to fewer losses. In order to reduce material losses, it is essential to design material-efficient products, for example, lightweight products. In addition, design with the aim to decrease the need for maintenance and increase the easiness of reuse and recycling. Minimizing waste quantities during production processes, for example, with the help of new processes or the best available technology, is also an integral part of this process. Increase life cycle performance through designing products that are easier to repair, upgrade or remanufacture and last but not least, material substitution for more sustainable ones (Cramer, 2013; Sánchez et al., 2014).

Having studied and evaluated all the available methods in the literature, it becomes clear that two methods comply with the sustainability values and have the potential to be further developed in business cases: the co-processing in cement kilns and urban regeneration projects. Those two solutions have been discussed and analysed in the article ‘Wind turbine blade waste circularity coupled with urban regeneration: A Conceptual Framework’ published by the author of this thesis Spyridoula Karavida and another researcher, Angeliki Peponi, in the journal Energies and is included here after the kind permission of the editor.

Wind Turbine Blade Waste Circularity Coupled with Urban Regeneration: A Conceptual Framework

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Energies **2023**, *16*(3), 1464; **https://doi.org/10.3390/en16031464**

Received: 31 December 2022 / Revised: 25 January 2023 / Accepted: 30 January 2023 / Published: 2 February 2023

Abstract

With the vast majority of scientists agreeing that the only hope in mitigating the adverse effects of climate change is to drop our carbon emissions to net zero by 2050, the decarbonization of the electricity sector is an environmental emergency. Wind energy can be a leader in the energy transition to a carbon emission-free economy. However, the wind energy transition must be carefully implemented to mitigate the economic, environmental, and social consequences of this change. Blade waste from end-of-life wind turbines is the Achilles' heel of this energy transition and the main impediment to its full acceptance. Aiming to support efficient blade waste management and therefore to ensure sustainable wind energy transition, we conduct a two-fold methodology. In the first part, we propose a novel conceptual framework of upcycling and downcycling end-of-life solutions in an urban regeneration setting. In the second part, we use the case study method to illustrate the aspects of our conceptual framework by analyzing real life case studies. This study suggests that end-of-life blades are used in the cement coprocessing of waste and in architectural projects under urban regeneration transformation processes, closing the material loop according to the circular economy and sustainability principles.

Keywords:
wind turbine blades; **urban regeneration**; **circular economy**; **waste management**; **energy transition**

1. Introduction

Recognizing the necessity for an effective and progressive response to climate change's urgent threat, it is vital to maintain global warming within 1.5° above pre-industrial average levels. To hold the average global temperature below this threshold and avoid the devastating impacts on the planet, it is essential to reach net-zero CO_2 emissions globally by 2050 [1]. The EU has committed to net-zero greenhouse gas emissions with the European Green Deal and its commitment to global climate action under the Paris Agreement [2]. During COP27, UN Secretary-General António Guterres said that more needs to be done to drastically reduce emissions now "The world still needs a giant leap on climate ambition [3]".

Given that the energy sector, which traditionally relies on the combustion of fossil fuels, is the largest and primary contributor to global greenhouse gas emissions [4], the decrease of fossil fuels has been the focus of climate policies and regulations. Electricity supply underwent considerable change over the last few years, with renewable sources increasingly gaining ground against fossil fuels [5]. Nevertheless, the aim of zero carbon emissions is far from becoming a reality in the next 30 years. Wind energy is one of the fastest-growing renewable energy sources worldwide. Using wind to generate electricity emits far less GHG in comparison with the use of fossil fuels. In addition, a wind turbine offsets the emissions produced by its manufacture and dismantling within six months of its function and, the resulting emissions represent around 1% of those it will avoid during its useful life in replacing production from coal, gas, or fuel oil power stations [6]. The transition to wind energy systems, except from cutting down on GHG emissions, can also bring socio-economic benefits by creating direct and indirect employment opportunities in manufacturing, installation, maintenance, and monitoring [7].

Nevertheless, wind energy is not developing as fast as it is deemed necessary in order to achieve zero carbon targets by 2050. One of the main reasons is that wind energy must compete with more traditional sectors that use fossil fuels, and some locations may not be windy enough to be cost-competitive. In addition, the societal acceptance of wind turbines is lagging behind their development, as they might cause noise and aesthetic disturbances, and interfere with wildlife. However, the main challenge of the transition to wind energy is to find a sustainable solution to recycle blades from decommissioned wind turbines. Estimations show that there will be 43 million tons of used blades by 2050. Research shows that the end-of-life waste stream will generate more than 2 Mt of global waste annually in 2050 and cumulative blade waste in 2050 will be between 21.4 Mt and 69.4 Mt with the most probable scenario being a waste level of 43.4 Mt [8]. Different projections considering the time of availability of end-of-life wind turbine blades, the geographical location of future end-of-life wind turbine blades, and the material specifications facilitate the future management of blade waste [9].

The outputs of these projections make apparent the need to adopt and adapt a roadmap for a sustainable transition to wind energy including circularity technologies and practices and end-of-life solutions. This study sets the pathway to wind energy transition through a novel conceptualization of solutions that would render end-of-life blade-suitable material for urban regeneration projects, aiming to ensure sustainability. The novelty of this study relies on the coupling of upcycling and downcycling end-of-life solutions with the urban regeneration concept. By illuminating different aspects of our theoretical conceptualization of blade waste circularity coupled with urban regeneration, we analyze and compare real case studies of recycling blade waste projects.

The remainder of this study is organized as follows. In **Section 2** we analyze the current end-of-life options of the blades. **Section 3** constitutes the methodological part of the study wherein **Section 3.1** we analyze, explain, and provide the novel conceptual framework of blade waste management coupled with urban regeneration under the broader concept of the circular economy. By shedding light on the different aspects and dimensions of our conceptual framework, we analyze and compare real-life case studies of recycling blade waste projects in **Section 3.2**. In **Section 4** we then discuss the key points and main challenges for the transition to sustainable wind energy, as well as the main limitations related to the proposed conceptualization's implementation. Lastly, in **Section 5** we present the main conclusions of the study.

2. Background: End-of-Life Blades

Large numbers of the first-generation wind turbines installed in Europe and North America are coming to their end-of-life (EoL). A life expectancy of a wind turbine is 20 years which can be extended to 25, but repowering projects alter their lifetime, and replacing them with newer technologies available on the market alter their life expectancy even more [10].

Wind turbine blades are composite structures, made of a variety of materials with varying qualities. Blades vary depending on the type of blade and the manufacturer but generally, they are manufactured with reinforcement fibers (glass, carbon, aramid, or basalt), polymer matrix (thermosets such as epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics), sandwich core (balsa wood or foams such as polyvinyl chloride and polyethylene terephthalate), coatings (polyethylene and polyurethane), and metals (copper wiring and steel bolts). This combination of fibres and polymers is known as fibre reinforced polymer (FRP) composites and represents the majority of the blades' material composition by weight: 60–70% reinforcing fibers and 30–40% resin [11]. A schematic representation of a blade is shown in **Figure 1** below.

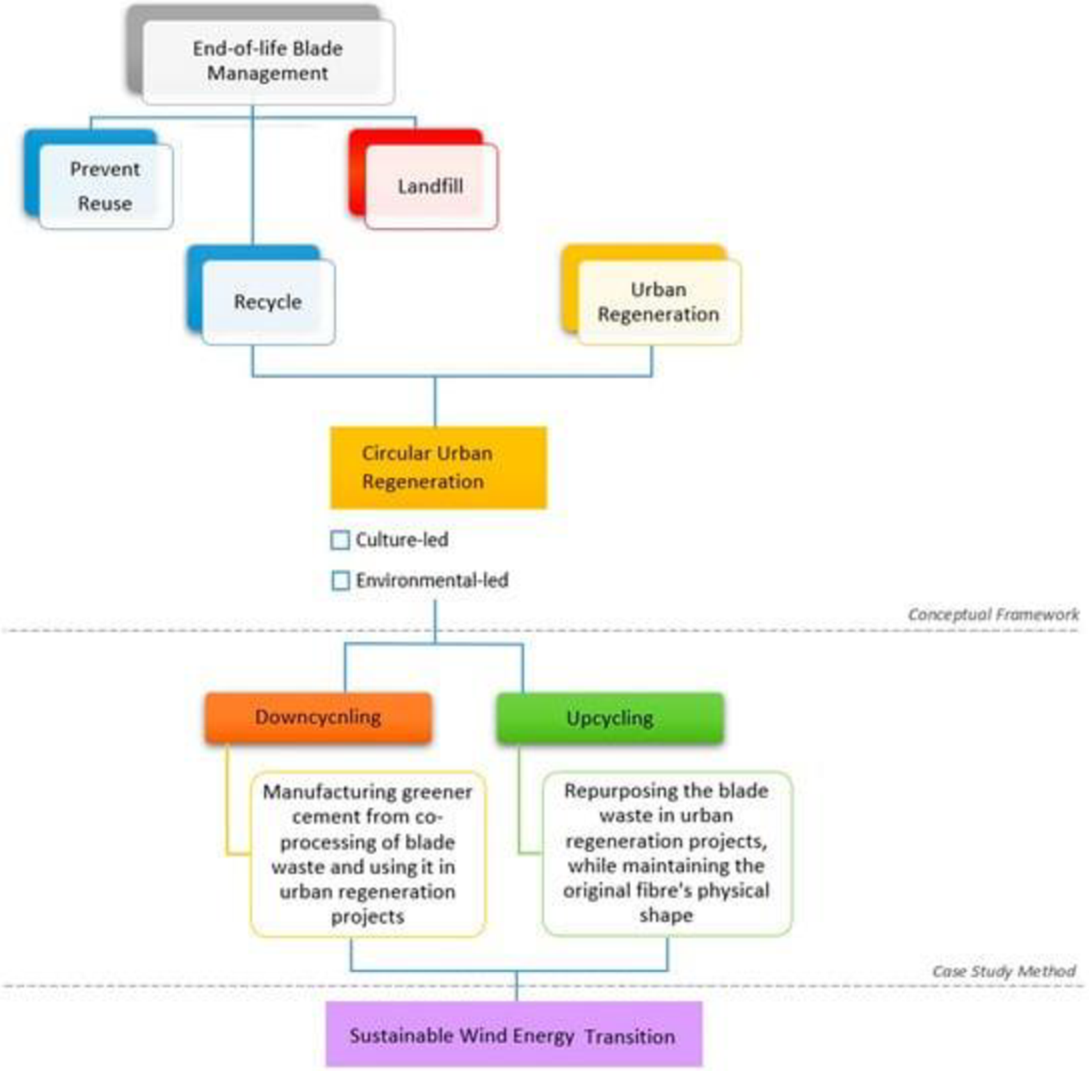

Figure 1. Schematic representation of the methodological framework for end-of-life blade management.

The blades must be detached from the rest of the wind turbine as a first step in decommissioning and cut into smaller sections before being transported for waste treatment. In the waste treatment facility, they are treated depending on their intended EoL application. Currently, the most typical method of dealing with wind blade waste is to discard it in landfills; however, many landfills are saturated and in some countries such as Germany the method has been banned [12]. In addition, material recovery is not possible with this method. The process of pyrolysis can be utilized, where the blades are cut into suitable dimensions and decomposed using conventional heating in an inert atmosphere (450–700 °C). In this way, material recovery is achieved in the form of fibers which can be used as reinforcements (glues, paints, and concrete), and the by-products syngas and char can be combusted for electricity and heat recovery and recycled as fertilizer, respectively [13]. The method of solvolysis and high voltage pulse fragmentation allows the recovery of clean fibers in their full length and the recovery of resin that can be reused. However, it demands high energy due to the high temperature and high pressure involved and the use of large quantities of solvents. In addition, the method has adverse impacts on human health and ecotoxicity [14,15]. Biotechnological methods have also been tested where microorganisms are used to degrade the matrix, but the availability of this method is limited even at a laboratory scale [16]. The same applies to electrochemical solutions, where an electrical current is applied through an electrolyte solution to degrade the composite matrix. Another option is to incinerate the blades at 800 °C for energy recovery, although this has a number of disadvantages, such as the non-flammability of the glass fibres and the large volume of non-combustible by-products. Alternatively, the blades can be burnt in cement kilns and a few businesses in Germany have lately inserted mechanically recycled fibres into concrete, boosting the material's structural integrity [17].

Other newly proposed solutions include using the blades as thermal insulation or noise-canceling screens. Even while mechanical and thermal treatment technologies exist, there is currently no connection to end users, and the low cost of virgin material and landfilling reduces the incentive for recycling [12]. Some of the wind turbines that have been dismantled have been sold to intermediaries who sell them for recommissioning in countries of eastern Europe and north Africa [18]. Last but not least, the practice of repurposing blades into second-life constructions is becoming increasingly common, for example, the Re-Wind Network is exploring civic buildings such as pedestrian bridges and transmission towers, among others [19].

3. Research Method

In this theoretical research, we use a two-fold methodology for wind turbine blade end-of-life management, as shown in **Figure 1**. The first part of the methodology comprises the novel conceptual framework of blade waste circularity coupled with urban regeneration. In our conceptualization, we prove how wind energy transitions can be sustainable through urban regeneration processes stressing the importance of integrating the cultural and the environmental dimension of these transformative processes. For the second part of the methodology, we used the case study method where we analyzed real-life case studies demonstrating the core drivers, the aspects, the dimensions, and the importance of our conceptual framework to the field of sustainable energy transitions. The specific case studies were chosen due to their relevance to our conceptual framework. They were considered excellent examples of projects that demonstrate how the waste of wind turbine blades can be efficiently used in an urban regeneration setting, thus ensuring sustainability.

3.1. Repurposing Wind Turbine Blades Coupled with Urban Regeneration

In the previous section, we demonstrated current methods of disposal of composite materials of wind turbines' blades. The blades' disposal at the landfill at the end-of-their-life still remains the most economically affordable option but at the same time, brings severe environmental pressure and causes energy and material waste. In this section, moving the focus to the management of blades after their end-of-life, we elaborate on repurposing them under the broader context of urban regeneration as an alternative to landfill disposal. Urban regeneration is a tool that includes a wide range of transformation processes placed in urban voids and deprived areas aiming to ensure simultaneously economic, social, and environmental sustainability. However, in most empirical cases, urban regeneration processes have been instrumentalized to attract investments, enhancing the urban area's economic competitiveness without facing the current local urban challenges [20]. In our work, we recognize two main dimensions of equal importance for urban regeneration processes: culture-driven, and environment driven. We argue that through a holistic integration of both dimensions in the planning, design, and implementation of urban regeneration projects, we are able to achieve urban sustainability, tackling current challenges. In the next two paragraphs, we present how culture and environment have been used to support urban regeneration and how we perceive these dimensions. At the end of this section, we theoretically conceptualize how repurposing wind turbine blades through integrated urban regeneration ensures three-dimensional sustainability.

A part of urban regeneration literature has focused on how the cultural dimension plays a critical role in these transformation processes for sustainable urban redevelopment [21,22,23,24]. A study published in 2017 states that cultural urban regeneration processes renew the image of a city and its neighborhoods, foster a sense of belonging in its inhabitants, attract investments and tourism, create jobs in cultural and creative sectors, and improve the quality of life and social cohesion [25]. However, when it comes to the impact of the cultural regeneration processes on the social and human capital, strong critics argue that the current implemented top-down instrumental initiatives lead to relentless gentrification, creating urban areas of consumption [24,26]. In line with multiple comparative analyses found in the literature, we support that culture-led urban regeneration applying mixed top-down/bottom-up initiatives can ensure social efficacy, encouraging community participation in the decision-making processes [22,27,28,29]. In this way, the interests of different stakeholders are communicated and considered in the transformation processes, resulting in urban economic revitalization, and reinforcing the identity of the urban area. Hence, this culture-led regeneration driven by community fulfills the need for place identity and a sense of belonging and, therefore, leads to community coherence and wellbeing.

Analyzing the environmental dimension of urban regeneration, we recognize that priority was given to facing three main challenges related to urban growth: climate change, pollution, and waste. In doing so, scholars have studied urban regeneration consistent with circular economy (CE) principles contributing to sustainable growth [30,31,32]. The concept of CE appears in the literature mostly related to waste management, without fully exploring the circularity of its R-principles (reduction, repair, reuse, recover, remanufacturing, and recycling [33,34]. The Circular Economy (CE) model is a systematic approach to economic development that can benefit businesses, society, and the environment. CE can be explained as an economic model with the main aim of resource efficiency through long-term value creation, waste minimization, and reduction of closed-loop products considering environmental protection [35].

The elimination of waste and thoughtful product design are among the key tenets of the circular economy, as is the separation of a product's consumables from its durable components, the use of renewable energy, and the replacement of the term "consumer" with "user." Disassembly or reuse is successful in eliminating waste. Recycling and waste disposal are regarded as energy- and labor-intensive processes. A product's durable components are built to be upgraded or reused. Consumable parts can be safely disposed of in nature because they are made of organic, non-polluting materials. The users will either be provided with the products, or they will be leased to them. The user will be liable for their return following their end-of-life if they are sold [36].

A recent study overviewed the six main principles of CE and studied the transition to CE business models of several organization typologies of different sizes and economic sectors [37]. Their study points out that recycling is the most preferred practice among the different organizations applied in the entire supply chain. Repair, reuse, and remanufacturing are evolving well, mostly in small companies, and some companies also promote CE culture, moving the focus from recycling to the dissemination of all the principles and practices of the CE concept. The authors found that implementing CE has the potential to achieve more sustainable development at a local and global scale, helping the better direct and indirect use of resources [38]. We support that implementing CE principles through circular urban regeneration processes establishing social, cultural, technological, and ecological synergies increases the resilience of an urban place and therefore ensures its sustainability.

In our theoretical conceptualization for the management of end-of-life wind turbine blades, we adopt an integrated approach to circular urban regeneration using culture-led and environment-led transformation processes. Core drivers of this approach are related to circular economy principles, mainly the primary recycling (upcycling), and the secondary recycling (downcycling) of the blades, as well as to the three-dimensional sustainability (social–economic–environmental). The blade waste is converted into products with equal or higher properties without undergoing any chemical damage through upcycling, while downcycling converts blade waste into products not as structurally strong as the original product and/or with lower quality [34]. Taking advantage of the durability and strength of the blades' composite materials, the recycled products can be used in various urban regeneration projects ensuring sustainability. For instance, projects related to architecture, spatial planning, and design can regenerate an urban place, reducing the projects' ecological footprint, and creating economic opportunities in addition to cultural and social benefits for the local community. In our theoretical conceptualization, we emphasize the circularity of the transformation processes related to this kind of urban regeneration project. The circularity is related not just to the upcycling of the materials per se but also to the coevolutionary synergies among different (transformation) processes and actors. Urban regeneration projects require the involvement of different actors, expertise, and a diversity of approaches to ensure their sustainability. The collaboration between the public and private sectors is essential to provide financial resources and governance structure. Moreover, through this collaboration, a supportive regulatory framework with guidelines and legislation is provided to ensure health and safety and to overpass technical challenges regarding project implementation. Community participation is necessary to ensure that these projects reflect the place's identity and cover the community's needs. In other words, the focus of circularity remains on the reuse, recycling, and recovery of natural resources but also on how to achieve social–cultural–economic prosperity via transformation processes (Table 1).

Table 1. Circular urban regeneration framework for recycling wind blades.

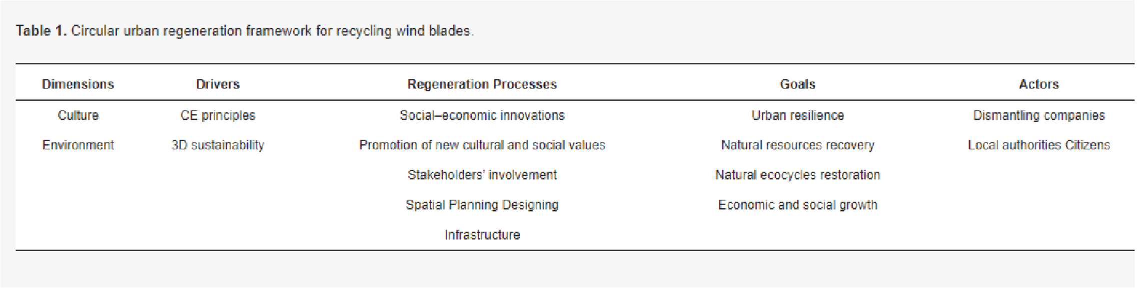

Table 1. Circular urban regeneration framework for recycling wind blades.

Dimensions	Drivers	Regeneration Processes	Goals	Actors
Culture	CE principles	Social–economic innovations	Urban resilience	Dismantling companies
Environment	3D sustainability	Promotion of new cultural and social values	Natural resources recovery	Local authorities Citizens
		Stakeholders' involvement	Natural ecocycles restoration	
		Spatial Planning Designing	Economic and social growth	
		Infrastructure		

3.2. Case Studies

In this section, we analyze and compare real life case studies of recycling blade waste projects, illuminating different aspects of our theoretical conceptualization of circular urban regeneration. By enabling an in-depth examination of these case studies, we investigate how we can maximize the benefits of wind power, capturing the complexity of circular regeneration. The series of case studies under analysis and testing concerns projects of the downcycling and upcycling of decommissioned and dismantled wind turbine blades as an alternative method of landfill disposal, tackling unnecessary waste pollution, and increasing resource efficiency.

3.2.1. Downcycling Wind Turbine Blades

Most of the components of wind turbines are recyclable with a recyclability rate of 85% to 90%, but the blades present a special challenge due to the complex nature of their composite materials. Currently, there are several downcycling technologies for this composite waste including physical, thermal, and chemical processes, and/or combinations of them [38]. Examples of these technologies include mechanical grinding (physical), pyrolysis and gasification (thermal), solvolysis (thermo-chemical), and high voltage pulse fragmentation (electro-mechanical). These different processing methods affect the quality of the fibers and therefore their second-life use. Through physical downcycling methods, long clean fibers, and the general matrix of the polymers cannot be recovered, and the overall material waste is 40%. Thermal processing is not economically viable with short-length recovered fibers out of the market's demand. Chemical processes can recover clean fibers, but these technologies have not been made available in industrial-scale recycling [37,39].

The downcycling method that we analyze in this study, coupled with circular urban regeneration is cement coprocessing, also referred to as the cement kiln route. Traditional cement production consists of three main stages: the initial raw material preparation, then the clinker burning, and lastly the cement preparation [40]. The raw materials, mostly sand, clay, and limestone, are crushed, homogenized, and placed into a rotary kiln. The produced clinker is burnt at a material temperature of 1450 °C forming new compounds. The cement preparation takes place in a grinding mill where gypsum and other additional material (blast furnace slag, coal fly ash, natural pozzolans, limestones, etc.) are added to the clinker and ground to a fine and homogeneous powder: the cement [41]. During coprocessing, shredded wind turbine blades are used as new materials in cement production, partially substituting fossil fuel and raw material dependency. Specifically, the glass fiber is recycled as a component material of cement clinker and the polymer matrix is burned as fuel (refuse-derived fuel) for cement production. The cement kiln route is considered the optimum way for blade waste recycling providing material and energy recovery; it has a simple supply chain and is cost-effective and efficient [39,41].

The process begins onsite with the dismantling of the wind turbine, where the blades are cut into sections of 10–12 meters with a mobile saw, mainly used in the mining and cement industry, a cable with diamond inserts, and a water mist. The sections are then transported to the reprocessing facility where they are cut into even smaller sections that are fed into a crusher that reduces the size to 50 cm. A shredder then reduces them even further and a hammer mill gives them their final shape before they are mixed with other wet waste to ensure that the fiberglass will be bound properly. The mixture is then added to Solid Recovered Fuel (SRF), an alternative fuel derived from mixed dry waste that is too difficult to separate and would otherwise end up in landfills. SRF is employed as a fossil fuel alternative in the cement and power industries across Europe [42]. The reprocessed blades are then used in cement production as a substitute fuel, replacing coal ash, and as a raw material, displacing some of its need for raw washed sand. The Holcim Lägerdorf cement industry in Northern Germany is currently the sole industry processing blade material on an industrial scale in Europe.

The greener cement produced by repurposing blade waste can be used for various urban regeneration projects adopting circular economy principles. Cement is the binder substance to form concrete which is used as the most common construction material in the urbanized world. Under our holistic theoretical conceptualization of urban regeneration transformations, the production and use of the greener cement and, therefore concrete, creates new business opportunities; safe and affordable housing; workplaces; industrial sites; transportation systems; and infrastructure for sanitation, energy, water, and telecommunication among other life-supporting and wellbeing structures that are commonly made having as base concrete. Replacing traditional cement with green and engaging all stakeholders during the whole design, implementation, and management of the regeneration projects offers essential opportunities for improving the sustainability of the urban space. Starting with the environmental benefits, we achieve CO_2 emission savings over the overall life of cement, optimizing its use and maximizing the life of the buildings and infrastructure, resulting in resource salvation, and reducing atmospheric pollution. Improving the service life of those urban regeneration projects, apart from environmental benefits, offers cultural benefits, including social and economic ones. The overall costs of construction, use, and maintenance of the projects are more effective while being energy efficient by reducing the emissions to the environment and improving the energy efficiency regarding cooling and heating costs. Therefore, indirectly the replacement of regular cement with cement produced from wind turbine waste positively influences the quality of life and wellbeing of the users of the regeneration projects.

3.2.2. Upcycling Wind Turbine Blades

Another way to tackle the challenges of wind turbine blade waste is to upcycle them and use them in urban regeneration projects. Repurposing the blades instead of completely deconstructing them via downcycling methods is a less costly option, producing fewer emissions and dust while maintaining the original fiber's physical shape. Various projects such as the Re-Wind project, companies such as Anmet, and architecture firms, such as Superuse studios, in collaboration with institutes and universities, have been working on repurposing discarded wind turbine blades, thus giving them a second life. The suggested/applied end-of-life solutions offer environmental, social, and economic benefits within the circular economy paradigm.

The Re-Wind project is a collaboration between the Georgia Institute of Technology, US; the Queen's University Belfast, UK; the City University of New York, US; and the University College Cork, IE. Their focus is on sustainable end-of-life strategies for composite material wind turbine blades using data-driven structural modeling coupling geographical information science with environmental, economic, and social Life–Cycle Sustainability Assessments (LCSA) [19,42]. Team members of the Re-Wind project have focused on wind turbine blade reuse options and designed an 8.5 m pedestrian bridge using two A29 wind blades (a modified version of the model from Vestas V27) as girders and proved that the conceptual design fulfills the strength criteria and the recommended Eurocodes serviceability requirements (see **Figure A1** in the **Appendix A**) [43].

A recent study designed a blade bridge for deployment on greenways scheduled for installation, repair, or bridge or culvert replacement on the Midleton-Youghal Greenway in Cork 2021, Ireland (see **Figure A2** in the **Appendix A**) [44]. The bridge will be used for foot passengers and cycling. In case of emergencies, it can support a vehicle of up to 10 t. Greenway blade bridges provide benefits to the environment, society, and the economy by substituting recycled steel for new steel in structural applications, promoting ecotourism and sustainable transportation, and maybe boosting local businesses in blade remanufacturing [44].

The authors of a recently published study are repurposing a portion of a decommissioned Clipper C96 wind turbine blade as a tangent pole with 230 kV capacity in a power transmission line application (see **Figure A3** in the **Appendix A**) [45]. However, dead-end blade poles and corner blade poles are also possible to design. Fibre-reinforced polymer (FRP) poles are expected to last longer than conventional steel, concrete, or timber poles. The authors have tested the structural analyses for different load cases: extreme wind, concurrent ice, and wind; extreme ice, differential ice, broken conductor, and broken shield; and governing load cases for bending, shear, and torsion. The results showed that the blade pole can resist the expected loads with reasonable safety factors and that the expected deflections are within permissible limits [46].

A study published in 2018 [45] discusses conceptual architectural and structural options for repurposing parts from wind turbine blades in new or retrofitted housing projects where harsh environmental conditions exist. Particularly, they studied how large-sized FRP pieces from a decommissioned SNL-100-01 wind blade can be used in affordable housing in coastal regions of the Yucatan province in Mexico on the Gulf of Mexico, where low-quality masonry block housing is vulnerable to severe hurricanes and flooding (see **Figure A4** in the **Appendix A**).

A bike shed made of decommissioned wind turbine blades was implemented by the wind turbine manufacturer Siemens Gamesa in collaboration with the Re-Wind project in Denmark (see **Figure A5** in the **Appendix A**). Denmark has the highest share of wind in the electricity mix globally and is in a leading position in the wind turbine industry, with high technological capability and a significant competitive advantage [47]. Simple repurposing of wind turbine blade projects as such in a country with an important share in wind energy constitutes a paradigm change, applying the principles of circular economy and urban regeneration.

Similarly, in the Netherlands where 200 blades are sent to landfills every year, in 2009 Superuse studios designed a blade-made playground named Wikado covering a 1200 m^2 area for the foundation Kinderparadijs Meidoorn in Rotterdam. The old playground required renovation. Superuse studios selected elements that could be reused in the new playground and used five decommissioned rotor blades placed around an existing concrete slab, thereby creating a maze-like space. The base of the blades has been used as four towers, and cut-off parts are spread around the garden connecting the towers (see **Figure A6** in the **Appendix A**). By reusing elements, carbon emissions are reduced up to roughly 90% compared to a conventional playground. At the same time, the abstract shape of the blades allows children to freely imagine where and what they play [48]. Another blade-made project from the same studio is a piece of urban seating furniture placed in Willemsplein square in Rotterdam. It is made using nine blades held by recycled concrete rubble blocks. The blades were initially painted red to give a little more color to the grey surroundings of the area, but in 2020 it was redesigned as a temporary LGBTQI+ monument painted in the rainbow flag colors (see **Figure A7** in the **Appendix A**).

In the municipality of Terneuzen, in the southwestern Netherlands on a small beach next to the harbor, Superuse studios constructed another iconic playground using two blades composited to look like a submarine in 2016. The location of the playground is flood-sensitive and turns from time to time into a swamp-like landscape. The studio took advantage of the durability of the blades to address the high demands of the topography of the area. In the East Pier Terneuzen in 2018, Superuse studios made seating furniture with the blades following the positive response from the residents on the submarine blade-made playground in the same municipality (see **Figure A8** in the **Appendix A**) [48].

In the same line, companies such as Anmet in Poland use blades as load-bearing structural supports for pedestrian bridges and for the strengthening of embankments and landslides (see **Figure A9** in the **Appendix A**). They construct blade-made animal passages, mole poles, and small size structures as lamps, sun loungers, and benches among others (see **Figure A10** and **Figure A11** in the **Appendix A**) [49].

The previous paragraphs described various conceptual and applied end-of-life solutions for upcycling blade waste, from small structures such as urban public furniture, to an entire community of blade-made affordable houses. These projects offer circular urban regeneration solutions for sustainable urban growth and resilience. In addition to the environmental benefits related to natural resource efficiency and the reduction of non-biodegradable waste pollution, upcycling blade waste offers social and economic benefits within the circular economy paradigm. Including blade made projects in the transformation processes for the regeneration of critical urban places benefits the local communities in various ways. Taking the conceptual design of affordable houses as an example, it can benefit local inhabitants that live under poor quality housing conditions such as refugees, homeless people, people living in favelas, and populations affected by natural disasters (earthquakes and hurricanes) by improving their living conditions and wellbeing. Smaller structures such as the seating furniture in Willemsplein, Rotterdam, offer a medium for people to rest and socialize but at the same time they can be symbolic and political, enhancing the identity of the urban place. The circularity of these projects in the design process connects the different stakeholders, the wind industry, the wind farm owners, the blade designers, the governments, and the communities. Communities can get involved with social enterprises that remanufacture blade waste supported by the wind industry and enhancement of the local economy by governments. Re-using blades can benefit local communities and offer the prospect of greater acceptance of wind turbines, while addressing wider societal goals linked to the decarbonization of energy systems: change demands an imaginative response [19].

4. Discussion

The transition from fossil-based energy to wind energy can be social, economic, and environmentally beneficial when meeting sustainability principles. To do so, the circular economy model is applied in our conceptualization for end-of-life wind blades solutions coupled with the urban regeneration concept.

End-of-life wind blade solutions coupled with circular urban regeneration ensure the sustainable transition to wind energy, preventing waste and offering economic and environmental benefits. Limitations of this transition can be the lack of legislation that permits the synergies between different actors and sectors along the life cycle of the wind turbine, the lack of modernized network infrastructure that reduces transmission losses, and limitations of the existing recycling technologies such as the limitation of co-processing to maintain the glass fiber shape during the process [50]. Legislation at a global scale that focuses on increasing the recycling rate and resource efficiency is required, as well as investments in research and innovation to develop alternative recycling technologies which produce higher-value recyclates but also high-performance new composites with enhanced circularity [39].

The existing European legislation on waste emphasizes a circular economy. For instance, the Waste Framework Directive is the cornerstone of EU waste policies and establishes a hierarchy in the approaches to waste management that prioritizes the prevention of waste, followed by reuse, recycling, recovery, and disposal. To limit the future waste volume and potential effects, waste prevention can be primarily accomplished during the planning and product development phases. The Commission Decision 2000/532/EC creating the European List of Waste, the Waste Incineration Directive (2000/76/EC), and the Landfill Directive (1999/31/EC) are other legal documents defining waste in the EU and are pertinent for wind turbine blade waste. Countries such as the Netherlands and Germany have banned composite materials from landfills and France has prohibited the disposal of waste containing more than 30% plastic. The end-of-life wind turbine blade waste is impacted by this legislation, which is a component of the anti-waste law. In Europe, the price of composite material landfills varies greatly. The price in Denmark is roughly EUR 120 per ton while in Germany, where composite materials are prohibited from being disposed of in landfills, the cost to treat the waste is EUR 300 per ton, and the pieces of the composite should not exceed 22 m in length [9]. Legislation to decrease blade waste and enhance blade waste regeneration circularity should be established to facilitate synergy between sectors and actors at a multiscale level from local to regional and global allowing sustainable wind energy transitions.

Government investment in innovation and research (R and I) could lead to the development of new smart composites with enhanced circularity that should manifest in the extended lifetime of the blade and improve the aging performance, to improve their separation and recyclability at the end-of-use. Implementing material efficiency in the life cycle of a wind turbine can help the transition towards sustainable wind energy under the circular economy model. Due to production losses, inputs are typically greater than outputs, which is referred to as the material efficiency ratio. In this instance, it means that more than 300 tonnes of materials are needed to create a 300-tonne turbine. Achieving material efficiency reduces the number of materials needed because there are fewer losses. It is crucial to develop material-efficient items, such as lightweight products, in order to minimize material losses. Additionally, products are made to be easier to reuse and recycle and to require less maintenance. This procedure also includes minimizing waste output levels, for instance, by utilizing new processes or the most advanced technology. Designing goods that are simpler to maintain, update, or remanufacture, as well as switching out materials for more sustainable options, will improve life cycle performance [47].

5. Conclusions

Blade waste management is a crucial issue and in order for it to be addressed, circularity must be integrated into the entire value chain from the design stage of next-generation blades to end-of-life solutions. One limitation of this study is that it only addresses end-of-life-related waste and does not take into consideration the waste generated during the manufacturing stage. Furthermore, in this study, we do not consider the cost and the business feasibility of the suggested solutions. Therefore, by focusing on end-of-life blade waste management we provide a novel conceptual framework driven by circular economy and three-dimensional sustainability principles. Specifically, what makes this study pivotal is the coupling of upcycling by repurposing the blade waste and downcycling the blade waste in green cement as part of urban regeneration projects. The main findings of this study indicate that the circularity of the blades does not require a universal approach. Depending on the amount of waste generated in each location and time span, different approaches can be employed. Through the analysis of real-life case studies, we demonstrate how our approach facilitates the circularity of the composite material and at the same time ensures three-dimensional sustainability enabling culture- and environment-transformation processes in an urban context. By coupling blade waste circularity with urban regeneration, an industrial symbiosis scheme could be sustained, where the waste of wind energy could be used on a greater scale as a raw material in the manufacturing sector, closing the loop of the blades and creating an exemplary circular economy community. Simultaneously, it engages a cost-saving policy creating new business and economic opportunities (e.g., new goods and services, job offers) meeting the sustainable development goal seven ("Ensure access to affordable, reliable, sustainable, and modern energy for all"). This study provides a conceptual framework and insights for its implementation in urban planning and design as an alternative to tackle the negative consequences of the current insufficient management of blade waste. By preventing waste and increasing resource-efficient solutions, this study contributes to the wind energy sustainable transition.

Directions for future work would be the life cycle assessment of urban regeneration projects related to upcycling and downcycling of blade waste. Considering that in this study we took into consideration only the end-of-life stage, we suggest that future research examines the entire life cycle, from the design phase and then from cradle to grave. That way, by employing eco-design techniques, part of the waste can be phased out during the design phase, rendering the end-of-life waste easier to handle.

Author Contributions

Conceptualization, S.K. and A.P.; methodology, S.K. and A.P.; resources, S.K. and A.P.; writing—original draft preparation, S.K. and A.P.; writing—review and editing, S.K. and A.P.; project administration, S.K. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

Not applicable.

Acknowledgments

A. Peponi is currently supported by a postdoctoral research scholarship under the project: mainstreaming ecological restoration of freshwater-related ecosystems in a landscape context. Innovation, upscaling, and transformation (101036337—MERLIN—H2020-LC-GD-2020). The Forest Research Centre (CEF) is a research unit funded by FCT(UIDB/00239/2020). The Associate Laboratory TERRA (LA/P/0092/2020) is also funded by FCT.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

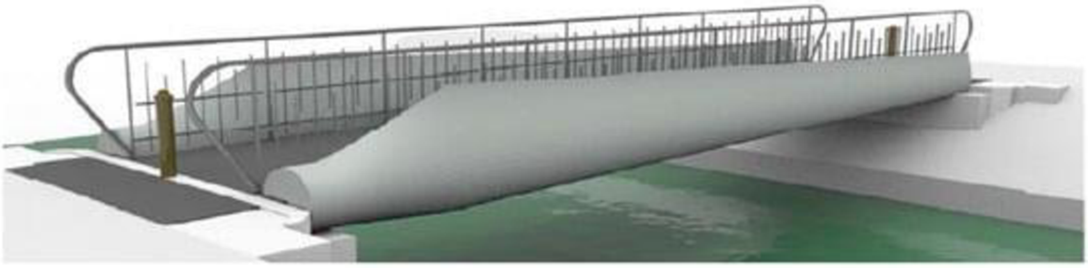

Figure A1. A conceptual design of a pedestrian bridge using part of A26 wind blades [44].

Figure A2. An existing structure on a greenway route at Roxborough, Midleton, Cork. A conceptual design of a blade bridge at the same location [44].

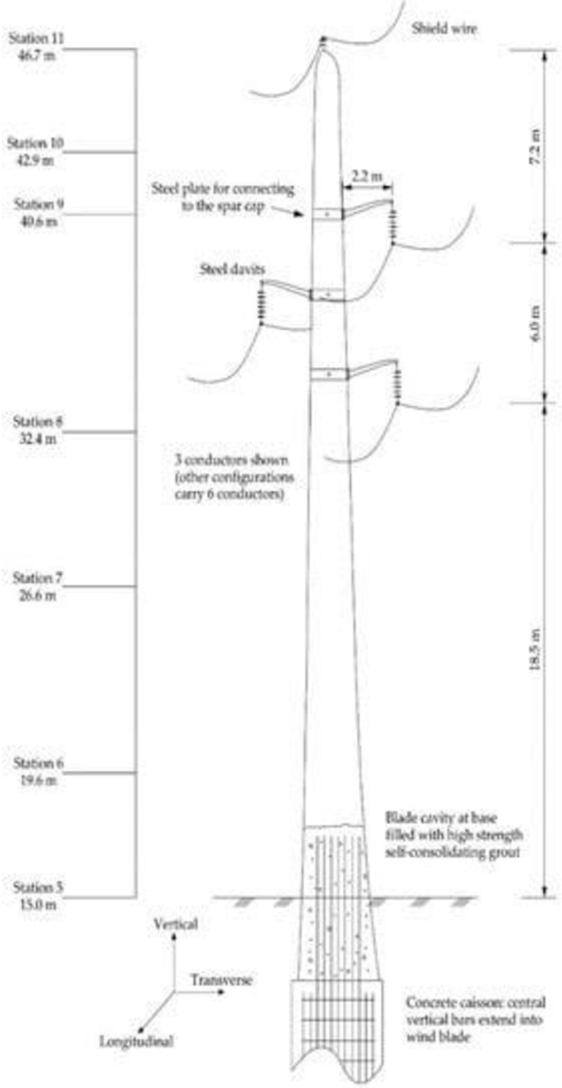

Figure A3. A clipper C96 blade configured as a tangent pole application [42].

Figure A4. A conceptual housing community made of wind turbine blade waste [46].

Figure A5. A bike shed in Denmark made from EoL blades [51].

Figure A6. Wikado playground [48].

Figure A7. Blade urban seating furniture ReWind at Willemsplein, Rotterdam, © Denis Guzzo 2012 [48].

Figure A8. A blade-made playground and seating furniture in Terneuzen [48].

Figure A9. Blade-made load-bearing structural supports for pedestrian bridges [49].

Figure A10. Blade-made sun loungers [49].

Figure A11. A blade-made bench [49].

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4.2 Ecological Barriers

4.2.1 Adverse Impacts of Wind Farms on Wildlife

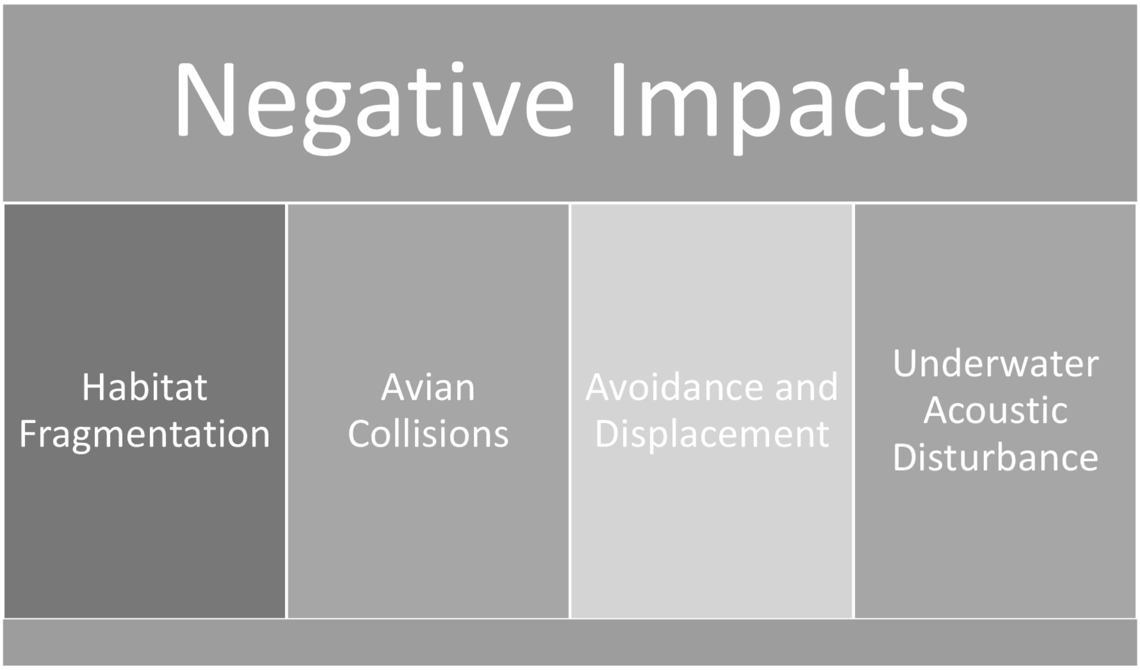
The negative effects of wind energy development on biodiversity have been the subject of an intense debate known as part of the 'green–green dilemma'. This umbrella term is used to describe two desirable goals with unfavourable counter-effects. In the case of wind energy, it implies that even though wind energy is needed to cut greenhouse gas emissions, it may pose a new threat to endangered animals, whose protection could impede the sector's growth.

The promotion and growth of wind energy production on a global scale is a contentious issue. While wind turbines promise to cut CO2 emissions and so help to address the global climate crisis, their persistent negative impact on animals has emerged as an important biodiversity issue. In this scenario, it is vital that both climate change and the biodiversity catastrophe are recognized as two of the century's key challenges, and that each of these pressing issues is recognized as a wicked problem. Wicked problems are characterized as "*ill-defined problems that are too difficult to be handled using logical systematic approaches*." ((Rittel & Webber, 1973), as cited in (Straka et al., 2020)). Many wicked problems are multicausal, which means there is no single, unambiguous answer and stakeholders may have competing solutions, each affected heavily, but not completely, by the stakeholders' separate background information (Straka et al., 2020).

Environmental assessments are required as part of the permitting and approval processes in the European Union (Pagh 2022, personal communication). The laws explicitly recognize the accumulation through space and time of human actions that degrade the environment; that an attempt to ameliorate combined adverse effects of those actions should be made; and that mitigation measures may be necessary when effects are unavoidable. As a result, decision-makers must evaluate the cumulative effects of anthropogenic acts on the environment, as well as viable alternatives to those actions (Wing Goodale et al., 2019). There is vast evidence that wind farm installations harm directly avian species through collisions, but also habitat fragmentation, disturbance, avoidance, and displacement. However, there is little research for terrestrial wildlife. Animals living near wind turbines may be harmed by noise from operating turbines, which can interrupt animal vocal communication or hinder the animals' ability to detect approaching predators. Species that use warning noises, such as deer, may be harmed. Other vocalizations, such as those used to create a territory, attract partners, or keep the group together, may also be muffled or disrupted (Helldin et al., 2012). With the introduction of offshore wind farm installations, new concerts have risen. Concerns about potential wildlife impacts are based on inferences drawn from impacts documented at wind farms in northern Europe and other offshore development activities, the latter of which informs questions about potential impacts on sea turtles and large cetaceans, which are underrepresented in studies at European offshore wind farms Lockhart et al., 2012).

Wind farms can have the side-effect of reducing, fragmenting, and degrading natural habitats for flora and fauna and in addition spinning turbine blades can pose a threat to flying wildlife like bats and birds, especially those of prey that depend on suitable wind conditions, just as the wind turbines. The potential for wind turbines to harm wild animals both directly, through collisions, and indirectly, through noise pollution, habitat loss, and reduced survival or reproduction, is a major concern for the business.

Table 1: Negative Impacts of Wind Farms on Wildlife



Habitat fragmentation

Wind energy installations can cover thousands of square metres, although the land affected by project-related buildings, such as access roads and turbine pads, accounts for only a small portion of that total. With each project, terrain, and type, the number of negative impacts from land alteration and the spatial scope of amenities will vary. Wind energy projects established on previously undeveloped terrain may have a higher impact than those built on ground that has been altered by human activity. When compared to facilities located in wooded regions, facilities erected in agricultural lands can take advantage of existing road networks and consume around one-sixth of the available land per MW (Diffendorfer et al., 2019). The overall amount of land converted by the construction of a wind energy plant ranges from 1000m^2 to 43000m^2 to per MW of installed capacity, which can account for 5% to 10% of the entire project area. Some land transformations are only temporary, such as burying cables or constructing staging zones. These regions that have been disrupted can be restored or may rebound on their own. Roads and turbine pads, which account for around 40% of the altered land area, are permanent throughout the station's life, but they may theoretically be restored when the plant is decommissioned (Diffendorfer & Compton, 2014).

Land transformation linked with the construction of a wind energy facility may result in the loss or fragmentation of habitat for one or more species. The loss and division of habitat into smaller portions is known as habitat fragmentation. Individuals in the remaining habitat segments may have a lower chance of surviving, reproducing, spreading, or using the region. Human activity is increased throughout the construction, operation, and maintenance of a wind energy installation, which may disrupt sensitive species and cause displacement from otherwise suitable habitat. Movement or migration patterns may be disrupted as a result of the operation of a wind energy installation. The

development and operation of a wind energy project may have varying consequences on predators, prey, and competing species, impacting ecological interactions between species (Thaxter, 2017).
Many of the research available have focused on grassland and shrubland birds, whose numbers are already dropping as a result of large-scale habitat modification for agriculture, range management, or other sorts of energy production. Species-specific responses are regularly seen in this research. For example, a 10-year study of nine grassland songbird species at three wind energy facilities in North and South Dakota, USA found that seven of them dropped, but the effects didn't show up until a few years after the facilities were built. Two species either had no effect or had a transient rise in abundance as a result of the experiment. The three wind energy plants did not show a consistent pattern of negative and positive effects (Shaffer & Buhl, 2016).

Schöll and Nopp-Mayr explored the effects of wind farms on wildlife in shrubland and woodland areas in Europe and North America. A systematic literature review determined that the construction, operation, and maintenance of wind power plants affect wildlife in terms of collision mortality, seasonal migration patterns, changed anti-predator behaviour, habitat use, abundance or absence of species, as well as biodiversity. With the wind energy sector growing and encroaching beyond open landscapes into shrublands and woodlands, the increased levels of noise emission, vibration, shadowing, presence of flickering warning lights, and enhanced human presence will have as yet unmeasured impacts in these landscapes. The authors advise additional studies in order to fill knowledge gaps and better support conservation needs, management options, and planning decisions including the effectiveness of mitigation measures and the micro-siting of wind farms (Schöll & Nopp-Mayr, 2021).

Avian collisions

There have been 300 species of birds killed in collisions with wind turbines in the United States for which data is available. Small passerines like the horned lark and red-eyed vireo account for the majority of the fatalities (about 57%). Diurnal raptors account for roughly 9% of all fatalities, and these rates are higher in the western United States, where these species are more common. Water bird and waterfowl fatalities at land-based wind energy plants have been rare to date (e.g., ducks, gulls and terns, shorebirds, loons, grebes, and others) (Erickson et al., 2014). Differences in the number of fatalities recorded between species should be treated with caution. During fatality searches, raptor carcasses, as well as large birds in general, are more likely to be discovered than smaller birds (Allison et al., 2019). Birds collide in large numbers with tall, fixed objects such as communication towers and skyscrapers, especially night-migrating songbirds. Lighting is suggested to be a factor in luring migrating birds to communications towers and buildings, especially during periods of low visibility. The illumination currently allowed by the Federal Aviation Administration and commonly utilized at wind turbines, on the other hand, does not appear to be a contributing factor in bird deaths (Allison et al., 2019; Calvert et al., 2013).

Although the relative importance of these elements for determining collision risk of different species is poorly known, it appears likely that a bird species' abundance and behavioural features influence its risk of collision. For raptors, abundance may be one of the most important indicators of collisions, and raptors appear to be among the most sensitive to collisions as a group. Crows and ravens, on the other hand, are among the most common birds sighted flying inside the rotor-swept region of wind turbines, yet they are only occasionally found during fatality surveys. Collision risk may also be influenced by landscape elements such as woodlots, wetlands, and particular landforms. These characteristics, for example, influence raptor abundance by concentrating prey or generating suitable breeding, feeding, and flying conditions. While landscape factors may influence the number of other bird species, no significant link has been shown between bird abundance and bird mortality in the majority of other bird species (Strickland et al., 2011). Northern gannets (Morus bassanus) have been identified as one of the most vulnerable species when it comes to collisions with offshore wind farm turbines (OWF) (Peschko et al., 2021).

Increases in turbine height and rotor-swept area are predicted to boost wind turbine power generation capacity and efficiency, allowing wind energy to expand to areas of the country where there is now minimal wind energy development. According to radar research, 90% of night-time bird migrants fly over the current rotor-swept zone of turbines (140 m) in most operational wind energy plants. There have been developments in land-based wind turbines that are nearly twice the height of present turbines, reaching higher into the space occupied by nocturnal migratory, raising concerns about increased bird collisions. Technological advancements that enhance turbine height and rotor-swept area are predicted to increase wind turbine power generating capacity and efficiency, allowing wind energy to expand to areas of the country where it is now underutilized. According to radar research, 90% of night-time migratory birds fly over the current rotor-swept zone of turbines in most operational wind energy plants. There have been developments in land-based wind turbines that are nearly twice as tall as present turbines, reaching higher into the space frequented by nocturnal migratory, raising worries about increased bird collisions (Strickland et al., 2011).

Huso et al. investigated the effect of upgrading wind farms on wildlife mortality rates in a study location in California. As the wind energy sector grows, so has the concern for reducing wildlife deaths caused by collisions with rotating turbine blades. Repowering involves replacing smaller, lower capacity, and closely spaced turbines with larger, higher capacity, and more widely spaced ones. The authors found that avian and bat mortality rates were constant per unit of energy produced. Rather than the size, spacing, or rated capacity of turbines, the determining factor on wildlife mortality was the relative amount of energy produced. Consequently, in a given location, newer turbines would be expected to be less harmful to wildlife only if they produced less energy than the older models, they replaced (Huso et al., 2021).

According to EUROBATS, the secretariat for the Agreement on the Conservation of Populations of European Bats, there were 6429 documented bat kills of 27 species collected at wind facilities in Europe from 2003 to 2014 (Rodrigues et al., 2014).
Arnett et al. argue that wind turbines kill bats all around the world, and the deaths aren't limited to migratory species at high latitudes. Regardless of continent, habitat, migratory patterns, or roost preferences, bats that regularly move and eat in less congested and more open airspace are most vulnerable to collisions with wind turbines (Arnett et al., 2015).

Twenty-two of the 47 species of bats found in the continental USA have been recorded as fatalities at wind energy plants in the United States. In available mortality monitoring studies at USA wind facilities, three migratory tree-roosting species (hoary bat, eastern red bat, and silver-haired bat) account for roughly 72 percent of the reported fatalities.

The species composition of bat fatalities varies by region and depends on the bat species present. The Mexican free-tailed bat, for example, can account for 50% or more of bat carcasses found at facilities that overlap this species' territory in the southwestern United States. When compared to wind energy facilities in other parts of the country, some wind energy facilities in the upper Midwest have had a disproportionately high number of cave-hibernating bat mortality (e.g., big brown bat and small brown bat). Bat fatalities have been found to peak in late summer and early fall, corresponding with tree roosting bats' migratory and mating season, and a lesser surge in mortality has been seen during spring migration (Allison et al., 2019).

Many hypotheses have been presented as to why bats, particularly migratory tree roosting bats, are killed in significant numbers at wind generating plants in certain parts of the United States. Some of these hypotheses propose that bats are drawn to turbines by the sounds made by whirling turbine blades, the possibility of insect concentrations around turbines, or bat mating behaviour. Bats have been seen examining the nacelles, towers, and blades of wind turbines from the leeward direction, especially at low wind speeds, according to infrared photography (Cryan et al., 2014).

It's been suggested that some bat species mistake wind turbines for trees and are drawn to them for roosting, foraging, or mating. Large percentages of mating-ready male hoary, eastern red, and silver-haired bats were detected in bat carcasses beneath turbines, demonstrating that sexual readiness coincided with high levels of deaths in these species. Bats seldom crash with stationary man-made structures, and no fatalities have been reported at wind turbines or meteorological towers. Although there is a positive association between bat fatalities and tower height, there have been few large-scale examinations of this relationship (Cryan et al., 2014). Forest gaps and edges have more bat acoustic activity than the central forest. Wind turbine installation increases the quantity of forest edge and the number of forest gaps, and it's thought that these changes lead to increased bat activity, which could explain why certain projects in forest areas have recorded higher bat mortality. This hypothesis has received little scrutiny. A few studies have been conducted to assess potential habitat consequences on other terrestrial species (Allison et al., 2019).

Kumara et al. (2022), raise conservation concerns with the aid of the collection of data regarding biodiversity, habitat loss, and fatalities due to direct collision. It was found that the collision of birds and bats to wind turbine blades is negligible at 0.26 animals per year. However, the disappearance of birds and mammals on the wind farms is clear. While recognised as an alternative and clean energy source, wind farms transform their locality with an as yet unknown range of environmental consequences. Continued study is vital to inform early decision-making and to manage and mitigate the potential harm of wind turbines on animals (Kumara et al., 2022).

Avoidance and Displacement

A multi-year study comparing higher prairie-chicken responses to the building of a wind energy facility in Kansas, USA to a control site found conflicting results. Between the pre-construction and post-construction periods, female survival increased dramatically in vicinity to the wind energy project, with no detrimental impact on nest site selection or survival. After wind energy development, female greater prairie-chickens expanded their home ranges and avoided locations near wind turbines inside their home ranges (Winder et al., 2014).

In close proximity to wind turbines, the persistence of leks, which are male showing and breeding regions, may also decrease. Female greater sage-grouse used locations farther away from disturbed areas near a wind facility for brood raising and summer habitat use in Wyoming research, but there were no other substantial detrimental effects of wind energy on this species (LeBeau et al., 2017).

Adult females survived at higher rates near turbines, according to long-term studies on Agassiz's desert tortoises at a wind facility near Palm Springs, California, but fewer tortoises were utilizing the area around the facility, implying displacement may not be apparent without nearly 20 years of monitoring (Thaxter, 2017).

Studies in North America have shown that endangered grassland species that prefer visually open biomes, avoid now wind energy installations (Pruett et al., 2009); while relevant studies in Denmark showed a 50% reduction in the percentage of avian passages through the maximum turbine sweep area after construction (Therkildsen et al., 2021). Vertical avoidance was demonstrated in this study, with birds dropping flight frequency by 12% while traveling between turbines at sweep area altitudes, while increasing flight frequencies by a similar proportion above and below sweep area altitudes. Pink-footed Geese Anser brachyrhynchus and other waterbirds have been observed vertically avoiding wind turbines in offshore windfarms, but not onshore, as in this example, which includes mostly local breeding, staging, and wintering avian populations (Therkildsen et al., 2021).

Northern gannets (Morus bassanus) have demonstrated a strong avoidance of OWFs. Within the boundaries of their largest breeding colonies along the European beaches, gannets are increasingly encountering OWFs. In their study based on telemetry data, Peschko et al explored the effects of OWFs situated 23–35 kilometres north of the colony on Helgoland in the southern North Sea on breeding gannets. Over the course of two years, GPS tags were placed on 28 adult gannets mating on Helgoland for several weeks. In both years, the majority of gannets (89%) avoided the OWFs, while 11 percent frequented them when foraging or travelling between the colony and foraging regions. Inside the OWFs, flight heights were near to the rotor-blade zone, especially for those who avoided the OWFs. When inside the OWF, gannets preferred a distance of 250–450 meters from the turbines. According to a point process modelling technique, gannet resource selection in the OWF area was reduced by 21% in 2015 and 37% in 2016 when compared to the surrounding area (outside OWF = up to 15 km from the OWF boundary).

Underwater Acoustic Disturbance

Offshore wind turbines are becoming more common as sources of low-frequency noise underwater. This fact raises concerns about wind farms' overall contribution to the underwater soundscape and potential influence on marine ecosystems. Available measurements of underwater noise from various wind turbines during operation are evaluated in this paper, and it is found that source levels are at least 10–20 dB lower than ship noise in the same frequency band. The distance between the turbines is the most important element in explaining the recorded sound pressure levels from wind turbines, with wind speed and turbine size having smaller effects.

Under very low ambient noise conditions, a simple multi-turbine model shows that cumulative noise levels can be enhanced up to a few kilometres from a wind farm. In contrast, except very close to individual turbines in regions with considerable ambient noise from shipping or high wind speeds, the noise is substantially below ambient levels. Because of the rapid growth in the number and scale of offshore wind farms, the cumulative contribution from the many turbines may be significant and should be considered in assessments for marine spatial planning as well as individual project environmental impact evaluations (P. T. Madsen et al., 2006).

Despite the fact that turbines are now larger, and more measurements are available, the underwater noise generated by individual wind turbines is minimal when compared to the noise radiated by cargo ships. A large wind farm's combined source level is smaller or comparable to that of a huge cargo ship. However, because several turbines within a wind farm (in some cases hundreds) contribute to the soundscape, and because wind farms are occupying more and larger portions of coastal and shelf seas, their combined impact of noise cannot be ignored. Wind turbines can be projected to make a major contribution in places with low natural ambient noise and low levels of ship activity, potentially large enough to cause worry about detrimental effects on fish and marine mammals. Such large-scale cumulative effects should be included in both strategic impact assessments and environmental impact assessments of specific projects in relation with maritime spatial planning (P. T. Madsen et al., 2006; Tougaard et al., 2020).

4.2.2 Possible Mitigation Pathways

Reconciling the shift to genuinely greener energy generation so demands meticulous and strategic planning that meets the dual goal of completing the transition while preserving wildlife existence. Wildlife managers and wind energy firms need adequate planning tools to reduce the deployment of wind facilities in places where large conflicts with biodiversity preservation would occur to avoid adverse consequences on endangered species.

Collaboration among stakeholders is important for finding common ground between achieving carbon neutrality and protecting wildlife.
During the energy transition, building and sustaining stakeholder trust may be the most crucial part. Building trust takes time and effort, but it also necessitates opportunities for communication between the parties involved in order to find shared concerns and solutions. It may also include identifying challenges as shared and being conscious of trade-offs as well as a readiness to share authority in terms of information and decision-making (Redpath et al., 2013; Young et al., 2016).

A study by Straka et al in Germany studied the connections and differences in value, orientations, pro-green energy views, emotions, and trust among stakeholders in the ‘green–green dilemma’ and discovered that stakeholders' pro-green energy beliefs and sentiments toward wind turbines differed widely, with members of the wind energy sector and NGO volunteers on opposite ends of the spectrum. Beliefs showed a larger predictive potential on trust than value orientations and beliefs were heavily influenced by emotions. The findings offer a practical and theoretical understanding of stakeholders' value orientations, beliefs, emotions, and trust, notably in the conflict between wind energy production and animal protection. In their study they discovered that stakeholders in the green–green dilemma had a wide range of beliefs and feelings towards wind turbines, with beliefs being a significant predictor of trust and emotions having an influence. (Straka et al., 2020).

They therefore recommended that during the development phase, being aware of similar or differing opinions about the benefits and trade-offs of wind turbines. As a first step in building trust, create a safe environment with opportunity to express and discuss these views, as well as sharing and exchanging knowledge from evidence-based studies on wind turbines. Transparency is a matter of trust. While this may seem like a difficult and unfamiliar task to some, stakeholders who better understand and monitor not only beliefs but also trust may be able to develop strategies to establish trust among themselves. While the question of what different types of trust or distrust may develop in these situations and what impact they have on natural resource management process outcomes remains unanswered, understanding human dimensions in relation to renewable energy sources is critical for realizing future energy systems with the support of all parties involved. Beliefs, as well as emotions, towards wind turbines, should be considered (Straka et al., 2020).

Regarding mitigation pathways for specific ecological hazards, multiple studies have been conducted and have proposed strategies that could minimize the negative effects of WT on the wildlife.

Vignali et al. have developed a model of predicting potential areas of conflict between eventual wind farms and the bearded vulture in the Swiss Alps, that the relevant stakeholders can apply before the planning of new wind farms in the Alps.

They constructed a spatially explicit model to anticipate probable regions of conflict with future wind turbine deployments in the Swiss Alps using the whereabouts of GPS-tagged bearded vultures, a rare scavenging bird reintroduced into the Alps. As a function of wind and environmental circumstances, including food supply, they calculated the likelihood of bearded vultures flying within or below the rotor-swept zone of wind turbines. Seventy-four percent of the GPS coordinates were taken below 200 meters above ground level, indicating areas where wind turbines could cause crashes. Flight activity is concentrated on south-facing mountain ridges, especially in locations where ibex carcasses are likely to occur, with important areas spanning broad swaths of the Swiss Alps. Their model provides a spatially explicit decision tool that will assist governments and energy firms in proactively planning the development of wind farms to limit danger to iconic Alpine animals. (Vignali et al., 2022).

Hartmann et al. recommend choosing a Small Wind Turbine (SWT) site that is bat-friendly, avoiding buildings, trees, forest edges, hedgerows, and waterbodies. If this isn't practicable, as it is with SWTs built for rooftop installation, curtailment algorithms will reduce the likelihood of bats colliding with SWTs during periods of high bat activity (Hartmann et al., 2021).

Song et al. propose increasing the farmland Shelterbelt network around potential nest sites and the distance to the wind turbine after their recent study of 2021. The differences in magpie nest density factors and character characteristics were examined across quadrats inside and outside a wind farm on Chongming Island, China, to assess the effect of wind farms on the nest distribution of magpie (Pica pica), a frequent bird species in agroforestry systems. In each quadrat, the link between magpie nest character characteristics and density variables was investigated, as well as the effects of landscape variables on magpie nest density variables. Nest density data (including total and in-use nest density) were measured in quadrats inside and outside a wind farm in an agroforestry system on Chongming Island, Shanghai, from March to December 2019. In each quadrat, three nest character characteristics and five landscape variables were also recorded, located in agroforestry systems on Chongming Island, China (Song et al., 2021).

Murgatroyd et al., 2021, built and cross-validated a simple generalisable model using GPS tracking data and a digital elevation model to classify the spatial likelihood of wind turbine collisions for resident adult Verreaux's eagles in any terrain with known nests. To verify the model and establish its ability to forecast actual collision mortalities, they used their approach to operational developments in South Africa. The variables distance to nest, distance to conspecific nest, slope, distance to slope, and elevation were all included in their collision risk potential model. Using the model instead of a circular buffer increased eagle protection by about 4% to 5% while preventing development from the same amount (but not shape) of area. In comparison to a circular buffer, the model can make about 20% -21% more territory available for wind energy development for the same level of eagle protection.
The model successfully predicted 79 percent of known collisions at operational wind farms in South Africa, but circular buffers (5.2 km radius) only recorded 50 percent of accidents, according to research. A larger area of land can be made available for wind energy development without increasing the danger of raptor mortality by utilizing predictive models to account for habitat utilization instead of simple barriers around a nest. The predictive model can be used to provide solid advice on where to put wind turbines in South Africa so that conflict between a fragile raptor species and renewable energy development is minimized (Murgatroyd et al., 2021).

Stereovision is one of the approaches that is extensively used in small and medium-sized airports, as well as on wind turbines. A robust tracking method, on the other hand, is necessary to offer long-term observations that allow for the identification of hotspots of bird activity and the prediction of future events. Krenc et al., 2022 discuss tracking algorithms commonly used in radar science and to assess the feasibility of using these algorithms to follow birds using a stereo-vision system. Conducting simulations to identify five state-of-the-art algorithms: the Kalman Filter, Nearest-Neighbour, Joint-Probabilistic Data Association, and Interacting Multiple Model, all of which have the potential to be implemented in a stereo-vision systems, found that the monitoring system succeeded and could be used to access bird behaviours and decide on the appropriate tackling method (Krenc et al., 2022).

Allen et al., 2022, propose a lidar-based openness index to aid conservation planning for grassland wildlife. Their research provides an index based on a remotely detected angle to the horizon, allowing for the mapping and quantification of openness over potentially enormous spatial scales while still maintaining a fine enough spatial resolution to accurately forecast patch-level occupancy patterns. They extend the possibility of similar indices that would require labour-intensive fieldwork, such as travel and numerous manual clinometer readings, to reach equivalent findings using this approach. They compared the predicted performance of two variants of the index (mean-angle and maximum-angle) for the within-field distribution of a grassland species, the Grasshopper Sparrow. They then showed how such models may be used in conjunction with digitally altered openness maps to forecast how people will react to various management scenarios (Allen et al., 2022).

Three main techniques are used today to attach wind turbine foundations to the seabed: gravitation, monopile and jacket foundations. Russell et al. in 2016, proved that seal abundance was dramatically reduced up to 25 kilometres away from the piling operation; within 25 kilometres of the wind farm's centre, utilization was reduced by 19 to 83 percent

(95 percent confidence intervals), equal to a mean estimated relocation of 440 individuals. Starting from expected received levels of between 166 and 178 dB re 1 Pa, this represents a considerable shift. Displacement was limited to piling activities; seals were dispersed according to the non-piling scenario within 2 hours of pile drive ceasing. He suggests therefor breaks in piling to allow seals to forage and travel unhindered (Russell et al., 2016).

Using large scale aerial surveys and extensive static acoustic monitoring, Dahne et al., 2013, analysed the effects of pile-driving on harbour porpoises. Pile-driving sound exposure levels (SELs) between 139–145 (25 km) and 146–152 (10 km) dB re 1 μPa²s most probably lead to a displacement of harbour porpoises, which could be seen in one aerial survey perfectly timed to pile-driving. as well as on the porpoise detectors (C-POD) data. These SELs are most probably overestimates indicating that the behavioural reaction threshold of harbour porpoises towards pile-driving sounds is lower. A major outcome was that the duration of pile-driving had a large impact on the WT with longer pile-driving durations leading to a longer displacement (Dähne et al., 2013).

Passoni et al., 2017, created a suitability model for wolf breeding habitat using Maxent, based on six environmental variables and 31 reproduction site sites collected between 1997 and 2015. Wind farms were prioritized to discover the best balance of energy capacity and overlap with important wolf reproduction habitats. The predictions of the habitat appropriateness model were consistent with current knowledge: the probability of wolf breeding site presence increased with distance to settlements, farming, and roads, and reduced with distance to forest. According to spatial optimization, current energy targets might be met with only 31% of currently proposed wind farms, selected in a way that decreases the potential ecological cost by 91%. This is a very efficient result, indicating the utility of this method for prioritizing infrastructure development based on the potential impact on a variety of animal species (Passoni et al., 2017).

Lastly, a very important mitigation measure comes from the research of Kuvlesky et al., 2007, that suggests that wind turbines on agriculture are an often-overlooked part of the present wind farm and wildlife difficulties. The majority planned wind farm locations in their study area, Texas, have centred on placing turbines on rangelands that are primarily covered in native flora. Alternatively, they offer various reasons why wind farms should be built on cropland. To begin with, the study area has vast areas of agriculture that is dryland farmed for cotton, grain sorghum, and occasionally corn. Without irrigation, farming these areas is a dangerous enterprise that is heavily supported by crop insurance during dry years. Second much of this cropland is well within the range of prevailing winds, which can be used to power wind turbines.
For these landowners, wind-generated electricity might be a significant drought-resistant source of revenue. Third, almost all of the native flora has been removed from these places, rendering them unappealing as a stopover site for migrating birds or as a habitat for galliforms. Fourth, cropland in Texas has a network of existing access roads and is traversed by a number of existing transmission grids. Fifth, numerous petroleum developments in the form of wells, collection and transfer stations, and other structures can be seen across these farmland areas. As a result, landowners have a history of dealing with energy-related businesses, which should transition readily to employing wind-generated electricity as a source of extra income (Kuvlesky et al., 2007).

Table 2: Pathways for Impact Avoidance and/or Reduction

Impact Avoidance

Macro- and micro-siting of Wind Farms, sites to avoid	sites of high conservation value
	wetlands
	major avian migratory routes
	habitat for endangered species
	coherent habitats should not be fragmented
	hibernation areas
	buffer distance of at least 400m should be kept from waterbirds' roosting areas
Stereovision and Tracking Algorithms	cropland siting opportunities
Radar sensors	allows object classification, detects hot spots of birds' activity and forecasting future events
	all weather and light conditions, can be used for planning and strategic management

Impact Reduction

Turbine Shutdown	Curtailment or feathering (change the angle of the blades)
Marine Piling	shorter pile-driving durations and breaks in piling

Table 3: Adverse Effects on Specific Species and Mitigation Pathways

SPECIES	ADVERSE EFFECT	MITIGATION PATHWAY
Pica Pica	Reduced nest density inside windfarms	Increasing the farmland Shelterbelt network around potential nest sites and the distance to the wind turbine (Song et al., 2021)
Gypaetus barbatus	Avian collision	predictive flight-altitude spatial model of Vingali et. al
Pipistrellus pipistrellus **Myotis mystacinus** **Pipistrellus pygmaeus** **Pipistrellus nathusii**	Avian collision with small wind turbines (SWT)	Avoid their placement near buildings, trees, forest edges, hedgerows, and waterbodies (Hartmann et al., 2021)
Aquila verreauxii	Avian collision	Predictive model of Murgatroyd et al.
Ammodramus savannarum	Avoidance	Lidar-based openness index of Allen et al.
Phoca vitulina	Underwater Acoustic Disturbance	breaks in piling to allow seals to forage and travel unhindered (Russell et al., 2016)
Phocoena phocoena	Underwater Acoustic Disturbance	shorter pile-driving durations (Dähne et al., 2013)
Canis lupus lupus	Avoidance	suitability model for wolf breeding habitat, developed by Passoni et al.
Anser brachyrhynchus	Avoidance	further research to test the hypothesis that smaller wind turbines can be better tolerated by the pink-footed goose

4.3 Public Acceptance of Wind Energy

Two of the main arguments for not accepting wind farms in one’s vicinity, have been noise and aesthetics. Below those two arguments will be analysed and their validity will be evaluated. In addition, the results of the surveys will be presented and analysed, linked eventually to the public acceptance of wind energy.

The NIMBY (“not in my backyard”) phenomenon has long been used as the prime explanation for the discrepancy between acceptance for the technology and resistance to concrete projects. There are two unique meanings and user groups for the phrase "not in my backyard." In some cases, it denotes people's resistance to adjacent firms' or governments' plans to build significant projects that could have an impact on their standard of living and property value. The phrase is frequently used in this way by project proponents, which typically include the sponsoring corporation, contractors, labor unions, and others. The phrase is also used by proponents of environmental justice and social services to suggest a lack of social conscience demonstrated by opposition to the placement of social-service facilities in areas based on factors such as class, race, or handicap. The phrase "not in my backyard" has a bad connotation since those who oppose high-impact initiatives on the basis of the environment are typically from the middle class or lower class. As a result, the statement might be cited by project proponents as a component of a wedge issue, which is a political issue that splits a candidate's supporters or a party's members. For those who have been given this title, the phrase has a double edge that makes it challenging to deal with. On the one hand, it implies that the project's opponents want poor people and poor neighbourhoods to shoulder the costs of toxic waste facilities or quarries, while on the other, it implies that the project's opponents are willing to forgo the blue-collar jobs that would be created by the facility's construction and operation (Krause et al., 2014).

Wind farms are one of the renewable energy sources that are proliferating and altering the land and seascapes of the world. They frequently encounter opposition, mostly because of their alleged "eyesore" impact. Arguably, the most controversial aspect of wind energy is the aesthetic influence of the WT on the landscapes. Some people are concerned that wind farms would impair scenic viewsheds, while others find them pleasing.

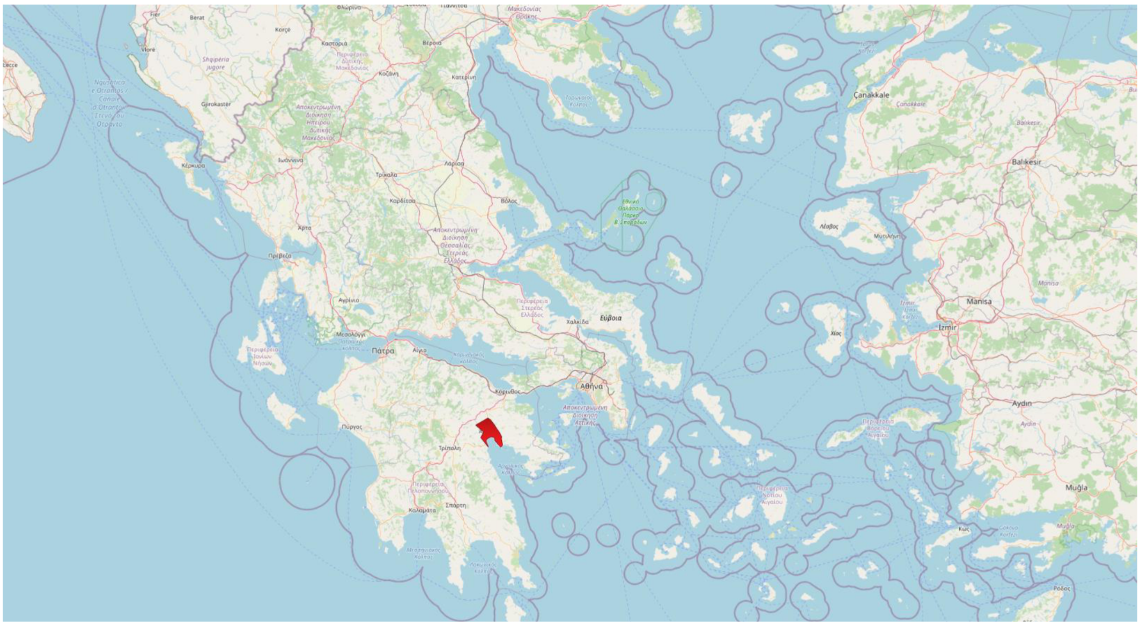
Researchers in Finland conducted an epidemiological survey of the influence of wind turbine and road traffic noise exposure on self-reported health effects, with a case group near wind turbine areas and a control group farther away from wind turbines. Because wind turbines are built near existing infrastructure so that large transport vehicles have access to install and maintain them, it is important to consider in aggregate all potential environmental stressors and their health effects on the public. The wind turbine areas met with modern tightened regulations where sound levels did not exceed 40 dB. They were associated with increased noise annoyance, but no other health effects. On the other hand, increased road traffic noise levels were associated with self-reported health effects including migraines, dizziness, impaired hearing, heart palpitations, and heart disease. The study found that when wind turbine sound levels meet with regulations, it is more important to control road traffic noise in these residential areas. The results provide significant contextual data for wind energy policy developers since noise is among the top objections affecting the social acceptability of wind turbines (Radun et al., 2022).

4.3.1 Population Surveys

For the purposes of this thesis, surveys of the local population in Argolis Plain in Greece were conducted. The objective of this survey was to define Argolis Plain as a case study of how people in rural areas are perceiving wind energy.

Argolida is a regional unit, former prefecture of Greece and geographical area that belongs administratively to the Peloponnese Region and geographically to the Peloponnese. It is located in the eastern part of the Peloponnese and borders Corinth to the north, Arcadia to the west and south, and Attica (Trizinia) to the northeast. It is mainly a semi-mountainous prefecture with a large coastline, however it includes the very productive and densely populated lowland area of the Argolic plain. In the 2011 census it had a population of 97,044 inhabitants and an area of 2,156 square kilometers.

The capital of the prefecture is Nafplio (14,203 inhabitants) and its largest city is Argos (22,209 inhabitants). Important settlements are also the towns of Kranidi, Ermioni, Nea Kios, Ligourio and Ancient Epidaurus. The economy of the prefecture is mostly based on the primary sector with significant production of citrus, olive oil and other tree crops. Livestock is also developed in the mountains of the prefecture. Of great importance is the tourism sector which is particularly developed around the world heritage site of Mycenae, the traditional old town of Nafplio and many summer resorts such as Tolo and the coastline of Ermionida. Finally, there is significant manufacturing activity around the primary sector.
To the west of the prefecture is the important Argolic Plain where the two most important cities of the prefecture are located and the majority of the prefecture's economy is concentrated. It is an alluvial plain formed by the Inachos river and the torrents that end in the plain. It is one of the most fertile areas of the Peloponnese and is systematically cultivated from citrus fruits, olive trees, peaches, pears, and vegetables.



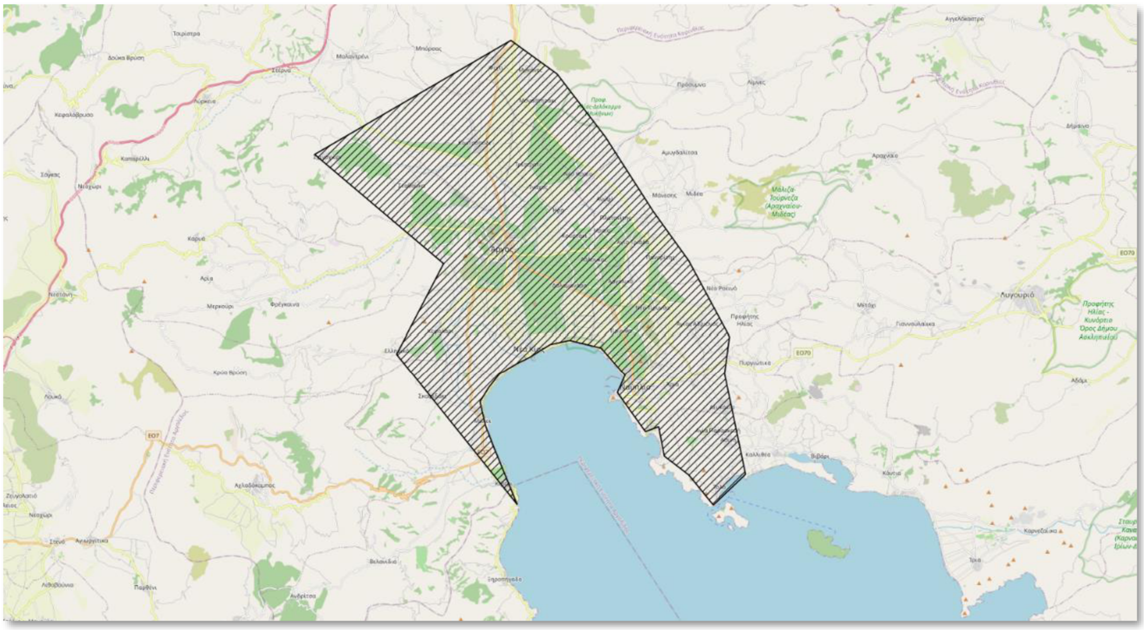


Figure 11: Study Area of Argolis Plain and its relevant position in Greece

The purpose of the surveys was to identify people's behaviours towards wind energy and to examine the factors that affect their behaviour.

The focus is placed on local acceptance by residents of the rural Argolis plain. In order to analyse the results of the survey, Structural Equation Modelling (SEM) and the methodology of Djurisic et al., 2020, was used. SEM is a set of statistical approaches that examines a set of relationships between one or more independent variables and one or more dependent variables, both continuous and discrete (Djurisic et al., 2020). The first survey's goal was to study residents' attitudes on wind energy in the Argolis Plain in Greece, as well as the elements that influence their behaviours. The objective was to look into people's awareness of wind energy and see what factors in their attitudes and perceptions influence and affect their behaviour when it comes to wind energy. The R package was used to do the structural equation modelling.

The survey was conducted from December 2019 to the end of January 2022. A total of 500 questionnaires were distributed, with 442 respondents answering and eventually 432 valid questionnaires kept for analysis. Incomplete or incorrectly filled questionnaires, were not taken into account (except for missing answers in the personal data). The survey was contacted over 10 visits in different periods of the year, at random time slots and it happened door-to-door in the beginning and online later due to the global pandemic of Covid 19. The main obstacle was the unwillingness of the respondents to share income and education information, fact that has been taken into consideration in the data validation. The questionnaire was in Greek and the original version as well as its English translation can be found in Appendix A.

The questions were designed to be simple and brief, and they always included a field 'other', in order to gather attitudes that would otherwise be lost in a strict closed-ended questionnaire. Before handing out the questionnaire, confidentiality was discussed and questions with sensitive personal data had the choice to be left unanswered.

All analyses were undertaken using R version 4.2.0.

The basic structural model contained five concepts, modelled according to the Theory of Planned Behaviour (TPB) explained in Chapter 3.3— Awareness level, Perception and Attitude towards wind energy, Subjective norms, Perceived Behavioural Control and finally Behaviour towards wind energy. Each concept has then observed variables. Awareness has the following variables: wind as a renewable energy source awareness, knowledge about climate change, knowledge about energy security, knowledge of Greece's electricity mix, knowledge of Greece's electricity production. The rating ranges from 1 - which represents very poor awareness to 5 - excellent awareness and then 6 'not sure' and 7 'I prefer not to answer.

Perception and Attitude have the following variables: concerns about climate change, concerns about energy security, the importance of renewable energy in economic development, the importance of renewable energy in sustainable development, the importance of renewable energy in job creation and, the importance of renewable energy in energy security. The concept of subjective norms has the variables: attitudes of friends and family, attitudes of role models. Perceived behavioural control includes the eventual choice of energy source for the household. The concept of behaviour has the following variables: eventual choice of renewable energy over fossil fuels, eventual positive attitude in a public hearing, eventual acceptance of a wind park in the vicinity, choices that the respondents make when buying a house and choices when buying electric appliances. The concepts, variables and their codes are illustrated in Table 4 below.

Table 4: Variables Measurement

LATENT VARIABLES	CODE	OBSERVED VARIABLE DEFINITION
AWARENESS LEVEL	A1	Self-reported knowledge about wind as a renewable energy source awareness
	A2	Self-reported knowledge about environmental issues
	A3	Self-reported knowledge about energy security
	A4	What is the main energy source for our electricity production?
	A5	Where does most of the electricity that Greece needs is produced?

	A6	How much of our electricity comes from renewable energy sources?
	A7	Which of the following is not a Greenhouse Gas?
PERCEPTION AND ATTITUDE	P1	Are you worried about climate change?
	P2	Are you worried about energy security?
	P3	The most important benefit of renewable energy is economic development
	P4	The most important benefit of renewable energy is sustainable development
	P5	The most important benefit of renewable energy is the creation of new jobs
	P6	The most important benefit of renewable energy is the country’s energy security

	P7	My property would lose value if there were a wind park nearby
	P8	Which best describes your opinion towards wind turbines?
	P9	Are you against or for building renewable energy sources in general?
SUBJECTIVE NORMS	S1	My friends and family would choose to use electricity suppliers that use renewable energy
	S2	People in my community would be willing to use renewable energy for their home's electricity
	S3	People that I value and admire would prefer electricity from renewable energy
PERCEIVED BEHAVIORAL CONTROL	PB1	If I was the only one to decide, I would use renewable energy for my electricity
	PB2	If I wanted to, I could easily use renewable energy for my home's electricity

BEHAVIOUR	B1	If I had the choice, I would choose renewable energy to supply my home's electricity
	B2	If I were participating in a public hearing for a wind park, I would express positive feedback
	B3	I would be willing to accept a wind park within 500m from my property
	B4	When you buy or build a home, you give importance to the location
	B5	When buying or building a home, I give importance to the level of energy efficiency
	B6	During my last purchase of an electric appliance/device, I considered primarily its energy efficiency
	B7	During my last purchase of an electric appliance/device, I considered primarily the design of the device

Survey Results

The original data collected from questionnaires had 442 observations which represent the respondents who responded to the questions.
The demographic data are only used for statistical purposes, and they are not used in causal relationship analysis. 57,5% of the respondents identified as females, 42% as males and the rest preferred not to answer. 12.64% of the respondents were between 20 and 29 years old, 57.47% 30 to 39 years old, 14.94% 40 to 49 years old, 8.05% 50 to 59 years old while 5.75% were more than 60 years old. 1.15% of the respondents preferred not to answer to this question.
In the category of level of education, 0.23% have only completed the mandatory education, 40.23% of the respondents have a high school diploma, 28.74% hold a bachelor's degree, while 26.21% hold a master's degree. 1.15% hold a Ph.D. or similar degree.
Regarding the income of the respondents, 62.4% had an income inferior to EUR 30K while 20% had an income between EUR 30 K and EUR 60K. 13% decided not to and answer to the question, while the rest of the respondents have an income superior to EUR 60K. The majority of the population ─with a percentage of 66,7%─ has lived in the Argolis Plain for more than 20 years, 17% between 11 and 20 years, while 10.3% for less than 10 years.

Below the demographic characteristics of the sample are shown in Table 5 and in a graphic form in Figures 12-16.

Table 5: Demographic Characteristics of the Sample

Variant	Frequency	Percent	Name
High school diploma	175	40.23	Level of education
Basic education of 9 years	1	0.23	Level of education
bachelor's degree	114	28.74	Level of education
master's degree	125	26.21	Level of education
I prefer not to answer	10	2.3	Level of education
Ph.D, MD, JD or similar	5	1.15	Level of education
20 to 29 years old	55	12.64	Age
30 to 39 years old	250	57.47	Age
40 to 49 years old	65	14.94	Age
50 to 59 years old	35	8.05	Age
60 + years old	25	5.75	Age
I prefer not to answer	5	1.15	Age
30.000 or less	265	62.35	Income
30.001 to 60.000	85	20	Income
60.001 to 90.000	10	2.35	Income
90.001 to 150.000	10	2.35	Income
I prefer not to answer	55	12.94	Income
female	250	57.47	Gender
I prefer not to answer	5	1.15	Gender
male	180	41.38	Gender
1-10 years	45	10.34	number of years staying in Argolis Plain
11-20 years	75	17.24	number of years staying in Argolis Plain
Over 20 years	290	66.67	number of years staying in Argolis Plain

Figure 12: Age of Respondents

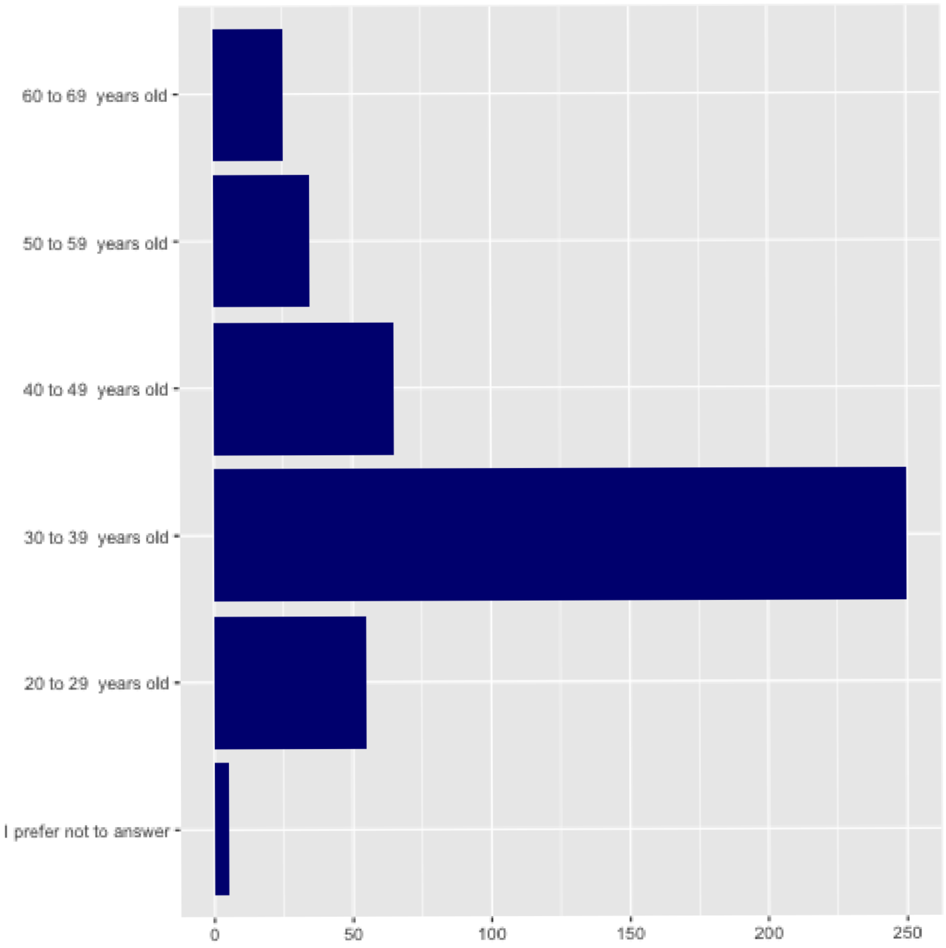


Figure 13: Educational Level

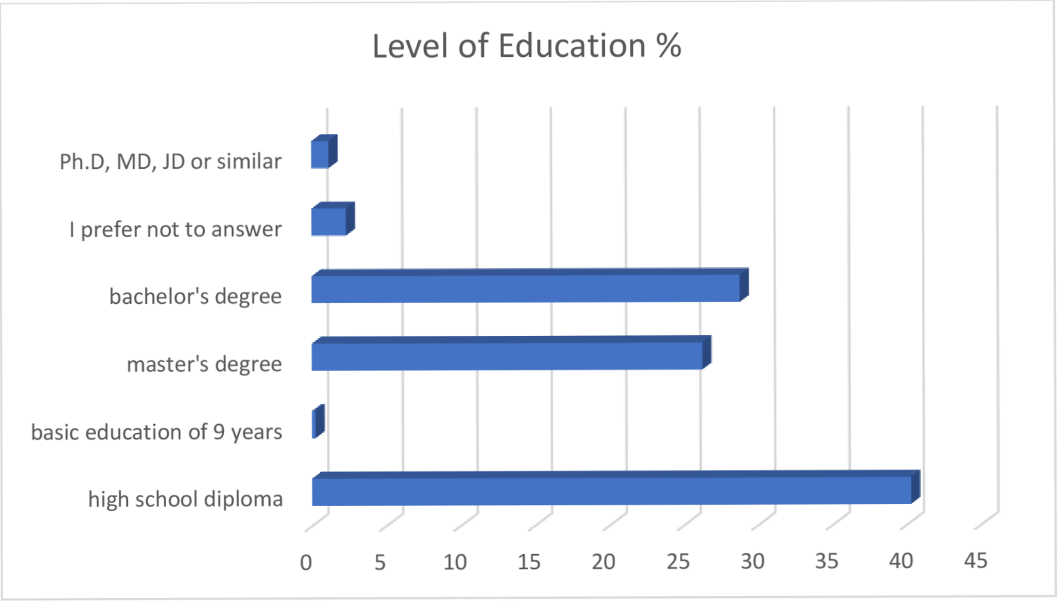


Figure 14: Family Income in EUR

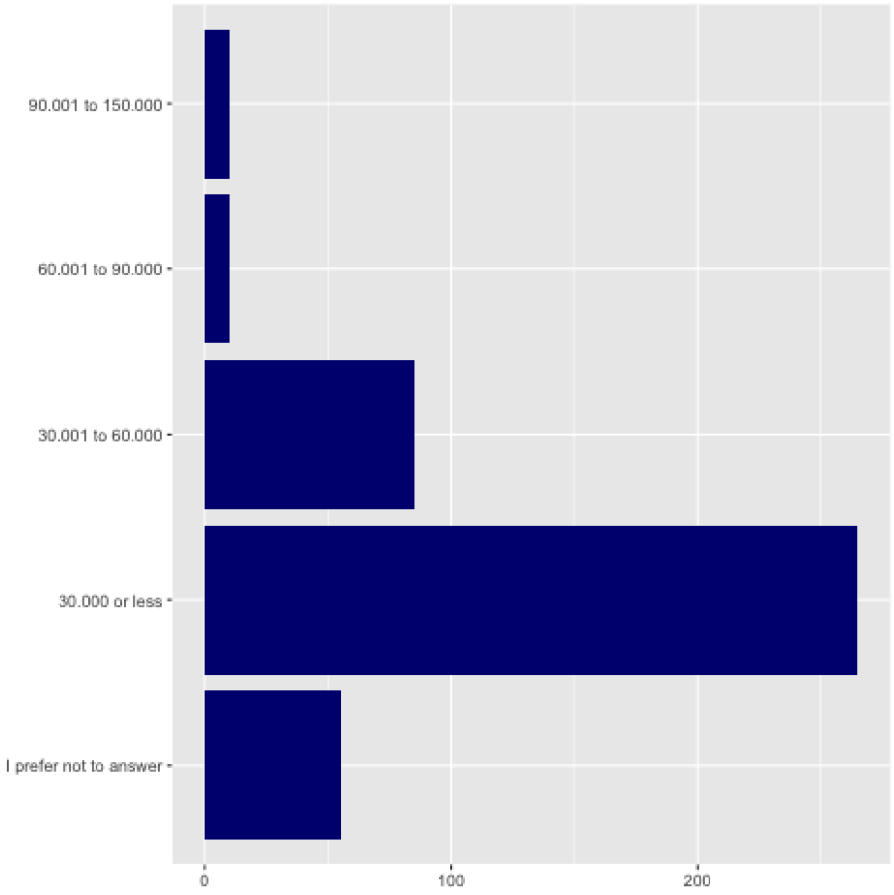


Figure 15: Gender

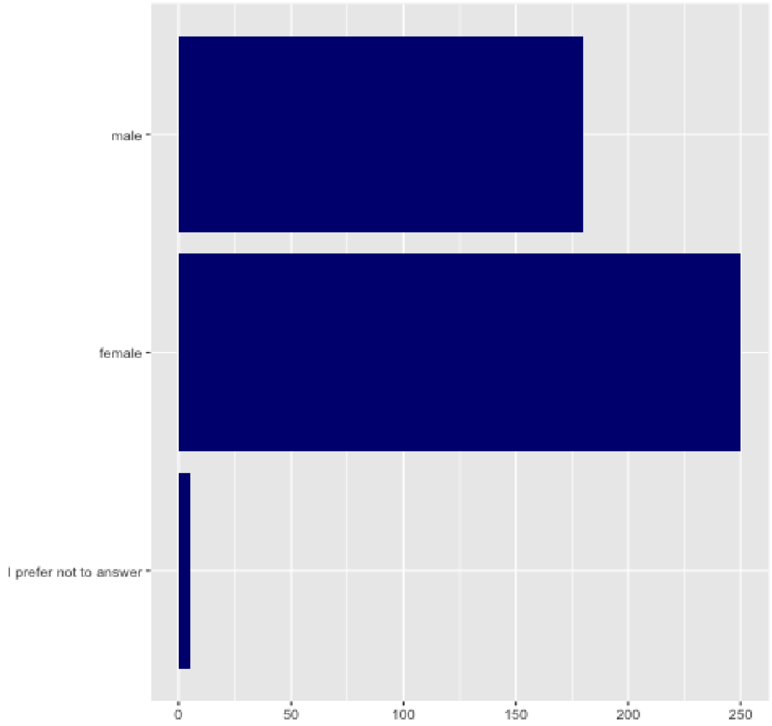
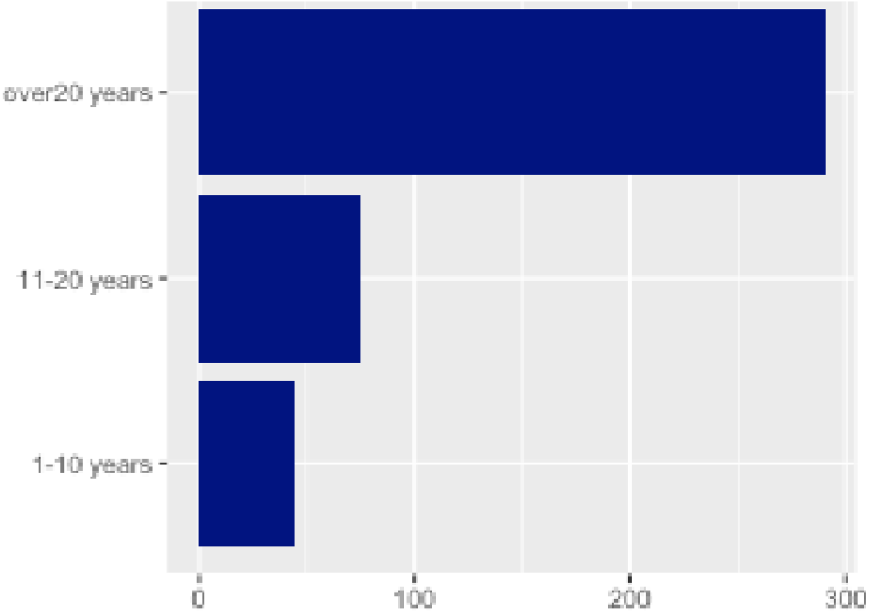


Figure 16: Years Inhabiting in Argolis Plain



The original data collected from questionnaires had 442 observations which represent the respondents who responded to the questions. The data set was composed of 29 variables; however, the main interest was focused on 25 variables which compose of the questions that were asked. Therefore, the unnecessary variables were removed from the data set for further analysis. The data had also missing values where some questions were left blank by the respondents. Those missing values were also removed from the data set, hence the final data set remained with 432 observations (rows) and 25 variables (columns). In Table 6 below the descriptive statistics are presented.

Table 6: Descriptive statistics

LATENT VARIABLES	CODE	OBSERVED VARIABLE DEFINITION	MEAN	S.D.	RANGE
AWARENESS LEVEL	A1	Self-reported knowledge about wind as a renewable energy source awareness	4.9838	1.9018	1-7
	A2	Self-reported knowledge about environmental issues	4.9097	1.6752	1-7
	A3	Self-reported knowledge about energy security	4.4676	1.8161	1-7
	A4	What is the main energy source for our electricity production?	4.7454	1.953	1-7
	A5	Where does most of the electricity that Greece needs is produced?	4.4722	1.8579	1-7
	A6	How much of our electricity comes from renewable energy sources?	4.5694	1.775	1-7
	A7	Which of the following is not a Greenhouse Gas?	2.6181	1.2299	1-7
PERCEPTION AND ATTITUDE	P1	Are you worried about climate change?	4.8981	1.8727	1-7

	P2	Are you worried about energy security?	5.0231	1.8378	1-7
	P3	The most important benefit of renewable energy is economic development	4.5463	1.8848	1-7
	P4	The most important benefit of renewable energy is sustainable development	4.6319	1.7675	1-7
	P5	The most important benefit of renewable energy is the creation of new jobs	5.1134	1.7203	1-7
	P6	The most important benefit of renewable energy is the country’s energy security	5.2801	1.2736	1-7
	P7	My property would lose value if there were a wind park nearby	4.8079	1.3427	1-7
	P8	Which best describes your opinion towards wind turbines?	4.4769	1.8353	1-7
	P9	Are you against or for building renewable energy sources in general?	4.3426	1.6847	1-7

SUBJECTIVE NORMS	S1	My friends and family would choose to use electricity suppliers that use renewable energy	2.1667	1.0575	1-7
	S2	People in my community would be willing to use renewable energy for their home's electricity	2.375	1.0523	1-7
	S3	People that I value and admire would prefer electricity from renewable energy	2.3264	1.063	1-7
PERCEIVED BEHAVIORAL CONTROL	PB1	If I were the only one to decide, I would use renewable energy for my electricity	4.6042	1.7242	1-5
	PB2	If I wanted to, I could easily use renewable energy for my home's electricity	4.6574	1.7549	1-5
BEHAVIOUR	B1	If I had the choice, I would choose renewable energy to supply my home's electricity	4.7708	1.7289	1-7
	B2	If I were participating in a public hearing for a wind park, I would express positive feedback	4.838	1.7807	1-7
	B3	I would be willing to accept a wind park within 500m from my property	4.9514	1.9471	1-7
	B4	When you buy or build a home, I give importance to the location	4.9954	1.4158	1-7

	B5	When buying or building a home, I give importance to the level of energy efficiency	5.2731	1.6119	1-7
	B6	During my last purchase of an electric appliance/device, I considered primarily its energy efficiency	4.6898	1.8243	1-7
	B7	During my last purchase of an electric appliance/device, I considered primarily the design of the device	3.9236	1.9781	1-7

Measurement Model

The basic hypothesized structural model contains five concepts — Awareness level (i.e., knowledge of wind energy, electricity sector, environmental problems), Perception and Attitude towards wind energy, Subjective Norms, Perceived Behavioural Control and finally, Behaviour towards wind energy. The Likert seven-point scale has been used with below assigned values shown Table *7*.

Table 7: Seven-point Lickert Scale Explanation

	KNOWLEDGE	**AGREEMENT**
1	Least Knowledgeable	Strongly Disagree
2	Somewhat Knowledgeable	Disagree
3	Knowledgeable	Somewhat Disagree
4	Neutral	Neutral
5	Least Expert	Somewhat Agree
6	Somewhat Expert	Agree
7	Expert	Strongly Agree

The hypothesised model is based on the Theory of Planned Behaviour that is described in Chapter 3.3

The awareness/knowledge level had 7 items labelled as A1-A7, with a Likert scale of 1-7. Seven-point Likert scales appear to be sensitive enough to record a more accurate evaluation of an interface while remaining relatively compact. A1 asked the respondents to rank their overall level of knowledge regarding wind energy on a scale of 1 to 7, 1 being least knowledgeable and 7 being expert. It was observed that those who were somewhat expert in the overall level of knowledge were 175 with 41% followed by those who were experts with 22%. Item A2 asked the respondents to rank their knowledge of environmental issues on a scale of 1 to 7, with 1 being least knowledgeable and 7 being expert. Similarly, those who were somewhat experts in this knowledge had the highest number of 123 which is equivalent to 28% followed by those who were neither knowledgeable nor experts whose proportion was 20%. Item A3 asked the respondents to rank their knowledge in energy security on a scale of 1 to 7, with 1 being least knowledgeable and 7 being expert. Similarly, those who were somewhat experts were leading (174) with 40% followed by those who were somewhat knowledgeable with 23%. Items A4-A7 tested respondents' knowledge on specific questions that had only one correct answer from 1-7 choices given. The correct answer was in all four cases in number 6. The questions that were asked were first to identify the main energy source for the country's electricity production, second to choose where most of the electricity that Greece needs is produced, third to choose how much of the country's electricity comes from renewable energy sources, and last to choose which was not a greenhouse gas from the list respectively. Item A4 indicates that 138 respondents whose proportion is 32% answered correctly about the main source of the country's electricity. 169 respondents with 39% answered correctly about the place where the biggest production of electricity is transformed in the country. 44% answered correctly about the amount of energy produced by renewable energy sources while only 2% found the gas which was not a greenhouse gas.

Table 8 below shows the results that were obtained for each item and in Figures 17 and 18 a graphical representation is given. Figures 19 to 22 illustrate the actual knowledge of the respondents on those issues.

Table 8: Results of Self-Reported and Actual Knowledge for Wind Energy, Environmental Issues, and Energy Security

A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
1: 7	1: 6	1: 17	1: 18	1: 16	1: 7	1: 38
2: 92	2: 60	2:100	2: 90	2:104	2: 99	2:207
3: 4	3: 14	3: 6	3: 4	3: 8	3: 12	3: 139
4: 56	4: 86	4: 74	4: 72	4: 75	4: 83	4: 14
5: 5	5: 65	5: 36	5: 23	5: 25	5: 14	5: 11
6:175	6:123	6:174	6:138	6:169	6:188	6:10
7: 93	7: 78	7: 25	7: 87	7: 35	7: 29	7: 13

Figure 17: Self-reported Level of Knowledge on Wind Energy (A1), Environmental Issues (A2), and Energy Security (A3)

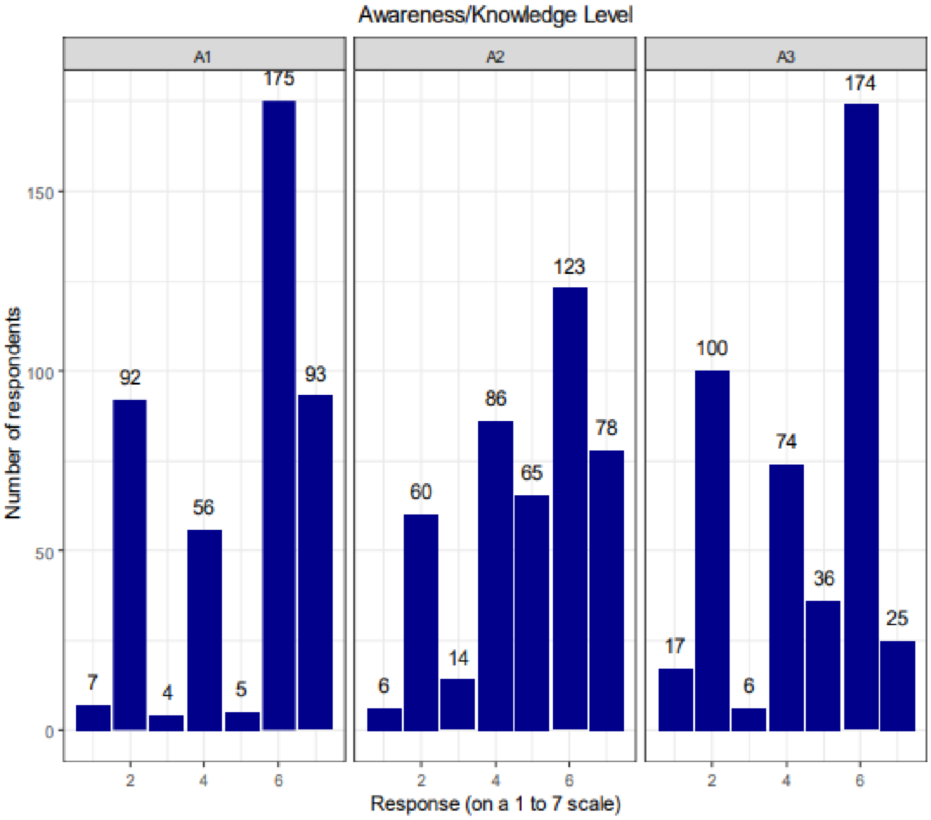


Figure 18: Testing the actual knowledge of the respondents, the fourth column being the correct answer

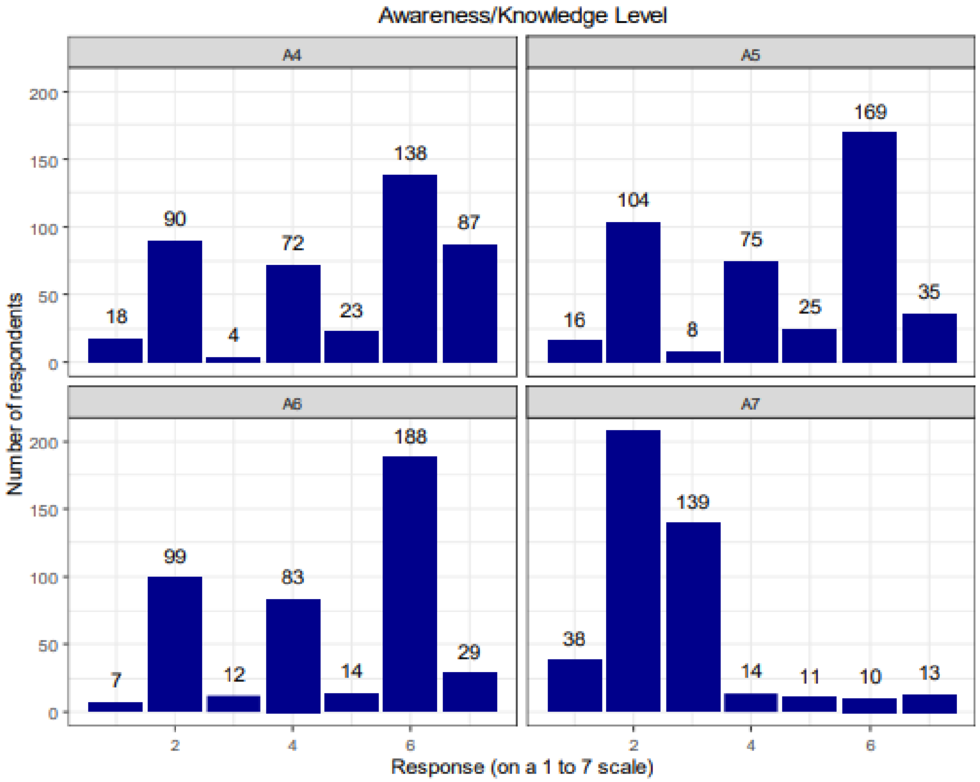


Figure 19: Variable A4- Testing energy knowledge of the respondents

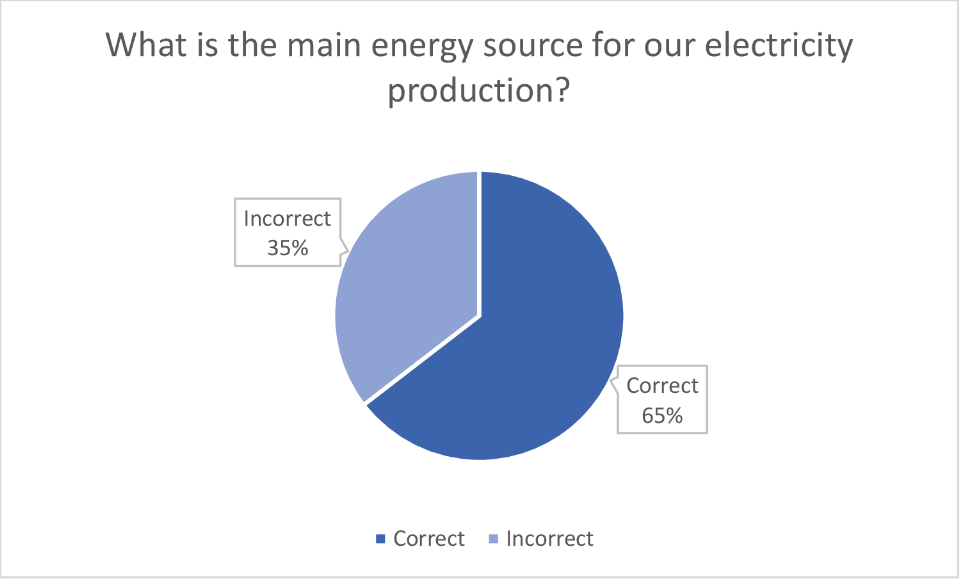


Figure 20: Variable A5- Testing energy knowledge of the respondents

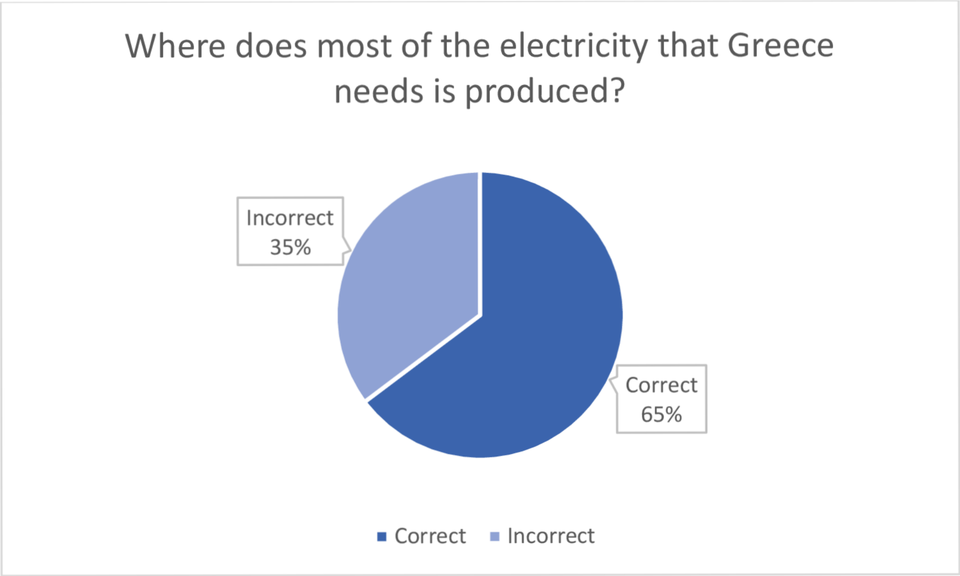


Figure 21: Variable A6- Testing energy knowledge of the respondents

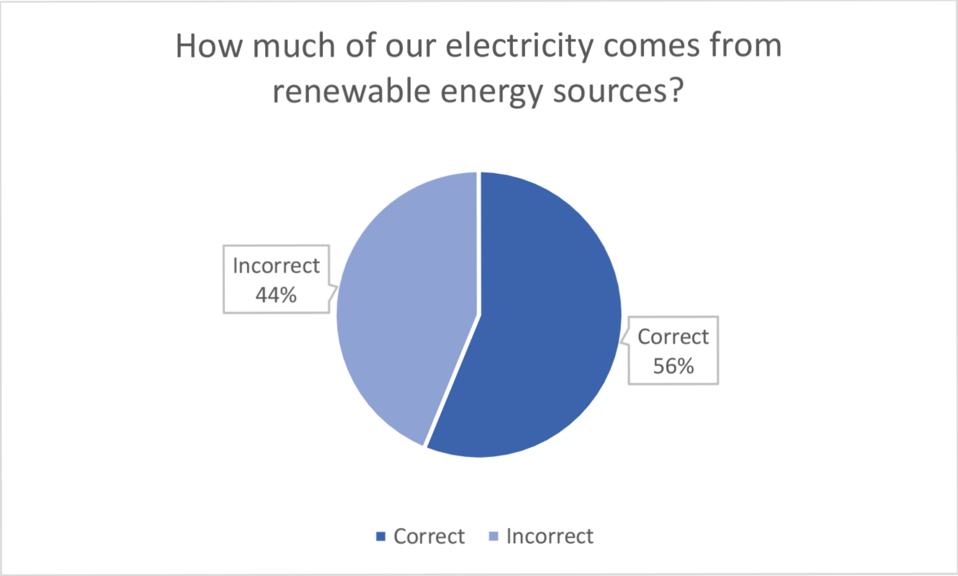
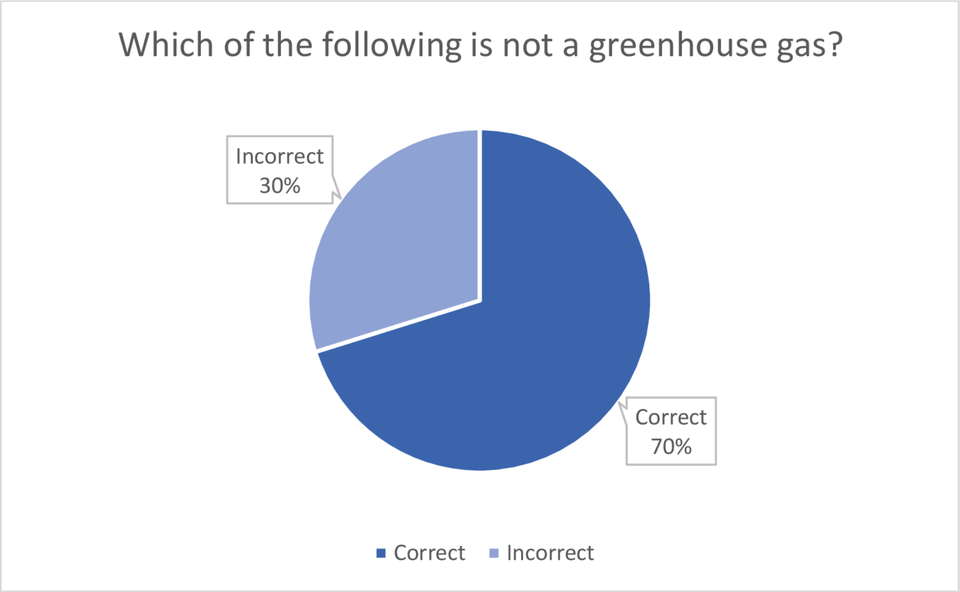


Figure 22: Variable A7-Testing Environmental Knowledge of the Respondents



The second group consists of variables related to perceptions and attitudes about wind energy. They are described using nine variables, which are labelled from P1 to P9, and they explore the respondents concern about climate change and energy security (variables P1 and P2) with the questions 'Are you worried about climate change?' and 'Are you worried about energy security?'. They also explore perceived benefits of wind energy (variables P3 to P9) with questions designed to explore the benefits of wind energy on the local population.

Observed variables P1 and P2 asked the respondents to rank how worried they were about climate change and energy security respectively on a scale of 1 to 7, 1 being the least worried and 7 being the most worried. It was observed that those who were more worried were the leading with 39% in both cases, but a good number were not worried at 19%. Items P3 and P4 asked the respondents to rank on how they agree with the statements; the most important benefit of wind energy is the country's energy security, and the most important benefit of wind energy is the creation of new jobs respectively on a scale of 1 to 7, with 1 being totally disagreed and 7 being I totally agree. The proportion of those who agreed that the most important benefit of wind energy is the country's energy security was the highest at 37% followed by those who disagreed with the statement at 25%. However, only 2% strongly disagreed with this statement. A similar trend was also observed in item P4 where the proportion of respondents who agreed was leading at 35% while those who strongly disagreed were the least at 6%.

Item P5 asked the respondents to describe their opinion towards wind turbines on a scale of 1 to 7 in the order of very negative, somewhat negative, negative, neutral, somewhat positive, positive, and very positive respectively. It was observed that those who were positive and very positive were the leading at 41% and 20% respectively. Those who were very negative were the least at 2%. Finally, items P6-P9 asked them to state whether they were against or for building renewable energy sources in general on a scale of 1 to 7 in the order of; very much against, against, for, neutral, very much for, not sure and I prefer not to answer respectively. Those who were not sure were the highest followed by those who were against the idea. Those results are summarised in Table 9 and illustrated in Figures 24 and 25.

Table 9: Results of the Perception Variable

P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
1: 11	1: 5	1: 10	1: 24	1: 7	1: 6	1:9	1: 11	1: 6
2: 83	2: 80	2: 108	2: 56	2: 56	2:10	2:15	2:106	2: 51
3: 8	3: 11	3: 11	3: 35	3: 22	3: 10	3:22	3:11	3:100
4: 66	4: 64	4: 75	4:60	4: 59	4: 117	4:129	4: 80	4: 92
5: 15	5: 12	5: 15	5: 63	5: 25	5: 16	5:149	5: 25	5: 87
6:167	6:164	6:161	6:153	6:178	6:234	6:45	6: 160	6: 7
7: 82	7: 96	7:52	7: 41	7: 85	7: 39	7:63	7: 39	7: 89

Figure 23: Concern about Climate Change (P1), Concern about Energy Security (P2), Statements about Perceived Benefits of Wind Energy (P3-P6)

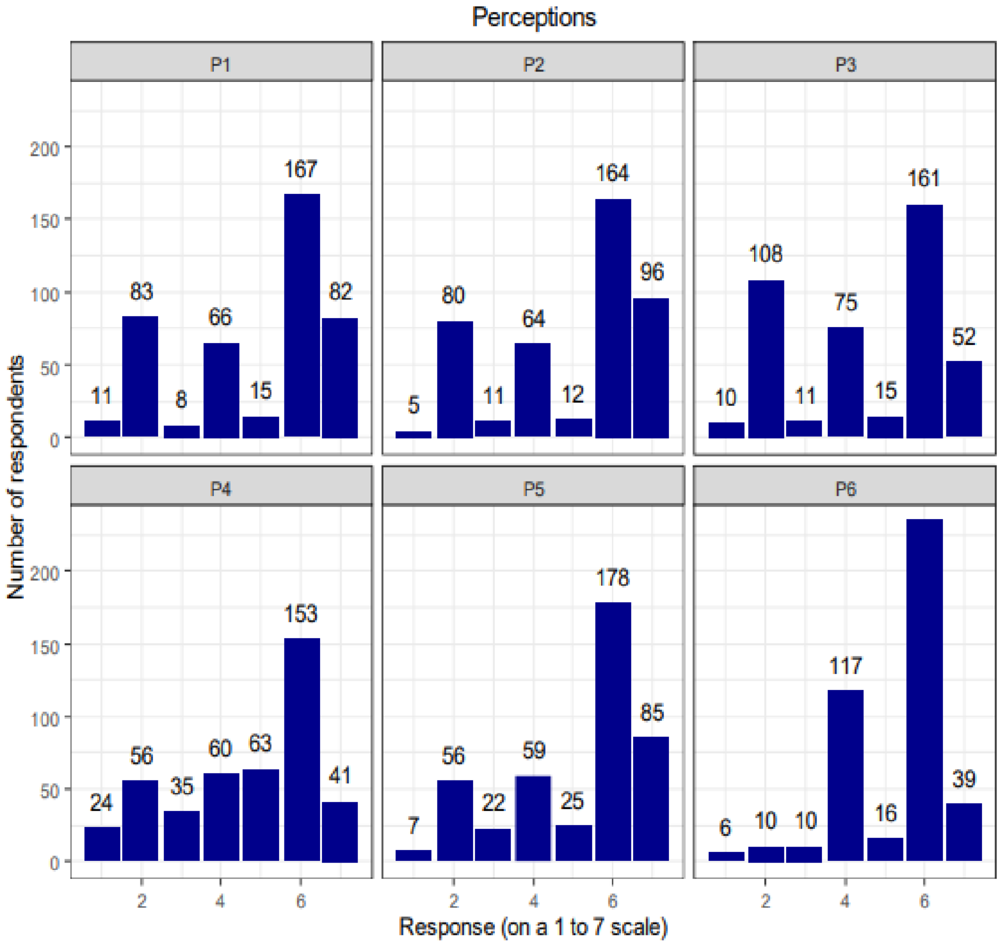
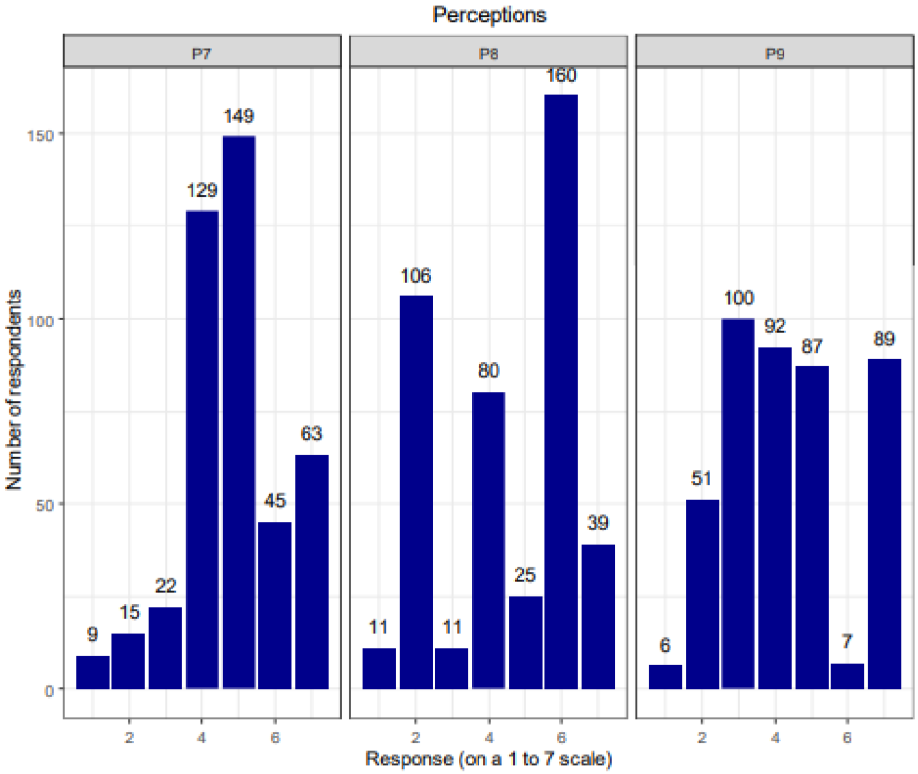


Figure 24: Variables P7 to P9, Perceived Value of Property; Opinion towards Wind Turbines and Renewable Energy Sources with 1-very negative

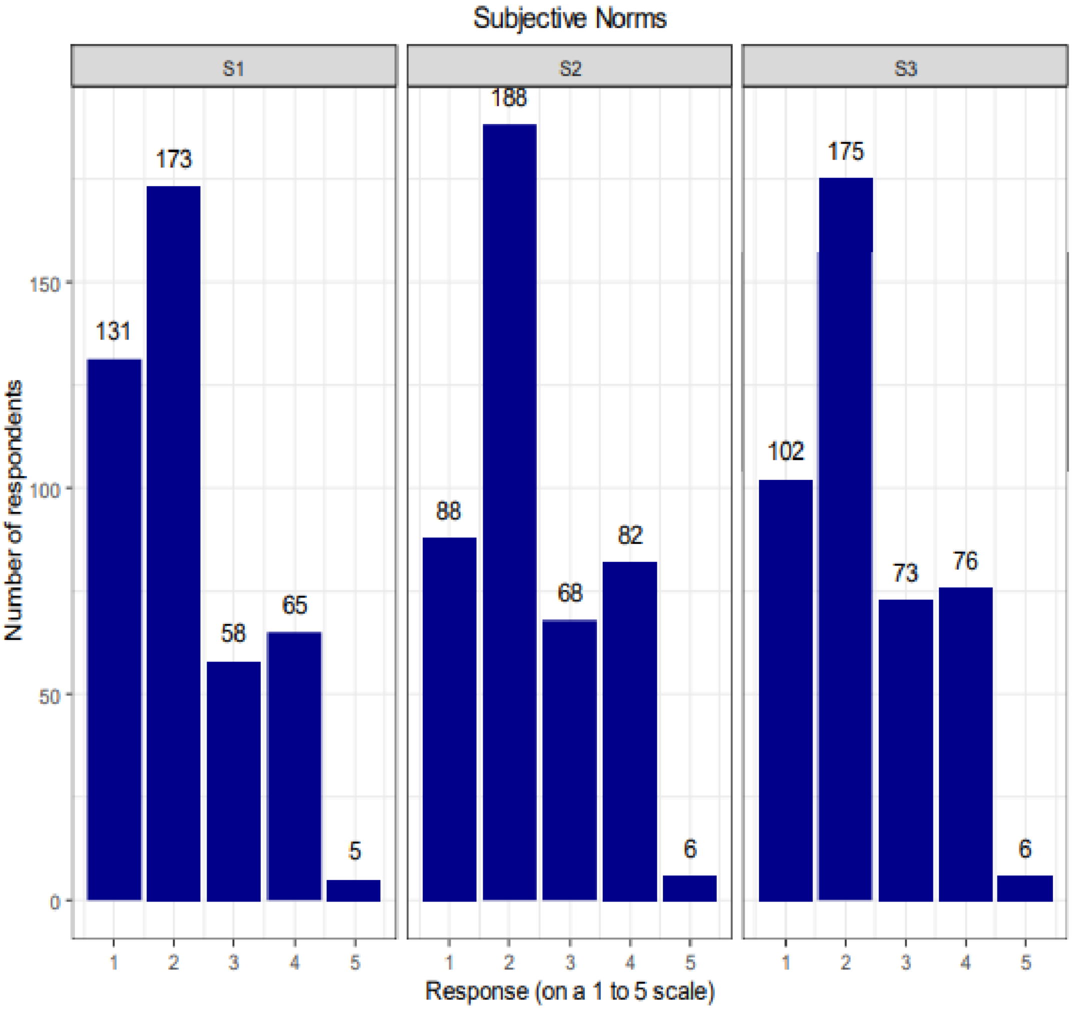


In this category, the respondents were asked to rank on much they agree with the following statements on a scale of 1 to 5, with 1 being strongly disagree and 5 being I strongly agree; my friends and family would choose to use electricity suppliers that use renewable energy, people in my community would be willing to use renewable energy for their home's electricity and lastly, people that I value and admire would prefer electricity from renewable energy. These statements were labelled by the items S1, S2, and S3 respectively. 40% disagreed that their friends and family would choose to use electricity suppliers that use renewable energy followed by 30% of those who strongly disagreed and lastly it was only 5% strongly agreed. Consequently, 44% disagreed that "people in my community would be willing to use renewable energy for their home's electricity", followed by those who disagreed at 20% and only 1% strongly agreed. In the last item, S3, 41% disagreed to the statement that "People that I value and admire would prefer electricity from renewable energy" followed by those who strongly disagreed at 24% and only 1% strongly agreed. The results are as shown in Figure *25* below and are summarised Table 10.

Table 10: Results of the Variable Subjective Norms

S1	S2	S3
1: 131	1: 88	1: 102
2: 173	2:188	2:175
3: 58	3: 68	3: 73
4:65	4: 82	4: 76
5: 5	5: 6	5: 6

Figure 25: Subjective Norms – Variables S1-S3

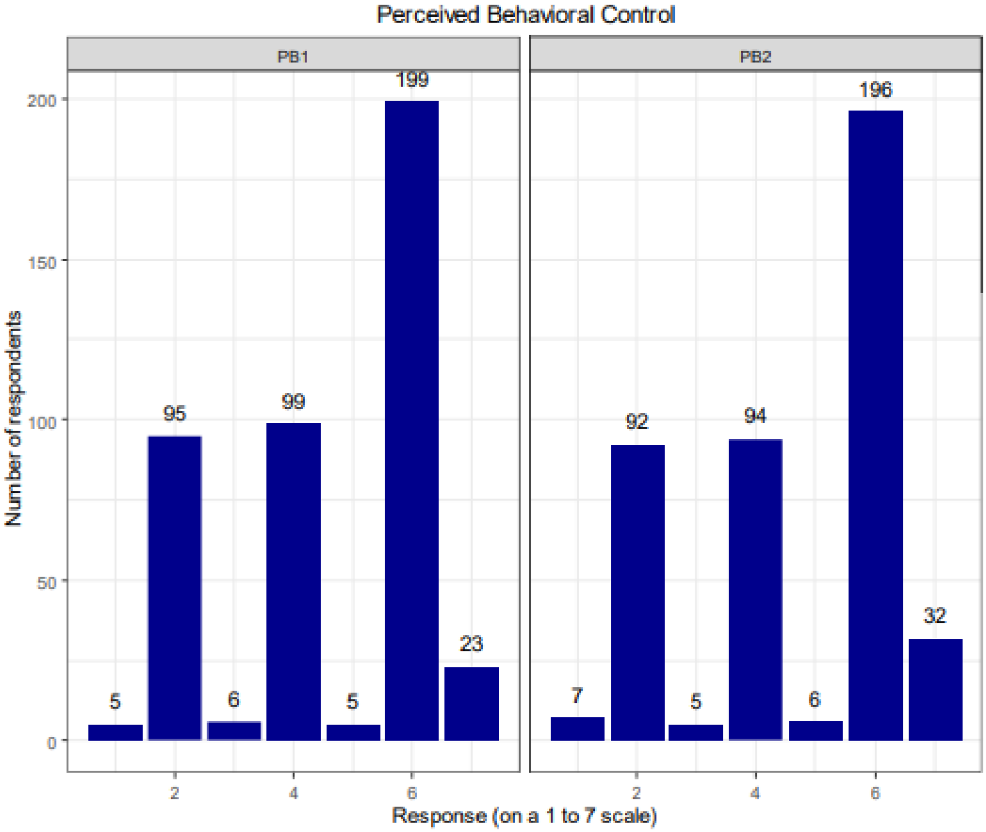


Perceived behavioural control is measured through two variables (PB1 and PB2) by exploring the following statements: ‘if I was the only one to decide, I would use renewable energy for my electricity’, and ‘if I wanted to, I could easily use renewable energy for my home’s electricity’. The category had two items where the respondents were asked to rank how much they agree with the following statements on a scale of 1 to 7, with 1 being I strongly disagree and 7 being I strongly agree. PB1 asked them to rank how much they agree if they were the only ones to decide, they would use renewable energy for their electricity. Those who agreed were leading at 46% followed by those who were neutral at 23% and the least proportion was comprised of those who somewhat agreed at 1%. PB2 asked them to rank how much they agree if they wanted to, they could easily use renewable energy for their home's electricity. 45% agreed, followed by those who were neutral at 22%, and the least proportion was comprised of those who somewhat disagreed at 1%. The results are summarised in Table *11* below.

Table 11: Results of the Variable Perceived Behavioural Control

PB1	**PB2**
1: 5	1: 7
2:95	2:92
3: 6	3: 5
4: 99	4: 94
5: 5	5: 6
6: 199	6: 196
7: 23	7: 32

Figure 26: Perceived Behavioural Control – Variable PB1and PB2



This last category aimed to explore the behaviour of the respondents towards the use of renewable energy. They were asked to rank on much they agree with several statements on a scale of 1 to 7, with 1 being I strongly disagree and 7 being I strongly agree. The items in this category were libelled from B1-B7. The results are presented in Table 12 below and a graphical representation can be found in Figures 27 and 28.

Table 12: Results of the Dependable Variable of the Model, Behaviour

B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
1: 8	1: 9	1: 13	1: 9	1: 11	1: 9	1: 58
2: 78	2: 87	2:81	2: 26	2: 50	2: 100	2: 74
3: 7	3: 5	3: 6	3: 11	3: 5	3: 5	3: 59
4: 96	4: 60	4: 78	4: 133	4: 43	4:67	4:69
5: 6	5: 11	5: 6	5: 7	5: 7	5: 5	5:52
6:196	6:223	6:132	6:225	6:267	6:213	6: 64
7: 32	7: 37	7: 116	7: 21	7: 49	6:33	7: 56

Figure 27: Dependable Variable Behaviour, Observed Variables B1-B4

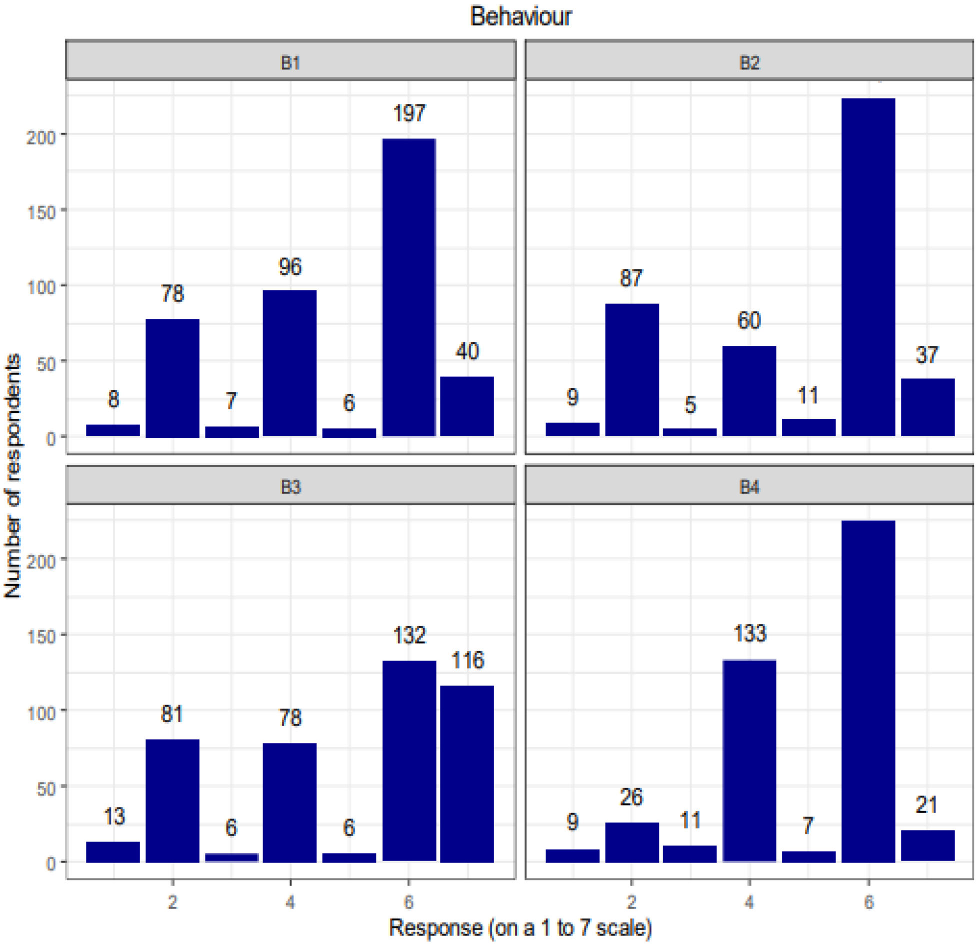
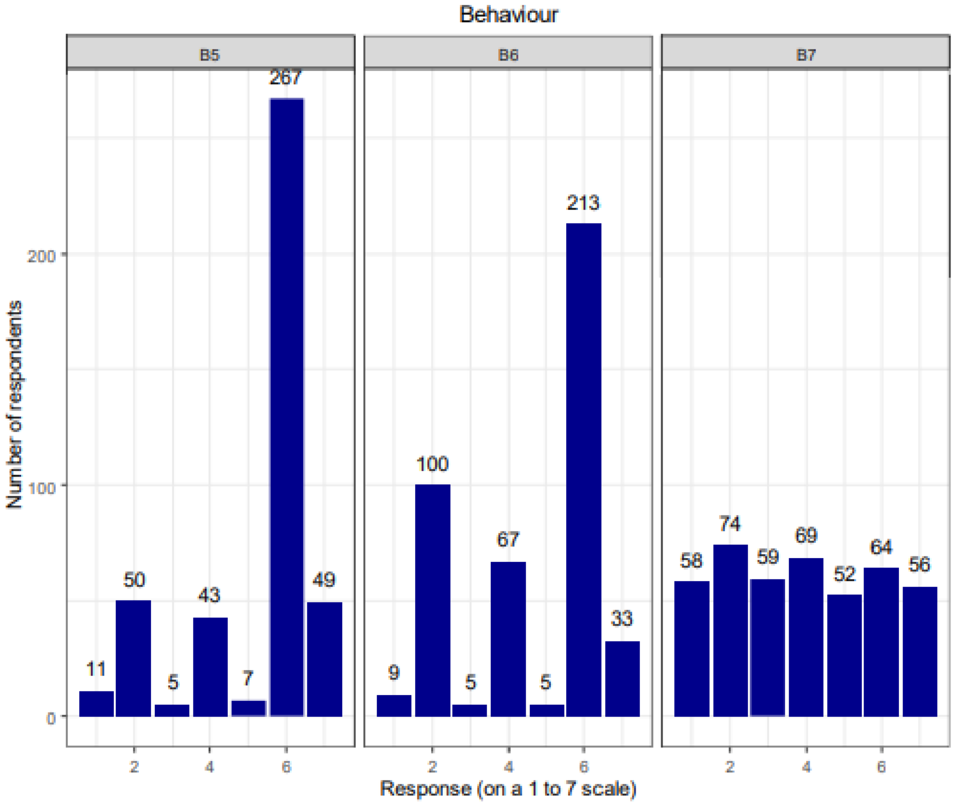


Figure 28: Dependable Variable Behaviour, Observed Variables B5-B7



Cronbach's Alpha

The Cronbach's alpha for the following variables was calculated: (A1-7; P1-P9; S1-S3; PB1-PB2 and B1-B7). These variables were grouped into five groups named; Awareness Level, Perceptions, Subjective Norms, Perceived Behavioural control, and Behaviour. The groups were composed of seven, nine, three, two, and seven observed variables respectively. The alpha values were calculated using R software and Table *13* below shows the results that were obtained.

Table 13: Cronbach's Alpha

Group	Cronbach's Alpha	Internal Consistency (Comment)
Awareness Level	0.84248	Very Good
Perception	0.73039	Good
Subjective Norms	0.79371	Good
Perceived Behavioural Control	0.86321	Very Good
Behaviour	0.74127	Good

The above results indicate that all the groups had an acceptable and reliable high internal consistency of the items. This suggests that the items in each group were reliable for further analysis and modelling such as Structural Equation Modelling (SEM).

Structural Equation Modelling

This is a multivariate statistical analysis technique that is used to analyse structural relationships. It combines both factor analysis and multiple regression analysis. It analyses the relationship between measured variables and latent constructs. It differs from other techniques because it tests the direct and indirect effects on pre-assumed causal relationships. The major assumptions of the structural equation modelling (SEM) are multivariate normality, no systematic missing data, sufficiently large sample size, and correct model specification. The main advantage of SEM is that it enables us to develop complex path models with direct and indirect effects. (Fan et al., 2016). As mentioned above, the five latent variables constructed were Awareness Level, Perception, Subjective Norms, Perceived Behavioural Control, and Behaviour. These latent variables were composed of the following number of items: 7,9,3,2 and 7 items respectively. All the latent variables were included in the model and the model converged.

A confirmatory factor analysis was performed for each group to assess the unidimensionality of the measure items. The results of the confirmatory factor analysis indicated that all the items loaded on their respective groups and also most of the items were significant at the 5% level.

Classical accounts of maximum likelihood (ML) estimation of structural equation models for continuous outcomes involve normality assumptions. Therefore, in order to test the hypothesis of the study, the structural equation model was estimated by the ML using the lavaan package in R. The model had 64 parameters with 432 observations. The results of the SEM model are presented in Table 14 below and the path analysis is illustrated in Figure 29. Table *14* below presents the estimation results of the structural equation modelling (SEM) where Behaviour is the dependent variable.

Table 14: Estimation results of the structural equation modelling (SEM) – Behaviour is the dependent variable.

Causal relationship	**Non-normalized Path Coefficient**	**Standard Error**	**P**	**Normalized Path Coefficient**
Behaviour ← Perception	0.550	0.061	0.000	0.543
Behaviour ← Awareness/Knowledge	0.402	0.153	0.009	0.449
Behaviour ← Perceived Behavioral Control	0.140	0.120	0.244	0.149
Behaviour ← Subjective Norms	0.137	0.100	0.170	0.073
Perception ← Awareness/Knowledge	0.734	0.054	0.000	0.829
Behaviour← B1	1.000	-	-	0.778
Behaviour ← B2	0.922	0.058	0.000	0.696
Behaviour ← B3	1.148	0.062	0.000	0.793
Behaviour← B4	0.238	0.050	0.000	0.226
Behaviour ← B5	0.555	0.056	0.000	0.464
Behaviour ← B6	1.130	0.057	0.000	0.832

Behaviour ← B7	0.080	0.071	0.261	0.054
Awareness/Knowledge ← A1	1.000	-	-	0.791
Awareness/Knowledge← A2	0.688	0.051	0.000	0.618
Awareness/Knowledge ← A3	0.888	0.053	0.000	0.735
Awareness/Knowledge ← A4	0.850	0.058	0.000	0.655
Awareness/Knowledge ← A5	0.983	0.053	0.000	0.796
Awareness/Knowledge ←A6	0.999	0.049	0.000	0.847
Awareness/Knowledge← A7	-0.011	0.040	0.788	-0.013
Perception ← P1	1.000	-	-	0.711
Perception← P2	1.071	0.070	0.000	0.776
Perception ← P3	1.025	0.072	0.000	0.724
Perception ← P4	0.446	0.067	0.000	0.336
Perception← P5	0.448	0.065	0.000	0.347
Perception← P6	0.119	0.048	0.014	0.124
Perception← P7	0.364	0.051	0.000	0.361
Perception← P8	0.893	0.070	0.000	0.648
Perception← P9	0.253	0.064	0.000	0.200
Subjective Norms← S1	1.000	-	-	0.674
Subjective Norms← S2	1.184	0.086	0.000	0.802
Subjective Norms← S3	1.172	0.087	0.000	0.787
Perceived behavioral control← PB1	1.000	-	-	0.832
Perceived behavioral control← PB2	1.116	0.047	0.000	0.912
X2	2370.339			
df	342			
RMSEA	0.117			
CFI (Comparative Fit Index)	0.731			
TFI (Tucker–Lewis Index)	0.702			

The statistical test used to test the goodness of fit of the model is the Chi-square test. The model is significant if the p-value is less than 0.05 at a 5% level of significance. The results showed that the model was a good fit to the data where the Chi-square statistic was 2370.339 with 342 degrees of freedom (p=0). The Comparative fit index (CFI) was 0.731, which is relatively good, and the Tucker–Lewis Index (TFI) was 0.702 which was also good. In addition to these indices, the Root Mean Square Error of Approximation (RMSEA) was 0.1 which is in the acceptable upper bound. Therefore, from these results, we can confidently say that the model was a good fit for the data.

The model indicates that the behaviour towards the use of renewable energy is significantly influenced by perception and awareness at 95% confidence where perception leads by 54.3%, then awareness level by 44.9%. There is a positive association between behaviour and all its predictors toward the use of renewable energy. However, the association is only significant at perception and awareness level. The model results also indicate that a unit increase in perception towards the use of renewable energy results in an increase in behaviour by 0.55 units if all other conditions are kept constant. This implies that perception has a positive association with the behaviour towards the use of renewable energy as earlier witnessed. A unit increase in awareness about the use of renewable energy results in an increase in behaviour by 0.402 units towards the use of renewable energy if all other conditions are kept constant.

In summary, the results show that the contribution of perception about the use of energy is the greatest among all other factors at 54.3% followed by awareness level at 44.9%, then perceived behavioural control at 14.9%, and lastly subjective norms at 7.3%. The interaction between perception and awareness is significant at a 5% level (p=0.000) and the interaction stands at 82.9%. This is a very strong association that tells us that based on the awareness itself, the perceptions towards the use of renewable energy may change.

The model also gave results for each construct with its respective items. Within the "Perceived Behavioural Control", the group has two variables PB1 and PB2. All the variables have a statistically significant impact on the perceived behaviour control about the use of renewable energy. It was also observed that the variables had a reliability of 86.32%.

The second group which is known as the Subjective Norms had three variables and all of them had a statistically significant impact on subjective norms about the use of renewable energy with p=0.000. The greatest contributor was item S2(People in my community would be willing to use renewable energy for their home's electricity) with 80.2% followed by variable S3 (People that I value and admire would prefer electricity from renewable energy) with 78.7% and the last contributing item was S1 (My friends and family would choose to use electricity suppliers that use renewable energy) with 67.4%. Most importantly, these variables had a good reliability of 79.37% amongst themselves in the group.

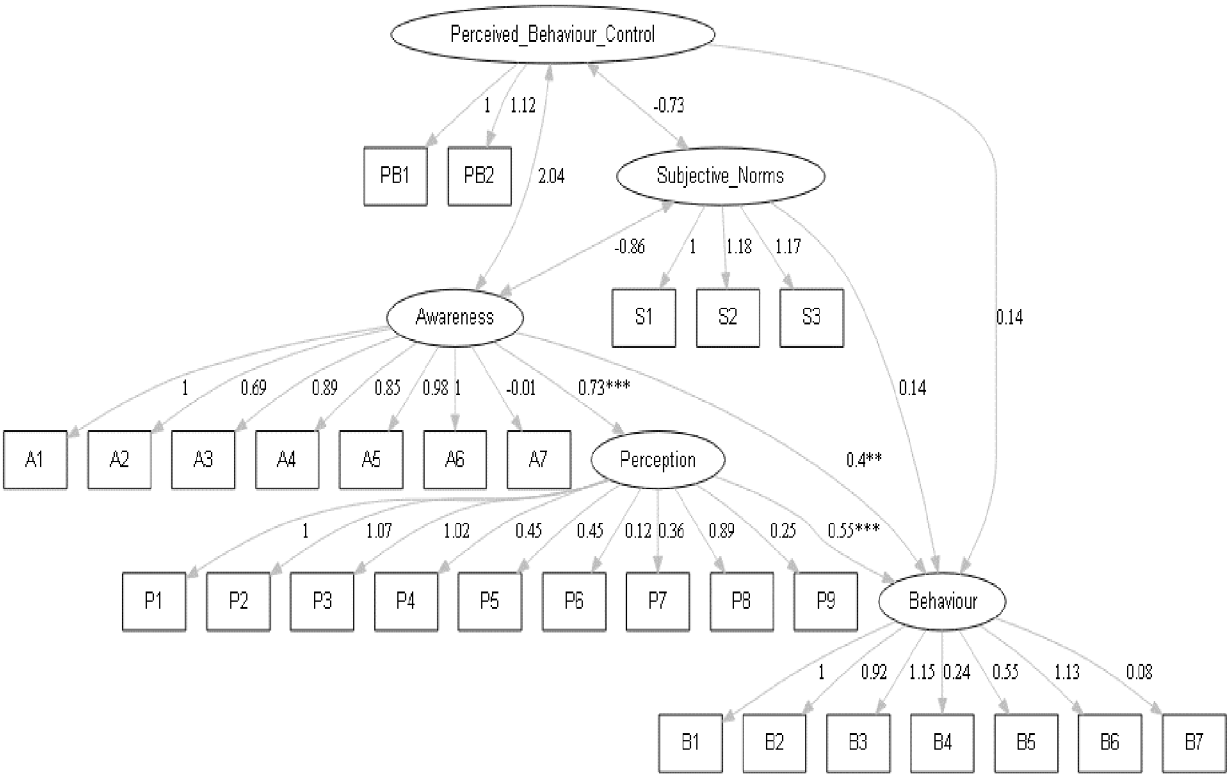
While looking at the awareness/knowledge level, the variables showed a statistically significant impact (p=0.000) on the level of knowledge or awareness about the use of renewable energy in the area. More specifically, the leading A1(the overall knowledge regarding wind energy) with 86.4%. The last contributor in this group was variable A2(the knowledge on the environmental issues) with 61.8%. Variables had a very good reliability of 84.25% amongst themselves in the group.

The second last group which refers to the perception of the use of renewable energy showed that all the nine variables had a statistically significant impact on the perception about the use of renewable energy. The greatest contributor was P2 (Please rank how worried you are about energy security on a scale of 1 to 7, 1 being the least worried and 7 being the most worried.) with 77.6%, followed by P3(The most important benefit of wind energy is an economic development) with 72.4% and the last contributor was P6 (The most important benefit of wind energy is the country's energy security) with 12.4%. In overall conclusion, consumers believe that the most important benefit of wind energy is the country's energy security. Therefore, they find that wind energy plays a great in the security of the country's provision of energy to its residents. Lastly, the variables had an acceptable reliability of 73.04%.

Finally, the last group is the behaviour on the use of renewable energy. This was the dependent variable in the model. Six of the seven variables in this group showed a statistically significant impact on behaviour towards the use of renewable energy and the group had a reliability of 74.13% which is acceptable. B6 (During my last purchase of an electric appliance/device, I considered primarily its energy efficiency) was the greatest contributor in the group with 83.2%. which means that the consumers were sensitive to the energy efficiency of the appliance. This variable was followed by B3 (I would be willing to accept a wind park within 500m from my property) with 79.3%. which means that the consumers were positive with the idea of a wind park. The least significant contributor to the group was B4 (When buying or building a home, I give importance to the location) with 22.5%. The insignificant item was B7 (During my last purchase of an electric appliance/device, I considered primarily the design of the device).

From the results obtained above, the five constructs were awareness/knowledge level, perception, perceived behavioural control, subjective norms, and behaviour. Behaviour was the dependent variable in the SEM model while the rest were its predictors. Perception and awareness/knowledge level were significant predictors of behaviour while perceived behavioural control and subjective norms were insignificant at a 5% level of significance. All the independent variables had a positive association with the behaviour toward the use of renewable energy.

Figure 29: Path Analysis



4.3.2 Possible Mitigation Pathways

Visual impacts are not taken into account throughout the siting process because of the subjective nature of this issue. Virtual views from specific locations in the surrounding area can be precisely depicted using computer modelling techniques, and careful design combined with community engagement can help ease many local worries.
Visual impacts cannot be avoided; however, they can be reduced through proper turbine location and the use of setbacks. Because terrain and other factors impact what is appropriate and acceptable, setbacks, or the distance between a turbine and another property use (home, road, or other business), vary from jurisdiction to jurisdiction and project to project.

Hofer et al., 2016, suggest that the wind farm siting can be improved by providing a holistic multi-criteria decision-making strategy that integrates techno-economic, socio-political, and environmental factors that are formulated in such a way that societal acceptance-related issues are especially stressed. They use a GIS-based Analytic Hierarchy Process technique, in which a group of local experts and stakeholders are asked to pairwise assess the included criteria to determine their relative relevance. According to the findings, 9.4 percent of the research area in Aachen, Germany is still open for wind energy development, while just 1.74 percent of the territory has high appropriateness. The northern half of the region, in particular, has a lot of untapped wind energy potential. The model's accuracy and dependability are confirmed by a comparison to the location of current wind farms (Höfer et al., 2016).

It is now possible to determine the WP visual influence on a landscape thanks to the recent presentation of a number of methods to this problem and the advancement of software that enables a realistic simulation of the natural environment. Kokologos et al., 2014, propose a computation that enables the installation's location to be controlled in terms of aesthetics (less visual impact, greater aesthetic integration of the project in the landscape). The methodology they describe combines 3D simulation and quantitative indicators (Spanish method). The findings indicated that this combination is a useful and simple tool with room for advancement in the future. The combined use of quantitative indicators and software is advised because it enables the practical examination of the visual impact prior to the construction of the wind farm, moving one step ahead of customary practices that are studying the gravity of the existing visual impact and enabling the implementation of measures to lessen it. The software application also reduces the amount of time needed to calculate some of the coefficients of the Spanish method's indicators, improves its efficiency and accuracy, and thus strengthens its credibility. A visual effect indicator is assessed independently for each of the attractive potential observation places at a certain distance (settlements, roads, in particular monuments like monasteries or landscapes of great natural beauty). This makes it easier to assess the overall effect on the wider area and identify any hotspots that require additional thought. A realistic simulation of the area with all the information required to determine the visual impact is possible because to the abundance of inputs for both the natural and the artificial environments (Kokologos et al., 2014).

Another study (Sklenicka & Zouhar, 2018), that examined the evaluation of 400 respondents from four countries over images of 32 landscapes, proposed a method for predicting the visual impact of WTs on a landscape based on indices. The proposed method objectivizes the visual impact assessments of these wind farms by taking into consideration three basic landscape components which are relief, land cover, and landscape pattern. The indices used are automatically measurable in a GIS environment, which facilitates their use for large regions, which would be impossible to achieve if we were to rely on indices that employ the subjective opinions of the evaluator.

According to a study published in 2021, 1000–1200 m zoning limits only have minimal externalities on the surrounding settlements (Peri & Tal, 2021).
This study created a scientific basis for choosing the ideal setback distance from populated areas. It starts by describing the trade-off between the environmental externalities of turbines and their potential for energy in Israel's northern region, where prospective wind farms are currently being taken into consideration. Using GIS software, the analysis can quantify the energy potential as well as the effects of noise and shadow flickering. They analysed six different regulatory approaches to setback distance for limiting wind turbines based on geographic data and assess how they might be implemented in northern Israel. The findings show that annoyance levels depend on site-specific variables, which in certain places are marginal, at setbacks of 700–800 m.

Another study published in 2022 (Haac et al., 2022) examined regulations governing shadow flicker in the case study areas and compared them to the exposure in the surrounding areas. They found that noise limits could serve as a proxy for shadow flicker exposure, as 90% of those exposed to wind turbine sound of no more than 45 dBA L1h had shadow flicker exposure of less than 8 h per year.

Research has provided evidence for the employment of economic and social incentives in order to implicate the public. The authors of a recent study (Rodríguez-Segura et al., 2023) support lines of finance and business models that enable olive growers to install photovoltaic and wind-power plants on their land, so as to ensure that they receive economic benefits from these projects (either by renting the land to the power company or by selling the electricity they produce). They also suggest that increased involvement of local governments in issues like information gaps, grants, and local initiatives might improve public opinion of RES programs. They also propose the creation of energy plans with input from, and with the help of, the local community. Knowledgeable locals who take part in energy plans and projects can ensure the success of such programs due to higher levels of social acceptance. Last but not least, they recommend the encouragement of the growth of energy communities to strengthen the population's identified shortcomings.

A recent study in Germany (Kirchhoff et al., 2022) examines the relationships between the evaluation of wind turbines and general attitudes towards them and determines that supporters of wind energy tend to rate landscapes with wind turbines substantially better than non-supporters. A possible reason for this is the structures' significantly different moral connotations. Their results support that statements about the visual impact of mast-like structures in landscapes are strongly affected by moral opinions on these structures that are influenced by their moral associations. Therefore, such statements reflect not opinions on scenic beauty but moral judgments. These outcomes have significant implications not only for the assessment of the impact of wind turbines on the landscapes' aesthetic qualities but for the interpretation of visual landscape quality assessments in general. They therefore propose a methodological approach for population surveys which necessitate to focus not on aesthetics, but on judgments on their necessity of construction to attain energy transition, impacts on human health ecological impacts and then impacts on the landscape's scenic beauty.

The results of the survey in Argolis plain show that behaviour is greatly influenced by perceptions and awareness. The findings indicate that promotion initiatives could help close the gap between perceptions and actual behaviour, which would ultimately increase people's willingness to accept wind energy and/or wind turbines in their vicinity. The implication of the results arising from the structural equation modelling indicates that the consumers should be made aware of the use of renewable energy either through promotional campaigns or social education groups about the benefits of renewable energy and thus contribute to or maintain proper behaviour towards the use of renewable energy. Lastly, it is an expectation that the announcement of capacity-building projects such as wind park for renewable energy sources to supply the citizens' homes with electricity will further empower the improvements in the awareness towards the use of renewable energy.

Table 15: Mitigation Pathways that Enable Social Acceptability

	Mitigation Pathway
Aesthetic Impact	Multi-criteria decision-making strategy proposed by (Höfer et al., 2016)
	Computational methodology proposed by (Kokologos et al., 2014)
	Methodological approach proposed by (Kirchhoff et al., 2022)
	Landscape indices-based method for predicting the visual impact of WTs proposed by (Sklenicka & Zouhar, 2018)
Noise and Flicker	Optimal setback distance of 1,000–1,200 m from the closest settlement (Peri & Tal, 2021)
	Regulating shadow flicker as proposed by (Haac et al., 2022)
Negative Public Attitudes	Economic and social incentives as described by (Rodriguez-Segura et al., 2023)
	Inclusion of the local population in the decision making as shown by the survey results in Argolis Plain
	Co-owning of the wind park with the local population as shown by the survey results in Argolis Plain

	Economic incentives such as discounts in their electricity bills as shown by the survey results in Argolis Plain
	Promotional campaigns that focus on the awareness of local populations, as shown by the survey results in Argolis Plain

5 Discussion

The production of electricity from wind grew by a record 273 TWh in 2021 (up 17%). Its growth rate was the greatest among all renewable power technologies and was 55% greater than what was achieved in 2020. This exceptional growth in wind capacity additions, which reached 113 GW in 2020 compared to just 59 GW in 2019, allowed for such quick expansion. However, to meet the requirements of the Net Zero Emissions by 2050 Scenario, which calls for nearly 7 900 TWh of wind electricity generation in 2030, average annual capacity additions must be increased to almost 250 GW, which is more than twice the record growth of 2020 (IEA,2022). The most crucial areas for improvement are streamlining onshore wind permits and lowering the cost of offshore wind in order to accomplish this level of sustained capacity expansion.

Even the widespread deployment of today's clean-energy solutions, such as wind-based electricity, has negative consequences. Wind power's positive and negative effects are not only complex, but they also vary depending on the season, climate, time scale, location, ecosystem type, and other pertinent aspects. It's worth noting that many of these variables are cumulative, and their environmental effects can combine in complicated behaviours and places linked to soil destruction in wind power installations, deforestation, and numerous human health changes. Assessing the effects of wind power development is difficult due to these complications, and it is dependent on a lack of research concerns. However, there are numerous types of information that can be used for future implementation. Although the environmental impact of wind farms is significantly smaller than that of electricity generated from existing sources, it should nevertheless be examined and mitigated if necessary.

Even though the technological requirements for such a deployment are sufficient, it is apparent that wind energy is not developing in a sufficient rhythm that is needed to get on the Net Zero Scenario trajectory. In this thesis, it was attempted to find the reasons for which wind energy is not progressing as expected and propose solutions that would overcome those barriers.

Studying the scientific literature, it soon became apparent that the reasons behind this lagging are complex and interconnected. The interrelations between capital costs, transmission and siting problems, disconnect between science and policies, reliability misconceptions and public attitudes, are difficult to unfold and pinpoint the exact combination of culprits. However, in an attempt to answer the research questions by detecting the reasons for which wind energy is lagging behind and propose mitigation measures, this thesis was created.

The main environmental problem that was identified was the recycling of the blades, that results as waste from end-of-life wind turbines. It's impossible to pinpoint a single major impediment to composite recycling because there are so many. Composites recycling is not a technological issue. Despite the fact that recycling composites technologies exist, they are generally used on a modest local and regional scale. In fact, an increasing number of businesses are providing composite recycling services in a variety of formats. Mechanical, pyrolysis, incineration, and landfilling are the most often employed commercial procedures today. The use of the recyclate in other applications and processes, on the other hand, is a major issue - secondary applications and market development for composites are still in their infancy. There are currently no established supply chains to absorb the anticipated quantities of recovered fibres. The impact of different processing methods on fibre quality (length, strength, and stiffness qualities) varies, determining the secondary use. Recycled fibres must first be examined and characterized, and then the qualities of the fibre must be matched to prospective uses. There have been far too few commercial applications of recycled composites examined to date.

Another issue is the economies of scale for commercial processing and recycling operations, as well as their geographic location in relation to wind farms. When recycling, we must consider the effects of sectioning and transferring the materials. In addition, securing a consistent supply of feedstock (waste composite) is problematic because it is dependent on wind farm owners' decommissioning decisions. Furthermore, recyclate materials are too expensive to compete with virgin materials. If waste is to be exploited as a resource after a lengthy lifetime of turbine operation, detailed product documentation (material specifications) must be kept, taking into account changes in component material composition between manufacturers.

Legislation plays an important role in composite recycling. The laws governing waste and recycling varied by location. Landfill is a reasonably inexpensive disposal option, although it is the least favoured choice under the Waste Framework Directive of the European Union. Some Member States have implemented landfill taxes to discourage disposal, while others have outright prohibited composites from being disposed of in landfills, such as Germany, with other EU members expected to follow suit. According to some, legislative trends tend to improve producer accountability, increase recycling rates, and minimize landfill availability. Others argue the contrary, stating that regulation can stifle innovation in small and medium-sized businesses.

To mitigate this problem, it was employed an integrated strategy for circular urban regeneration using processes that are driven by culture and the environment in a theoretical conceptualization for the management of end-of-life wind turbine blades. The primary recycling (upcycling) and secondary recycling (downcycling) of the blades, as well as the three-dimensional sustainability, are the core circular economy ideas that underpin this strategy (social-economic-environmental). Upcycling transforms blade waste into items with comparable to or superior to the original product's qualities without causing any chemical deterioration, whereas downcycling transforms blade waste into products that are less structurally sound and/or of inferior quality (Ghisellini et al., 2016). In this conceptual framework the two concepts of blade management and urban regeneration were coupled. The composite materials used in the blades' durability and strength allow the recycled products to be employed in a variety of urban regeneration projects while still being sustainable. For instance, initiatives in architecture, planning, and design can revitalize urban areas while minimizing their environmental impact, generating employment possibilities, and enhancing the cultural and social life of the neighbourhood. The circularity of the transformation processes associated with these kinds of urban regeneration programs is emphasized in this theoretical framework. The circularity is related to various (transformation) processes and players, not just the upcycling of the materials per se, but also to co-evolutionary interactions among them. To ensure the sustainability of urban regeneration programs, a variety of players, skills, and techniques must be utilized. Providing financial resources and a governance structure requires cooperation between the public and private sectors. A supportive regulatory framework containing norms and legislation is also made available through this collaboration, helping to assure health and safety and get over technical obstacles to project implementation. To guarantee that these projects represent the area's identity and address the community's requirements, community involvement is essential. In other words, the circular economy continues to place emphasis on the recovery, reuse, and recycling of natural resources while simultaneously emphasizing the application of transformational processes to create social, cultural, and economic progress.

Another approach for the recycling of blades is the cement co-processing. In co-processing, shredded wind turbine blades are employed as fresh materials in the manufacture of cement, reducing the reliance on fossil fuels and raw resources. In particular, the polymer matrix is burned as fuel (generated from waste) for cement manufacturing, and the glass fibre is recycled as a material for cement clinker. The cement kiln route is regarded as the best method for recovering blade debris since it offers material and energy recovery, has an easy supply chain, and is economical and effective (Cembureau, 2013; Schmid et al., 2020). Using the ideas of the circular economy, many urban regeneration projects can make use of the greener cement created by recycling blade waste. Concrete, the most widely used building material in urbanized areas, is created with cement as the binder. According to the proposed comprehensive theoretical conceptualization of urban regeneration transformations, the production and use of greener cement and, consequently, concrete, creates new business opportunities, safe and affordable housing, workplaces, industrial sites, transportation systems, infrastructure for sanitation, energy, water, and telecommunication, as well as other life-supporting and well-being structures that are frequently made using base concrete.

Urban sustainability can be enhanced by using green cement in place of conventional cement and by involving all stakeholders in the planning, execution, and management of regeneration projects. Beginning with the advantages for the environment, we minimize CO2 emissions over the course of cement use, extending the lifespan of buildings and infrastructure, saving resources, and lowering air pollution. In addition to environmental benefits, extending the useful life of these urban regeneration projects brings cultural advantages, such as social and financial ones. By lowering environmental emissions and raising the energy efficiency of cooling and heating, the projects' overall expenses of development, use, and maintenance are more cost-effective while being more energy efficient. As a result, the indirect benefits of using cement made from wind turbine waste instead of ordinary cement have a favourable impact on the users' quality of life and wellbeing.

Wind farms can have damaging effects on local biodiversity by reducing, fragmenting, and degrading natural habitats for flora and fauna and by resulting to avian collision for bats and birds. The green-green dilemma, idem the risk for wind turbines to harm wildlife either through collisions or through noise pollution, habitat loss, and reduced survival or reproduction rates, is a major obstacle for the acceptability of wind energy. Analysing the energy and environmental legal frameworks, it is obvious that a conflict would arise thereof. In order to solve this dilemma and promote a fair and equal energy transition without compromising biodiversity, policy makers should harmonise the legal and regulatory framework. Decisions about siting and development should be taking into consideration biodiversity issues and scientists and decision makers should be informing each other for new developments and projects. Our politics cannot continue being ignorant to the scientific consensus and the political agendas must include environmental protection. As shown in the respective chapter of this thesis about the ecological barriers (chaper 4.2), there is a big number of research papers indicating mitigation measures for avoidance and reduction of the negative effects. From radar-based solutions and tracking algorithms to science-informed decisions of the siting process, there are numerous measures that can mitigate the negative effects. The next step is to bring scientists and politicians to work together, in order to achieve our climate goals and enable the decarbonisation of our societies.

Regarding the public acceptance of wind farms and after analysing the results, the conclusion is that, of most of the components identified in this study (awareness/knowledge, perception, perceived behavioural control and subjective norms), explain how people behave toward wind parks and/or wind energy. These results build on existing evidence that behaviour is influenced by perceptions and attitudes. The practical implications of this findings are that promotional initiatives should focus on raising people's awareness on the advantages of wind energy and educating them on these advantages in order to help promote wind energy in the right way. There is now a lot of room for improving public attitudes and opinions not only in the study area, but also worldwide. The findings indicate that those promotion initiatives could help close the gap between perceptions and actual behaviour, which would ultimately increase people's willingness to accept wind energy and/or wind turbines in their vicinity.
Literature also indicates that the inclusion of the local population in the decision making, the co-owning of the wind park with the local population and other economic incentives such as discounts in their electricity bills, are shown to increase public acceptance of wind energy and/or wind turbines.

This thesis' limitations include mainly data and statistical limitations, as well as impact limitations. It would be optimal to have an even bigger number of respondents and there is the risk that the results of the survey can be population specific and have a strong regional focus. Even though the results were generalised, it must be noted that the case study was a rural area in Southern Greece, with its own cultural and demographical characteristics. Another limitation was the global pandemic of Covid-19, which hindered me from having more surveys and delayed the process. However, it was easily overcome with the use of online questionnaires, which eventually proved to be a more reliable method.
For future researcher, therefore, I would advise that the surveys are only online. When administered face-to-face, respondents tend to be more reluctant to tell the truth, out of fear that they will be judged by the researcher.
Future surveys can expand the target respondents to visitors of recreational areas that cater to tourism. Researchers could explore the willingness of visitors to return to the studied areas, and their perception of the wind energy/wind turbines. The results could be compared to the attitudes of local and permanent populations. Last but not least, the surveys could be administered anew, after the latest geopolitical events and the war in Ukraine, where the energy security variables will have significantly different results. Since the survey in this thesis was already finished by the time that the war began, it is highly likely that the results would be significantly different now.

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