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Using a GIS to enable an economic, land use and energy output comparison between small wind powered turbines and large-scale wind farms: the case of Oslo, Norway.

Figure 1. Photograph - Oslo View.

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Colin Robert Potter (2023). Using a GIS to enable an economic, land use and energy output comparison between small wind powered turbines and large-scale wind farms : the case of Oslo, Norway.

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Dedicated to my late father John Potter, who always encouraged me to learn, and to my granddaughter Charlotte Catherine, I hope my work will help to make the world you are inheriting a little better.

Thanks and gratitude to Mitch Selander, a scholar and a gentleman, your endless support, coaching, enthusiasm, eye for detail and friendship are greatly appreciated!

Abstract

Responding to an identified knowledge gap, the study aims to determine if smaller wind turbines located on top of existing urban buildings are more resource efficient (land utilization and economically) than large scale wind farms. To answer this question, using a GIS, the resource efficiency of the Roan wind farm in Northern Norway was compared to a theoretical modeled installation of small-scale wind turbines on top of buildings within a 2km radius study zone in central Oslo.

This research is quite timely, with recent community resistance against the ecological and lifestyle impacts of large wind farms and people now considering personally sustainable alternatives to large scale wind farms including using smaller wind turbines and on-site power generation. It is anticipated that a study of this type using a GIS will inform better decision making within both governments and the private business sector.

To create the model, a GIS was used to combine a range of map layers supplied by the Norwegian Mapping Authority to digitize the buildings within the urban study zone. This process included an estimation of roof areas and a suitability selection based on the elevation of the buildings, resulting in turbines placed across the study area. These layers were combined with turbine and wind speed mapping data to estimate power outputs and 20-year life cycle costing data for the turbines. From this modelled installation, a GIS was used to calculate the kWh per m^2 and profit or loss per kWh which were then compared to the same 20-year data for the Roan Wind farm

In the study there were data limitations due to accuracy issues of the GIS processes engaged, the problematic nature of modeling and estimating wind speeds in urban areas and a reliance on a manual digitization process. However, the results indicate that the modeled installation in Oslo does use land more efficiently than the Roan wind farm to generate power, however, it was not as economically viable as the wind farm. Of significance is that if only those buildings greater than 60 meters high in the study area were used to generate power that this would result in a small profit per kWh produced, which increased with building heights. However, this was still not comparable to the profits achieved by the wind farm.

Recommendations for further research include the potential for high resolution 3d modeling of the study area and the testing of on-site turbine installations. Of note is a potential study on the use of small-scale wind turbines coupled directly to heat pumps to supply heating and cooling requirements, this later application holds great promise for the future.

Keywords.

Geography, GIS, Wind power, Renewable energy sources, urban wind energy, urban areas, planning, vertical axis wind turbines, comparative studies, urban integrated energy systems, Oslo, Roan

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List of Abbreviations

AMSL	Above Mean Sea Level
ASL	Above Surface level
AWEA	American Wind Energy Association
BWT	Built environment wind turbines
CBD	Central Business District
CICERO	Center for International Climate and Environmental Research
CHP	Combined Heat and Power
COP	Co-efficiency of Performance
DEM	Digital Elevation Model
DOM	Digital Surface Model - Digital model includes the heights of buildings and human infrastructure
DTM	Digital Terrain Model – Digital model only includes the natural heights (terrain) of the land
GIS	Geographical Information System
Gwh	Gigawatt hours
HAWT	Horizontal Axis Wind Turbine
kW	Kilowatt
kWh	Kilowatt Hours
LCOE	Levelized cost of energy
LCC	Life cycle costing
LiDAR	Light Detection and Ranging
m	Meter
m/s	Meters per second
NIMBY	Not in my backyard
NMPE	Norwegian Ministry of Petroleum and Energy
NVE	Norwegian Water Resources and Energy Directorate
PCS	Projected coordinate system
POP	Population
PV	Photo-voltaic
TWh	Terawatt Hours
USD$	US Dollar
UTM	Universal Transverse Mercator
VAWT	Vertical Axis Wind Turbine
WWEA	World Wind Energy Association

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1. Introduction

1.1 Wind Energy status

According to the Global Wind Energy Council (2020) the amount of energy generated through renewable wind power increased by almost 20% between 2018 and 2019. This increase has been mainly because of countries expanding their renewal energy capacity in an effort to limit their greenhouse gas emissions in order to meet the Paris Agreement global target temperature increases limit of 2°C above the pre-industrial era level. In addition to this, wind energy generation is also becoming an increasingly economic viability clean energy source.

The introduction of new technologies and materials has resulted in the international implementation of cost-effective large-scale wind farms consisting of banks of huge propellers mounted on towers over 100 meters above the land and sea surface driving large turbines to generate electricity. This technology is now a proven effective sustainable energy resource, and its introduction has recently accelerated rapidly due in part to peak oil fears (US Energy Information Administration, 2020).

In addition to this, recent events including the conflict between Russia and Ukraine have resulted in huge global increases in the price of oil, gas and coal and the general cost of power. Specifically In Ukraine bomb strikes have resulted in damaged electricity grids and power stations and this has resulting in critical reductions in the availability of power for heating and cooking, an impact that has also been felt in neighboring countries. These events have highlighted the need for countries to consider independent power generation strategies that are not reliant on the importation of fossil fuels or the use of large power stations. Wind being a free and available resource across the world could be considered as an ideal supplement to existing power generation.

1.2 Large scale wind farm energy generation in Norway

Because Norway has a massive hydropower network that accounted for 90% of the country's electricity production in 2019 (NVE 2019) the development of the land-based wind power has been limited in comparison to other European countries (Inderberg et al., 2019). Even though it has some of Europe's most productive wind-based wind resources (NVE, 2019).

However, the Norwegian Government has been increasingly supportive of land-based wind power generation, and this has stimulated its development. (Dugstad, et al, 2020). This is due to several economic, political, and environmental factors including the increased integration between the European and Norwegian Energy market, with the exporting of electricity and shared grids across boundaries viewed as a profitable enterprise and falling installation costs for wind power generation (Inderberg et al., 2019). Furthermore, there is a need for clean energy to further electrify and convert fossil fuel-based industries in Norway to meet the Norwegian government strategy under the Paris Agreement (United Nations, 2015) to reduce emissions by at least 50% and up towards 55% by 2030 compared to 1990 levels (Norway Parliament, 2019).

Another alternative energy resource: photovoltaic solar generation is not highly suitable for Norway and only represents a very tiny fraction of the total national energy production (approximately 1/1000000) (NMPE,2022). This is in part due to the countries location of 60 degrees north (humid continental climate (Koppen-Geiger Classification) resulting in very short daylight hours in winter limiting the effective generation of power over this season. Wind power on the other hand is a relatively constant and reliable renewable energy source all year.

These factors have resulted in an increase in the amount of both on and offshore large scale wind farms in Norway, from 17 in 2010, with a total output .906 TWh from 202 turbines to 50 wind farms in 2020, with a total output of 9.9 TWh from 1164 turbines (NVE, 2022). In 2021, wind power accounted for 10% of Norway's energy capacity. (NMPE, 2022).

1.3 General Factors in the feasibility of large-scale wind farms

The key primary factor in considering the feasibility of installing a large-scale wind farm is its location (Gil-Gracie al, 2019). This consideration can be further broken down into several sub factors that could be addressed through a location decision making process to minimize the risk of failure.

Firstly, in relation to technical and economic considerations, wind speed is a key technical factor and is coefficient of elevation, as elevation increases so does wind speed, therefore, wind turbine propellers need to be as high as possible to maximize available wind in locations. Coastal areas typically tend to be windier than inland areas because of the temperature difference between the land and sea and the convection effect. In addition to this, wind farms should be located as close as possible to existing power grids to make the transmission of power from source to the market as cost effective as possible. The large-scale deployment of wind energy requires potentially large areas of available and affordable land (Denholm et al, 2019). The importance of large areas of land also enables increases on economies of scale, as the number of wind turbines located in the same area increases there is an increase in the economic viability/ profitability of the wind power farm.

Secondly, in relation to Environmental / Community concerns, large scale wind power turbines and infrastructure: roads and service lines placed in pristine natural environments can impact sensitive ecosystems; they can kill birds and affect nesting and habitats. In addition to this, large wind power turbines are huge and can be perceived as ugly banks of turbines and propellers strung across a landscape that can destroy the aesthetic beauty of an area; "The industrialization of country areas". They are also noisy and can impact the amenity of large land or sea areas. Finally large-scale wind farms in decentralized locations can impact on the land use rights of local people and could be perceived as an inequitable process, the generation of power for the cities to the detriment of people living in regional areas (Diógenes et al., 2020).

1.4 Issues with Wind Farm installations in Norway

The issues and considerations for the location and establishment of wind farms are challenges for town planners and government regulators, who struggle to balance the optimum structure and location of green space wind farms and the aesthetic, social and environmental concerns voiced by communities.

Specifically, in Norway community concerns have caused a major slowdown in the development of wind power farms. (Taraldsen, 2020). Of note is a recent report published by CICERO (Aasen, et al., 2020), to analyze and measure changes in public attitudes in Norway to climate change and mitigation measures including onshore wind farms. *Figure 2. Graph - Norway should Increase wind power production on land?* is reproduced from this report below and illustrates how much opinion and responses have changed in only a couple of years from being mostly positive towards the establishment of onshore large scale wind farms in 2018 to conflicted negative responses in 2020.

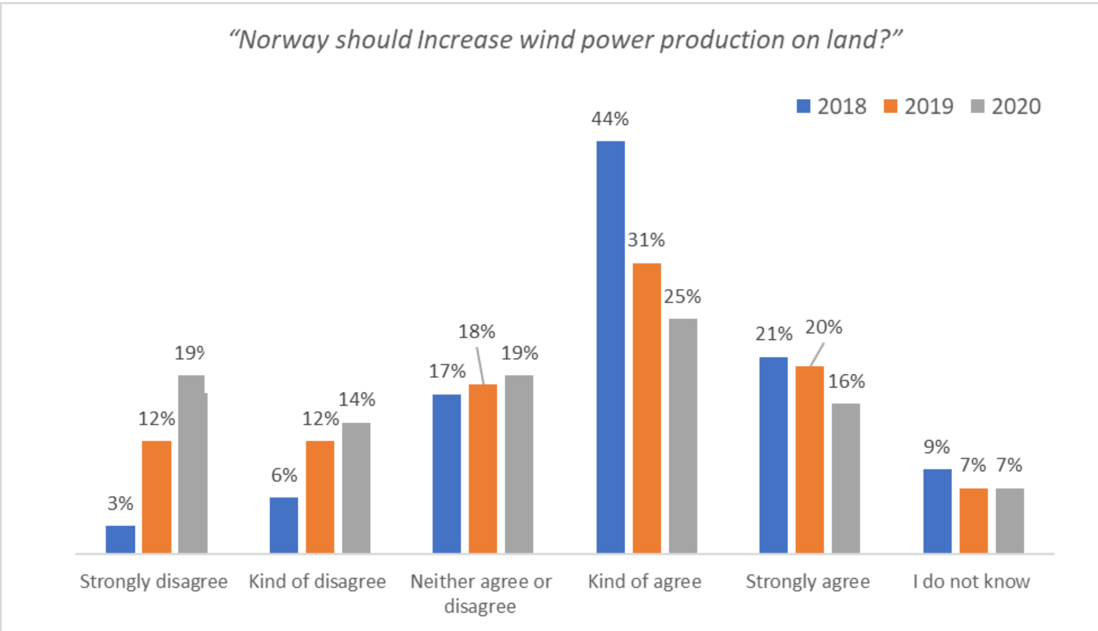

Figure 2. Graph - Norway should Increase wind power production on land?

These responses are also reflected in the community rejection in 2019 of a proposal by the Norwegian Water Resources and Energy Directorate (NVE) for a national framework for onshore wind power development (NVE, 2019) which identified 13 areas most suitable for the establishment of wind farms.

The Framework met with such strong community criticism that the Norwegian government abandoned the plan. The grounds for this criticism were mainly related to the "not in my backyard" phenomenon, where people consider something important, but did not want to see it or be impacted by it and the potential impacts on the Indigenous Saami people’s reindeer herding, through the installation of wind farms in traditional grazing and track herding areas (Andrew L. 2019).

Although the Norwegian wind power industries claim negligible social impacts and cite large scale wind power as a harmless strategy to slow down climate change, research from around the world suggests that that the installation of large-scale wind farms can be seen as a human rights issue, as their installation can potentially endanger sustainable life systems and effect the way of life of traditional people, including the Saami (Normann, 2020) (Wolsink, 2007).

These issues of community acceptance and human rights and the notion of fairness or equity is not confined to the Norwegian context. The question of whether it fundamentally right that people and industries in the cities should be powered by wind generated through large scale wind farms located in less populated regional areas to the detriment of these local communities is an emerging global issue (Vasstrøm et al., 2021). History suggests that these large-scale installations can negatively impact on the traditional life systems, and the happiness and ecology of those people living in these less populated areas. Indeed, there is some research that indicates feelings about equity and fairness from the general community appear to be bigger determinants of resistance than purely selfish ‘NIMBY”’ motivations. (Wolsink, 2007) Further evidence of recent community backlashes against the establishment of wind farms in Norway is the increase in membership into national environmental organizations because of wind power concerns (Stranden, 2019) and the emergence of new local and national protest networks (Normann, 2020).

These pressures and the rejection of the national framework for onshore wind power development have resulted in the Norwegian government tightening the licensing and environmental standards for new wind power stations. Making the process of establishing new farms more difficult and onerous, this has led to recent slowdowns in their development and establishment (Adomaitis, N., 2020).

In Norway, it is timely for governments, businesses, and organizations to consider and investigate alternatives to large scale wind farms, including the installation of smaller more discreet wind turbines in urban areas to generate power from the wind.

1.5 Small wind turbine developments and applications

Small turbines for the purposes of this study are defined as those turbines which have a rated output capacity of ≦ 100 kW; this is in alignment with the American Wind Energy Association definition (AWEA, 2002).

The urban installation of small wind turbines has some merit given the current wind energy issues in Norway. In recent years there has been substantial development in the public and private sector related to the design and manufacture of small turbines that could be used to generate power in both urban and regional locations. These developments and reduced costs through economies of scale coupled with government subsidies and support has resulted in an increased demand for this green technology. According to the Small Wind Word Report (Gsänger et al., 2017) at the end of 2015 there was almost 1 million small wind turbines installed worldwide, which was an increase of 5% on the previous year.

There are two primary types of small wind turbines, Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT).

HAWTs feature a propeller rotor mounted on a horizontal axis, the rotor is positioned to face into the wind using a tail or yawl. These turbines are sensitive to changes in wind direction and turbulence which negatively impact on their performance as they must be turned by a yawl to optimize power production. (Cace et al., 2016). They are most effective in low wind turbulence large open areas with consistent wind direction and frequency with little obstacles. They are the prevailing type of large turbine used in commercial wind farms and are also commonly used in some urban applications.

Figure 3. Photograph - Evance HAWT R9000 5kW small wind turbine.
Photo – Tobi Kellner March 2013 (Creative Commons Attribution-Share Alike 3.0 Unported license https://creativecommons.org/licenses/by-sa/3.0/legalcode)

VAWTs feature an axis with rotor or blades that are vertically positioned in relation to the wind direction. Because of the blade profile or the use of rotor arms, these turbines can capture incoming wind from any direction, and can take advantage of wind turbulence to generate power. (Casini, 2016). Generally, most VAWTs are not as efficient in generating power as the HAWT types; this is mostly due to the extra drag (resulting in energy loss) that is created as their blades drag into the wind. These types of small turbines are particularly suited to higher turbulence areas that feature inconsistent wind speeds and direction. They also feature low installation costs and emit less noise than HAWTs. Because of these characteristics they have been used quite extensively in urban areas (Siddiqu et al., 2021).

There are two main VAWT configurations, the Savonius and Darrieus types.

The Savonius type generates power from the aerodynamic drag that is created as the wind hits and rotates a cupped blade on an axis. These are self-starting turbines that have some energy efficiency limitations, because on one half of the rotation the wind is positively driving the blade around the axis, however on the other half of the rotation the wind is acting as counter force against the positive rotation. In addition to this, due to its drag design, the rotation speed is always lower than the wind speed (Cace et al., 2016).

Darrieus type turbines on the other hand are classified as lift type turbines, as the wind flows around the turbine structure it creates a low-pressure suction area at the front of the turbine causing the blades or winds to rotate or lift. Once the rotation commences, these turbines spin faster than the wind that is causing the rotation. These types of turbines are not self-starting and require an additional energy force to commence rotation. (Johnson, 2021). Darrieus type turbines can feature either straight (called H-blade Darrieus) or circular wings. There are other more recent configurations including the Gorlov type which has a helicoidally winged design, this type has proven to be more efficient than the more traditional designs (Casini, 2016) (Hand et al.,2021).

Figure 4. Photograph - Gorlov Turbine - Helgoland, micro wind turbine “QR 5”
Photo- Sozialutopist August 2012 ((Creative Commons Attribution-Share Alike 3.0 Unported license
https://creativecommons.org/licenses/by-sa/3.0/legalcode)

The associated problems and challenges related to the expansion in numbers of large-scale winds farms in Norway and the increased efficiency of smaller VAWTs and their suitability in an urban setting presents a timely proposition that is worthy of further scientific research. Specifically, that the use of small wind turbines to generate power that are mounted on top of existing buildings, within Oslo, could be technically, socially, and economically a viable alternative to using large scale wind farms to generate power.

1.6 Specific Study objectives

The broad hypothesis of this research is.

"That smaller wind turbines located on top of existing urban buildings are more economically viable and use space more effectively than large scale open wind farms"

There are two main sub-factors to be investigated that are related to testing this major hypothesis.

1. Feasibility/site selection
2. Resource efficiency – a comparison in resource efficiency between the installation of small wind turbines and a large-scale wind farm.

Consequently, a multi-faceted research approach will be adopted in this study. Questions regarding these factors will form the sub or minor hypotheses that will be tested through related specific research questions to confirm the broad research question.

Sub hypothesis 1 – Feasibility/site selection

"That small wind turbines located on top of existing urban buildings are a practical option for the generation of wind power"

Research questions

a) What is the total footprint required for a small scale "typical" wind turbine?

b) Are there sufficient wind energy resources available in the Oslo study area to generate power using small wind turbines?

c) Where and how many buildings are suitable to mount small turbines and generate electricity in the Oslo study area?

d) What is the total surface area that is suitable and available to mount wind turbines located on top of existing urban buildings in the Oslo study area and how many small scale wind turbines could theoretically be mounted on buildings in the Oslo study area and be effective?

Sub hypothesis 2- Resource efficiency

"That small wind turbines located on top of existing urban buildings are more resource efficient than large scale open wind farms"

Resource efficiency in the context of this research study for both the large-scale wind farm and the smaller wind turbines in the urban study area include.

(1) Economic efficiency; the costs to generate power and profits and losses per kWh based on the domestic retail price of electricity in Norway and

(2) Land use efficiency based on the amount of electricity generated per m^2 and the profit /loss per m^2 based on the domestic retail price of electricity in Norway.

Research questions

a) What is the total whole of life cycle costs for buying installing and maintaining (1) small scale wind turbines and (2) operating large scale turbines installed on wind farms (specifically Roan Wind farm Trøndelag County)

b) What is the potential annual energy output per m^2 land footprint of both an existing large scale typical modern wind farms in Norway (Roan Wind farm Trøndelag County) and smaller wind turbines located on top of suitable existing urban buildings in the Oslo study area?

c) Across a 20-year life cycle what is the net profit/loss $ value per kWh of the energy produced in total and per m^2 for both small wind turbines located on top of suitable urban buildings in the Oslo study area and large turbines on the Roan wind farm?

d) At what height do small wind turbines located on top of suitable urban buildings in the Oslo study area start to deliver a net profit (if any) per kWh and per m^2?

2.Background

2.1 General GIS applications

As noted earlier in the Introduction section of this report, the issues related to the operation and expansion of large-scale wind farms and the feasibility of small-scale urban wind power generation are primarily related to site suitability. For this reason, geographical information systems (GIS), which are systems that enable the storage, analysis, and visualization of a wide range of geographical (spatially and location) based cost and technical data are ideally suited to for this research. This technology can create map-based information and evidence to support the specific study objectives and enable the creation of new data. One of the key strengths of a GIS for this type of research is that it enables the user to design and create data and visual models to test, modify and evaluate potential data combinations and scenarios in a cost-effective way, without the need to physical attend the site of the modeling. This cost-effective process using remote sensed data enables customized analysis and visualization and through this provides researchers with a greater insight into the spatial relationships and scale of a range of phenomena based on certain data conditions.

Studies that used a GIS to compare and evaluate the efficiency of small wind turbines installed on top of buildings in an urban area to large scale wind farms were not specifically located within a literature search. However, the process required for this research which is comparing the two potential sites based on suitability factors is common. In this context, a site suitability analysis from a GIS perspective to enable an optimum location for wind power generation is mostly based on the use of multi-criteria decision-making method (Xu et al., 2020), based on integrative approaches developed in the 1990's (Carver, 1991).

This decision-making method involves the listing and weighting of criteria based on the relative importance of several performance and/or acceptance factors both positive and negative based on potential locations, with these weightings added to the GIS and then processed and analyzed to generate final ranking and location selections, spatial analysis, and visualization. The process ideally should enable effective decision making by locating the optimum site locations through considering the importance of range of factors in the acceptance and efficiency of wind power generation. Of relevance to this report is the measurement and analysis of two key criteria, economic and land use efficiency which will be evaluated to determine whether the Oslo Study area or the Roan Wind are more suitable.

2.2 Modeling urban wind strengths

Modelling wind speeds is an important component of conducting feasibility testing for turbine performance. However, instead of conducting expensive and time consuming actual on-site testing, remotely sensed data can be used at the desk top level to provide indicative wind speed estimations and indicative results. It is important to note that here are challenges and limitations to modeling estimating wind strengths in the urban landscape (Tasneem et al., 2020). This is mainly because of the diversity and structure of this environment, and the resultant high level of variability in wind speeds and direction Although some recent modeling research shows promise, there appears to be more investigation required (Siddiqui et al., 2021) (Rezaeiha et al.,2019) (Emejeamara et al., 2021). This is due to the highly variable roughness and drag impacts on surface objects and the effect of adjacent objects on wind flow strength and consistency (Stathopoulos et al., 2018). Furthermore, seasonal fluctuations in wind speed make estimation modeling difficult (Liu et al., 2018).

Generally, there is no accepted single accurate method for modeling wind strength in the urban environment, with the most dependable method to directly measure wind strength on site (full scale measurement) at the turbine height (Stathopoulos et al, 2018) (Kassem et al., 2019). This lack of knowledge and methodology is slowing down the growth of urban wind generation using small on-site wind turbines (Stathopoulos et al., 2018).

The application of other methods, including using an online digital wind maps have been used in several urban wind speed studies (Dutton et al., 2005). The recently developed Global Wind Atlas (DTU Wind Energy, 2022), which includes urban roughness indexes within its wind speed algorithm has also been used in several urban wind speed studies. This publicly available dataset underwent a major upgrade in 2015 (IRENA, 2015) which has resulted in more refined data and mapping (Norouzi et al., 2021), however the mapping data resolution of 250 m is somewhat coarse for micro scale modeling and can be limiting (Papadopoulos, 2018).

2.3 Installing small turbines in urban areas

There are several recent reports into the installation of small turbines into urban areas. Of relevance to this research is an actual on-site case study that focused on the effectiveness of small wind turbines that was conducted in 2012. This research involved the temporary installation of small VAWTs on top of the highest building in Oslo; Biskop Gunnerus Gate 14 tower building in Oslo.

The study was inconclusive due to turbine breakdowns, however it highlighted how little was understood about the built environment and wind resources, this was evident in the reported disparities between actual weather conditions on the roof top (at 115 meters AMSL) and nearby weather stations. Of note the report concludes that small VAWTs are relatively easy to install and that it would be useful to evaluate these against PV and CHP systems (Haase et al., 2014).

Useful information of the site analysis factors for the installation of small wind turbines on buildings was of relevance, despite having a focus on fluid dynamics and wind flow models (Ledo et al., 2011). This was also the case for research identified which used a GIS to create computational fluid dynamics models as this work provided relevant information regarding energy yields from small turbines mounted on buildings in the city of Sicily. (Gagliano et al., 2013).

2.4 Types of small wind turbines

References related to types of small wind turbines tended to be more general in nature and included lists of available small turbine manufacturers and sites of installations, including an overview of the UK domestic sector. (Peacock et al.,2008). Of note is a more recent work which provided a very clear analysis and overview of small turbines in the marketplace and how they operated (Casini, 2018). Furthermore, guidelines for small turbines specifically in the urban environment that also featured an overview of the types of small wind turbines and other data were also identified in the literature (Cace et al., 2016). A study that featured VAWTs and the latest developments and research in small turbine design and advances in the Gorlov type turbines was specifically relevant in informing decisions regarding the selection of the type of VAWT for this research. (Chidambaram et al., 2020).

2.5 Economics of large-scale wind farms and urban wind power

Several studies were identified that examined the economic measurement and assessment of large-scale wind farms. A number used a Life cycle costing (LCC) model scaled over 20-year periods that assessed a range of cost factors (Abu-Rumman et al, 2017), (Badgujaret et al., 2013), (Maklad, 2014), (Haapala et al., 2014).

Other references provided more generalized economic assessment including a research paper which featured break even points on the installation of large turbines (Johnson, 2009) and another focused-on maintenance costs (Kerres et al., 2014).
Relating to the costs and economic modeling of urban applications research was identified that formed a foundation for some of the costing approaches applied that could be applied in this research. These included one recent urban study in China which concludes that the direct economic benefits of using wind power to generate central heating are poor for several reasons, mainly relating to government policies and subsidies (Wang et al., 2021).

2.6 Effectiveness of small wind turbines

There are challenges to evaluating and measuring the effectiveness of small wind turbines in urban settings. A range of studies were identified which discussed these methods and limitations. Of note were the reported discrepancies between manufacturer outputs and power curves created in laboratories for several small turbines to the turbine's actual performance in harnessing fluctuating and unpredictable urban wind resources. A recent study highlighted the complexity of measuring and modeling fluctuating urban wind characteristics and identified this as a major obstacle in developing accurate power curves for turbines (Emejeamara et al., 2020). This challenge is also reflected in other studies, including a recent turbine review which focused on methods to overcome the challenges of reliably estimating power outputs of small turbines due to urban turbulence and roughness impacts (Anup et al, 2019).

In addition to this, the challenge of measuring potential wind turbine power curves in the urban context is made more difficult and less reliable because a standard independent test method for this testing is not used. This has resulted in the unreliable turbine energy measurements and power yields and the comparison of different turbines based on these measurements as highly problematic (Peacock et al., 2008).

This research is somewhat extended by a recent Norwegian study to analyze the effects of turbulence and ground elevation on the performance of small turbines mounted on roof tops (Siddiqui et al., 2021). There have also been earlier attempts made to establish a methodology to estimate the energy outputs of building mounted wind turbines (Walker, 2011).

More generally, there are a few examples of basic overviews of small wind turbine performance characteristics (McIntosh et al., 2009) and a comprehensive review of lift type VAWTs (Hand et al., 2021) which outlines design and performance parameters. These were helpful in identifying potential types of small wind turbines for this study.

3 Data and Methodology

3.1 Study areas

This research models and evaluates the feasibility of small-scale wind powered electrical generation in an urban setting by comparing the efficiency and practicality of a potential urban site with an established large scale wind farm in a regional area.

Two locations within Norway are compared:

1. Study Area – Roan
   A large scale operating commercial wind farm located in a rural coastal location in Trøndelag County in Northwestern Norway near the village of Roan.

2. Study Area – Urban area in Oslo.
   A model will be developed based on mounting small wind turbines on the roofs of existing building to generate power. The study area is a circular zone of 2 kms radius from the central railway station in Oslo, an urban centre and capital city of Norway.

Roan Wind Farm

Located at 64.17° N, 10.22°E, Roan is a privately owned installation occupying a site area of 22,460,460.5 m^2 (Approximately 3,145 football fields) which is located 8 kilometers southeast of the village of Roan, at Åfjord in Trøndelag County. (StatKraft, 2021). The installation which entered operation in 2019 comprises of 71 large HAWTs with an installed capacity of 255,600 kW (The Windpower, 2021).

The population of the Roan municipality in 2018 was 953 people who occupied an area of 375 km^2 with a population density of 2.7 people per km^2. (Statbank, 2021, table - 11727). The area has experienced a gradual decline in population, with a 5.4% drop recorded over the last 10 years. (Statbank, 2021, Table - 0693). Traditionally people live in small communities scattered across the municipality, engaging in the traditional industries of fishing (fish farms and open water) and agriculture (primarily sheep and reindeer herding), there is no major industrial activity in the region (Patonia, 2017).

The site is characterized by relatively high wind speeds, for example at a height of 50 meters ASL; the wind farm has an average annual wind speed of 7.42 m/s (26.7 kph). Notably the 10% most windy parts of this site recorded annual average wind speeds of 9.74 m/s (35 kph) (DTU Wind Energy, 2021). The wind farm area has a Köppen-Gieger climate classification of CFC (Sub-polar oceanic climate), (World Bank Group, 2021) and is characterized by undulating hills and valleys with elevations ranging from 400 to 600 meters AMSL. (Norwegian Mapping Authority, 2022).

The Roan Wind Farm was selected for this research because it is a relatively new installation that is in a regional part of Norway with a very low resident population density (in contrast to Oslo), with readily available cost data. Also, issues relating to the site have been highly publicized due to several community protests regarding its operation and the impacts on local people. Because of this interest there have been several analytical studies conducted on this installation. (Normann, 2020) (Skorstad 2014).

Oslo Study area

Located at 59.91°N, 10.75°E, the Oslo study area is an inner urban ring of 2,000 meters radius from the Oslo Sentralstasjon. This area of 12,570,000 m^2 (approximately 1,760 football fields) covers the central business district within the greater municipality of Oslo which is the capital and most populous city in Norway. The study area is characterized by administrative, commercial, political, mixed residential; tourism and cultural land uses and includes all or part of 4 municipal boroughs. These boroughs are the most densely populated settlements in Norway (Tiitu et al, 2021), with a combined average population density of 9,125 people per Km^2. (Municipality of Oslo, 2021). The area is mainly comprised of a built environment (3,200 buildings), with many structures erected within the last 150 years, although there are a number of green areas and parks and older historic buildings scattered across the site (Maija, 2021). The two tallest buildings within the study area are the Radisson Blu Plaza Hotel (117 meters ASL) and Biskop Gunnerus Gate (111 meters ASL) (Council on Tall buildings and Urban habitat, 2020), however these two structures are the exception with most buildings being between 10–20 meters ASL.

The study area is located on the coast at the most northern end of the Oslofjord and has an average elevation of 17 meters AMSL (Norwegian Mapping Authority, 2021). Due to its coastal location on the northern end of a fjord, the city is exposed to mainly southerly winds funneling through the fjord, with the dominant wind direction being between 180 ° and 210 ° south (approximately 60% annually). However north easterly winds (between 30°and 60° north) are not uncommon and equate to approximately 30% of all winds across the site. (DTU Wind Energy, 2021). At 50 meters AMSL, the average annual wind speed within the area is 4.14 m/s (14.9 kph). Notably the 10% most windy parts of the site at 50 meters AMSL recorded an annual average wind speed of 4.82 m/s (17.3 kph) (DTU Wind Energy, 2021).

Oslo has a Köppen-Gieger climate classification of DFB (Warm Summer – humid continental climate), (World Bank Group, 2021). The average temperatures range is between 17° C in July and -3°C in January and the average annual precipitation for the area over the past 19 years is 760 mm (WeatherBase, 2019).

Although as noted in earlier in the introduction section of this research, Norway uses predominantly renewable hydro-electrical power nationally, in Oslo there are strategies being implemented to shift to more flexible, local, low energy sources for heating with a focus on reserving the use of high-end electricity sources for city transport purposes. (Oslo City Council, 2019). This shift indicates that a study that evaluates the installation of small-scale turbines in the city area may be timely and of relevance to town planners and government decision makers.

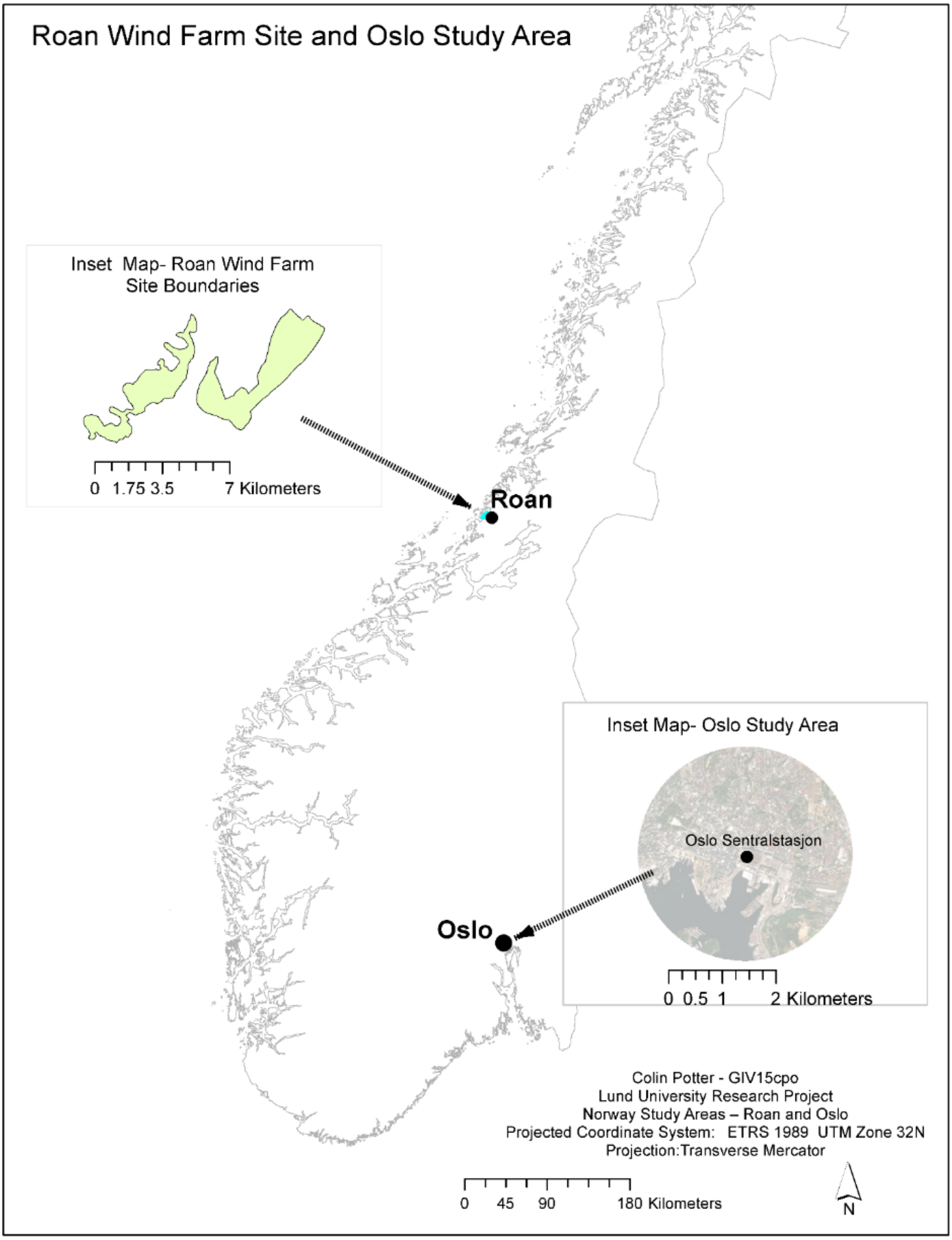

Figure 5. Map - Norway - Roan Wind Farm and Oslo Study Area

3.2 Data

Datasets that were utilized in this study are summarized in the table below;

Table 1. Summary of data types

Study Area	*Data sources and sets*
a. Mapping and digitization datasets	1.Digital Terrain and surface models – Oslo
	2.Map cadastre for property boundaries and building outlines for Oslo and Roan
	3.Municipality map of Roan wind farm
	4.General Imagery – Roan wind farm and Oslo Study Area
	5.Photogrammetric map– Oslo
	6.Street maps - Oslo and Roan
b. Wind Data	7.Digital wind atlas. Mean wind speeds at heights above Oslo study area
c. Technical data	8.Roan wind farm profile and data
	9.QR 6 wind turbine data
d. Costs and economics	10.Norway residential energy costs
	11.Roan wind farm 20-year life cycle costs
	12.QR6 wind turbine 20-year life cycle costs

a. Mapping and digitization datasets

1. Digital Terrain and surface models

Oslo-DOM - Høydedata Oslo kommunetynnetlaserskanning
(Digital surface model derived through airborne laser scanning which includes the heights of buildings and human infrastructure),
Produced by the Norwegian Mapping Authority
Resolution 10 meters- Projected Coordinate System - UTM Euref89 (*EPSG25832)*
Mapping Area Tile – UTM Zone 32.
Accessed 2020-03-21.
Note -the data is gathered from airborne topographical LIDAR sensors established as point clouds. With a systemic accuracy (distance to true value) of 0,10 for both vertical and horizontal distances.

Oslo-DTM - Høydedata Oslo kommunetynnetlaserskanning
(Digital terrain model derived through airborne laser scanning which includes the heights of buildings and human infrastructure),
Produced by the Norwegian Mapping Authority
Resolution 10 meters - Projected Coordinate System - UTM Euref89 (*EPSG25832)*
Mapping Area Tile – UTM Zone 32.
Accessed 2020-03-21.
Note -the data is gathered from airborne topographical LIDAR sensors established as point clouds. With a systemic accuracy (distance to true value) of 0,10 for both vertical and horizontal distances.

Both the DOM and DTM were identified and freely available through the Norwegian Mapping website (https://kartkatalog.geonorge.no) and ordered expressly for this analysis.

2. Map cadastre for property boundaries and building outlines for Oslo and Roan

CadastreMatrikkelenEiendomskartTeigBoundaries - Version 3
(Cadastre Map)
Produced by the Norwegian Mapping Authority
Projected Coordinate System - UTM Euref89 (*EPSG 25832)*
Accessed 2020-03-21

The cadastre was accessed through the Norwegian Mapping website (https://kartkatalog.geonorge.no) and ordered expressly for this analysis.

3. Municipality map of Roan wind farm

Municipalities of Norway
Second Level administrative Divisions, Version 2.8, Global Areas
Produced in 2015
University of California, Berkeley, USA
Projected Coordinate System - UTM Euref89 (*EPSG 25832)*
Accessed 2020-04-21
Note – The administrative Divisions map was accessed from the University of California, Berkeley Geodata Library website-
https://geodata.lib.berkeley.edu/?utf8=%E2%9C%93&q=Norway

4. General Imagery – Roan wind farm and Oslo Study Area

Municipalities of Norway
Second Level administrative Divisions, Version 2.8, Global Areas
Produced in 2015
University of California, Berkeley, USA
Projected Coordinate System - UTM Euref89 (*EPSG 25832)*
Accessed 2020-04-21

Esri World Imagery
Produced in 2021
Produced by; Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Resolution .5 meters - Projected Coordinate System - WGS 1984 Web Mercator
Accessed 2021-05-22.

5. Photogrammetric map – Oslo

Ortofoto (Orthophoto) Oslo County
Produced by the Norwegian Mapping Authority
Produced in July 2018
Resolution 10 meters- Projected Coordinate System - UTM Euref89 (EPSG 25832).
Note -Multi-purpose aerial orthophoto derived from color images with an image scale of 1:8000/10000 - analog camera or resolution (GSD) 20-25 cm - digital camera.
Estimated accuracy of ± 0.35 m.
Accessed 2021-05-06

The Ortofoto Oslo County dataset was identified through the Norgebilder website (http://www.norgeibilder.no/?id=2745) produced by the Norwegian Mapping Authority. However, I could not obtain the appropriate license to download the map. I acknowledge the support of my colleague Oskar Vågerö at the University of Oslo for enabling me to get access to this dataset.

6. Street maps - Oslo and Roan

Google maps
Produced by the Google Corporation
Resolution 1.5 meters- Mercator projection accessed via Google Maps - https://maps.google.com.auAccessed2021-08-01

ArcGIS Map Service- ESRI world street map of Oslo.
Produced by ESRI
Projected Coordinate System - WGS- 1984-Web Mercator Auxiliary Sphere
Accessed 2021-09-01.

b. Wind Data

7. Digital Wind data

Global Wind Atlas Digital online map
Produced by the Wind Energy Department of the Technical University of Denmark.
Resolution 250 meters, Average wind speeds measured in m/s.
Projected Coordinate System - WGS- 1984-Web Mercator Auxiliary Sphere
Note -The DEM data base map is created by combining NASA Shuttle Radar Topography Mission (SRTM) elevation data with NASA Viewfinder DEM data (30-meter resolution interferometric C- band Synthetic Aperture Radar data). This DEM

is combined with wind data from the ERA5 dataset (European Centre for Medium-Range Weather Forecasts) and processed through a micro-scale modeling system based on 250 interval areas at heights of 10, 50,100, 150 and 200 meters to create the map. The mean bias of 35 validated wind sites across the world for this data source is -1% (under estimation of wind speed).
https://globalwindatlas.info/Accessed 2021-04-01.

c. Technical data

8. Roan wind farm profile and data

A profile of the wind farm (The Windpower, 2021) and a fact sheet created by the owners (Tronderenergi, 2016)

Figure 6. Photograph - Roan Wind farm
Photo Ole Martin Wold , August 2018 (Attribution-Non-Commercial-No Derivs 2.0 Generic (CC BY-NC-ND 2.0- https://creativecommons.org/licenses/by-nc-nd/2.0/legalcode)

9. QR 6 Wind Turbine data

Information about the installation, power outputs and power curve at different wind speeds, footprint, and other technical data for the selected “typical” small wind turbine, were utilized in this research. The QR6 wind turbine, a Gorlov type VAWT manufactured by Quiet Revolution in the U.K, with a rated maximum capacity of 8 kW was selected for this study. Most of this information was derived from the manufacturer data sheet (Quiet Revolution, 2020).

Figure 7. Photograph - QR6 Turbines on site. (Quiet Revolution, 2020).
(Reproduced with permission from Quiet Revolution)

d. Costs - economics

10. Norway residential energy costs

Residential energy costs were obtained from a recent costs table identified in the literature search (Alves, B., 2021).

11. Roan wind farm 20-year life cycle costs

20-year cycle costs were derived from a Master research thesis (Skorstad, M. H., 2014). This data was then cross checked and verified against a commercial consultancy report (Thema Consulting Group report, 2019).

12. QR6 wind turbine 20-year life cycle costs

The QR6 wind turbine 20-year life cycle costs were derived through a Skype interview with the owner Chris Newland of Quiet Revolution, the manufacturers of the turbine. The following cost and life cycle factors related to the QR 6 were addressed, Installation costs and requirements, turbine Weight, roof load and engineering factors, price of the unit, effective operating life, and turbine output levels.

3.3 Methodology

As a general guide a simplified flowchart for the main GIS processes engaged is presented below in *figures 8 and 9*.

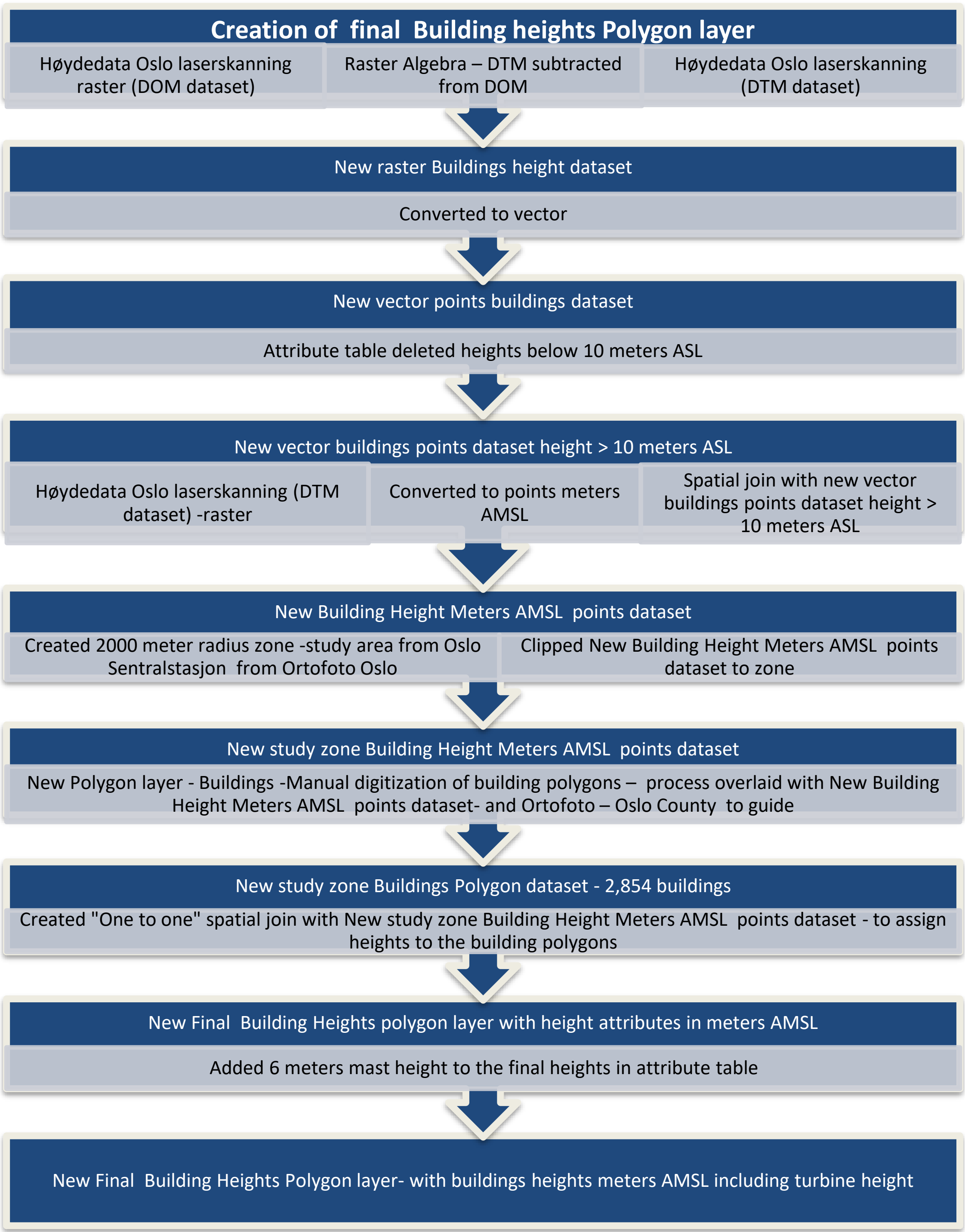

Figure 8. Flowchart - Main GIS processes used in the methodology Part 1

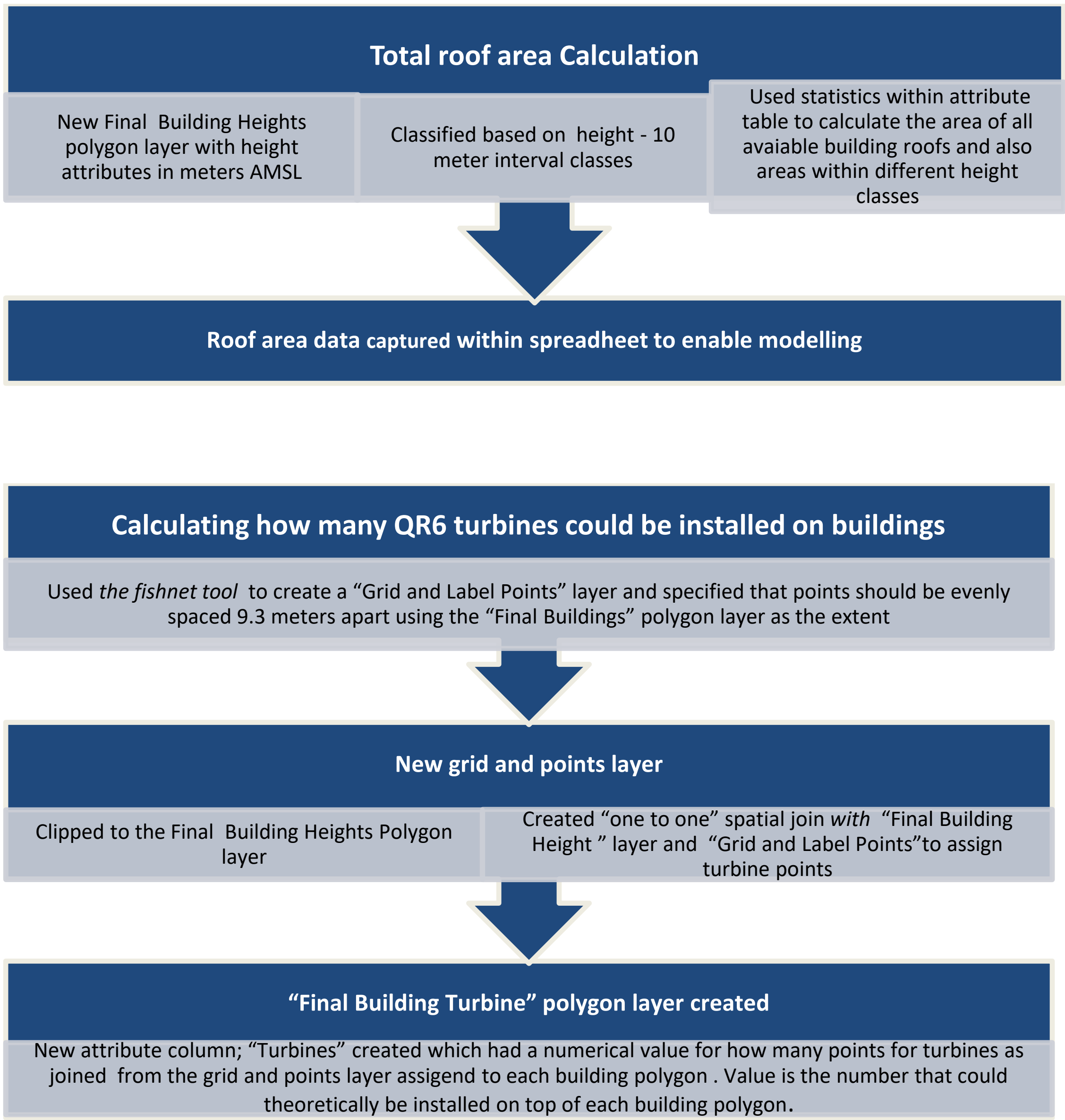

Figure 9. Flowchart - Main GIS processes used in the methodology Part 2

The following methodology for ease of understanding is broken down into the same order as the hypotheses and related research questions. A more detailed description of the methodology is also provided at *Appendix 1 -Methodology*.

Note that most datasets and maps used in the processing aspects of this research had the same projected coordinate system - UTM Euref89 (EPSG 25832). Therefore, there were minimal transformations or re-projections required to process the data sets within the GIS.

Sub hypothesis 1 – Feasibility/site selection

"That small wind turbines located on top of existing urban buildings are a practical option for the generation of wind power"

a) **What is the total footprint required for a small scale "typical" wind turbine?**

Methodology

Data supplied by the manufacturer; Quiet Revolution QR 6 data sheet (Quiet Revolution, 2020), which included installation and spacing specifications and diagrams was utilized. In addition to this a "zoom" web interview with the manufacturer was conducted to confirm specifications.

b) **Are there sufficient wind energy resources available in the Oslo study area to generate power using small wind turbines?**

Methodology

The Global Wind Atlas (DTU Wind Energy, 2021) for the study area was used to identify average wind speeds measured in m/s however, it only covered 3 heights, 10, 50 and 100 meters AMSL. In order to estimate potential wind power at building heights other than these and to enable the calculation of power generation, the values of wind speeds at heights between 10 and 100 meters were interpolated based on 5-meter intervals and extrapolated for heights above 100 meters from the known average 10-, 50 and 100-meters values by using the log law method (UC Santa Cruz-School of Earth and Planetary Sciences, n.d) applying the following logarithmic expression;

$$v \approx v_{ref} \cdot \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

where:

- V = velocity to be calculated at height z
- Z = height above ground level for velocity v
- V_{ref} = known velocity at height z_{ref}
- Z_{ref} = reference height where v_{ref} is known
- Z_0 = roughness length in the current wind direction

The premise of this method is that during day and near the surface of the land the velocity of the wind will vary through a semi -empirical relationship according to a logarithmic equation based on height. (Garratt, J.R, 1992). Surface roughness length is also factor used in the calculation of average wind speeds at different heights, with rougher surfaces such as urban terrains having the effect of reducing the wind speeds.

This was factored in the calculation derived through the Global W*in*d Atlas (DTU Wind Energy, 2021) . This is also accounted for in the log law equation with an urban roughness length of .85 applied to the other interpolated wind speed calculations to account for the increased surface roughness in the final wind speed estimation.

The graphs of average wind speeds at 3 heights were downloaded (10, 50 and 100-meters AMSL) and the corresponding raster data sets maps were re-projected and transformed from WGS 1984 Mercator to UTM Euref89. (*See Appendix 2 – Wind Speeds – Study area*).

c) Where and how many buildings are suitable to mount small turbines and generate electricity in the Oslo study area?

Methodology

Determining where and how many buildings are suitable to mount small turbines and generate electricity in the study area required the creation of a new GIS layer of the modeled buildings. This process required 3 distinct stages;

1. Creation and digitization of the Oslo Study area

The DTM raster dataset (natural terrain) was subtracted from the DOM raster dataset (surface) to create a new raster data set which featured only the elevation values of buildings and other man-made infrastructures across the city of Oslo. Both the new DOM and the DTM raster datasets then converted to a point dataset "Buildings". These were then added together to get the actual heights above surface level for the buildings and built structures.

The points dataset "buildings" had the Z values of heights of buildings only from the surface of the land (ASL) and the DTM (natural terrain) point dataset has the Z values of land height in relation to meters AMSL. These two data sets were added together to create a dataset for the actual heights of the buildings above sea level, then using this point height data, those points <10 meters AMSL were deleted.

There were 2 reasons why these buildings <10 meters AMSL were deleted. (1) Wind speed data available for heights below 10 meters for the Oslo city area was not available to calculate energy generation and (2) For aesthetic purposes if wind turbines were installed on the roofs of buildings below 10 meters in height, people walking and cars driving past these buildings may be able to see and hear the bank of turbines and this would detract from the amenity of an area.

The study area was created by creating a buffer zone which constructed a circular area based on a 2000-meter radius using the Oslo Sentralstasjon as the central point, with the layer clipped to this extent. The size and shape of the study area was selected to make the research and datasets more manageable and minimize the amount of manual digitization. In addition to this, this location was selected because the area represented an identifiable CBD for the urban center of Oslo and was based on a major transport hub, enabling future comparative research with other urban areas. Another factor confirmed in initial investigations was that this area contained the highest buildings in Oslo.

An Ortofoto of Oslo and map cadastres with building outlines was overlaid against the height point data set to manually digitized building outlines as polygons; to create the Building Heights polygon layer. Only those building polygons which contained the final building heights points were digitized. Parliament, royal palaces, churches, cathedrals, or historic protected buildings were excluded from the study area. 2,854 buildings within the study area were digitized.

A Spatial join was executed between the" Building heights" polygon dataset and the "Buildings" point dataset. This process was implemented based on one-to-one join*,* the polygon dataset "Buildings "was selected as the target dataset and the "Final Building Heights "point layer as the join features dataset, all target features were kept. Using this process, a single average points value was assigned to each building polygon to create the "Final Building Heights" polygon dataset.

A new "Final Buildings" polygon layer was created which included the final building heights in meters AMSL. In the new layer 6 meters was added to each building polygon to account for actual turbine height. This is the Z or elevation value for buildings to be used in the modeling. Then each polygon was classified based on height classes of 10 meters AMSL intervals.

2. Identifying average annual wind speed at different heights within the study area and applying this to the final building's polygon layer

The average wind speed values derived from the Global Wind Atlas (DTU Wind Energy, 2021) were applied to the attribute table of the "Final Building Heights" polygon dataset, these speeds at different height speeds were assigned to the corresponding heights of suitable building polygons within the study area based on a 5-meter classification.

3. Applying these wind speeds to the selected power output specifications of the selected turbine to determine which buildings at what heights are exposed to sufficient wind speeds that will enable the generation of electricity.

The average wind speed values at different heights derived from the Global Wind Atlas (DTU Wind Energy, 2021) were checked against the selected turbines manufacturers power curve (Quiet Revolution, 2020) to determine potential power generation. From this data, buildings of a specified height and wind speed were identified as suitable.

d) What is the total surface area that is suitable and available to mount wind turbines located on top of existing urban buildings in the Oslo study area and how many small scale wind turbines could theoretically be mounted on buildings in the Oslo study area and be effective?

Methodology

Those buildings at heights that were exposed to sufficient wind speeds to generate electricity were identified in the "Final Buildings" polygon layer. Based on the statistics of the layer attribute table, the area of these buildings was calculated.

In the research process it is assumed that all areas of all building roofs are suitable for turbine placement, therefore, the processes that follow allocate/fit the theoretical maximum number of turbines on each roof. Initially it was determined from the QR6 turbine datasheet (Quiet Revolution, 2020) that each turbine required footprint of 86.49 m^2 (9.3 x 9.3 m).

A fish net tool which creates a feature class containing a net of rectangular cells across all polygon areas based on a specified distance, was applied across the Final Building Heights polygon layer extent to create a "Grid and Label Points" layer (Turbines), a distance of 9.3 meters was specified. This resulted in all possible areas of the roof polygons covered with label points indicating turbine placements. To highlight this level of saturation please see *Figure 21. Map - Oslo – Detailed - Estimated kWh output annually- per m^2* which displays all areas of building roof polygons taken up by turbines.

A "one to one" spatial join which connects different feature classes based on their shared spatial relationship was performed between this new points layer and the "Final Building Heights" polygon layer with the specification that all target features were to be kept. A new polygon layer "Final Turbine – Building Heights" layer was created which assigned the maximum turbine points / numbers to the individual building polygons.

At this stage in the methodology a new final polygon layer model; “Final Turbine – Building Heights“ was created which included in its attribute table; (1) Building roof areas boundaries (2) Heights of each building which accounts for meters above sea level and turbine heights (3) Average wind speeds at the top of each building and (4) the maximum number of turbines (points) on the roofs of every building.

Sub hypothesis 2- Resource efficiency

“That small wind turbines located on top of existing urban buildings are more resource efficient than large scale open wind farms”

Resource efficiency in the context of this research study for both the large-scale wind farms and the smaller wind turbines in the urban study area includes;

(1) Economic efficiency; the costs to generate power and profits and losses per kWh based on the domestic retail price of electricity in Norway and

(2) Land use efficiency based on the amount of electricity generated per m^2 and the profit /loss per m^2 based on the domestic retail price of electricity in Norway.

Research questions

a) **What is the total whole of life cycle costs for buying installing and maintaining (1) small scale wind turbines and (2) operating large scale turbines installed on wind farms (specifically Roan Wind farm Trøndelag County)?**

Methodology

For the Oslo Study Area, life cycle costing data was obtained by interview from the manufacturer Quiet Revolution which covered installation, supply, insurance, and maintenance costs over a 20-year lifecycle.

In relation to the Roan Wind farm, the data within the costs table from Skorstad, Mona (2014) which included both operating and capital costs per kWh and total costs over a 20-year period was used and require no further processing. In addition to this a Thema Consulting Group report (2019) was also used to correlate and check some kWh cost ratios and other estimations. Note these costs include the entire wind farm installation, which encompasses 71 turbines and related infrastructure and services with all values in U.S dollars (calculated conversion rate 25.10.21).

2O-year lifecycle costs were calculated for both types of installations, this lifecycle time period was selected because cost data was readily available for the Roan wind farm for this period and the small turbine manufacturer claimed a 30-year life span for the QR6 turbine model used in the analysis. Therefore, the 20-year lifecycle length was considered sufficient to enable a comparative analysis between the two.

b) What is the potential annual energy output per m^2 land footprint of both an existing large scale typical modern wind farms in Norway (Roan Wind farm Trøndelag County) and smaller wind turbines located on top of suitable existing urban buildings in the Oslo study area?

For the Oslo Study Area, the QR6 wind turbine power curve spreadsheet was used to plot and map the output in kWs of a single turbine at different wind speeds in .1 increments from 2.1 to 20 m/s. (See *Appendix 3 - Wind Speeds and Power Curve*). This value was added in the attribute table of the “Final Turbine – Building Heights” layer, against the corresponding wind speeds based on the different heights of the suitable building polygons.

In the same layer, the total energy in kWh per building polygon was calculated by multiplying the kW output per turbine by the number of turbines assigned to each building. Then in the same attribute table, this kW per building value was multiplied by hours in a year in a new column “kWh power” to calculate the annual kWh output of each building and by height class.

To calculate kWh per m^2 values, using the same layer, in a new column in the attribute table the “kWh power” value was divided by the corresponding “Shape Area” value to calculate kWh output per m^2

In relation to the Roan Wind farm, the site was manually digitized into a vector layer. The area of the site was calculated through using a calculator within the GS based on the boundaries of the site. The Tronderenergi, (owners) fact sheet of power outputs (Tronderenergi, 2016) was used in conjunction with data from a web-based wind farm resource (The Windpower, 2021) to calculate kWh annual output. This total energy produced in Kwh per year was divided by the site area to calculate kWh output per m^2

c) Across a 20-year life cycle what is the net profit/loss $ value per Kwh of the energy produced in total and per m^2 for both small wind turbines located on top of suitable urban buildings in the Oslo study area and large turbines on the Roan wind farm?

Methodology

For the Roan Wind Farm, the net/profit loss per kWh calculations were based on the 20-year life cycle costings within the costs table from Skorstad, Mona (2014) which included both operating and capital costs per kWh and total costs over a 20-year period. This data required no further processing. This per kWh cost was subtracted from the residential cost of electricity in Norway to determine the profit or loss. The retail value of the power in Norway in 2020 was USD$ 0.150 per kWh. (Users with a consumption greater than 2,500 and lower than 5,000 kilowatt hours paid an average of 13.39-euro cents (USD$ 0.15) per kilowatt hour in 2020 (Alves, 2021)). The Profit loss per m^2 over 20 years was calculated by dividing the total profit or loss value by the site area of the wind farm.

In relation to the Oslo Study Area, the net/profit loss per kWh was calculated using the life cycle costing data per turbine over a 20-year cycle that was obtained by interview from the manufacturer Quiet Revolution. Using an Excel spreadsheet, this per turbine cost value, was multiplied by the number of turbines per 10-meter height classification over a 20-year period. Then the annual kWh values per 10-meter height class were copied from the “Final Turbine – Building Heights“ layer to the corresponding layer classifications in the spreadsheet. The total kWh output per 20-year period was divided by the costs of the installations to calculate the total cost to create power over the life cycle. The profit or loss for different heights was calculated based on the 10-meter classes and the total of all classes combined by subtracting the per kWh cost from the residential cost of electricity in Norway to determine the profit or loss. As in the Roan Wind farm profit calculations, the same retail value of the power in Norway in 2020 was applied.

The Profit or loss per m^2 over 20 years was calculated by dividing the total profit or loss over 20 years by the area of each individual height class and the total area for all height classes.

d) At what height do small wind turbines located on top of suitable urban buildings in the Oslo study area start to deliver a net profit (if any) per kWh and per m^2

Methodology

Using the Excel spread sheet data for per turbine costs, based on the 10-meter height classifications, the profit or loss per height class over the 20-year life cycle was identified. This value was also inputted into a new column in the “Final Turbine – Building Height“ layer attribute table to enable visualization and identification of those buildings within the study area.

4. Results

4.1 Sub hypothesis 1 – Feasibility/site selection

Research question (a) what is the total footprint required for a small scale "typical" wind turbine?

The "typical" small wind turbine selected for this study is the Gorlov type QR6 VAWT manufactured by Quiet Revolution in the UK. See *figures 10 and 11*, from the Quiet Revolution QR 6 data sheet (Quiet Revolution, 2020) which specified the spacing requirements for the turbine.

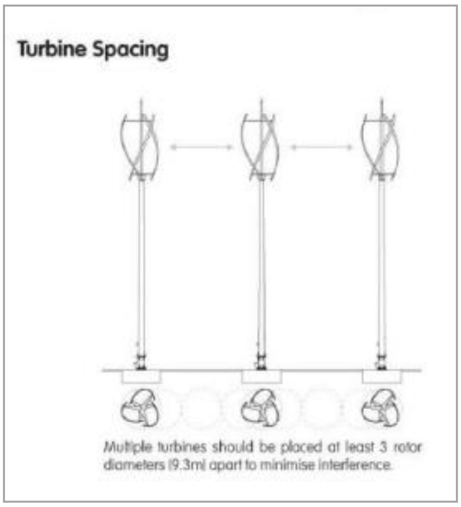

Figure 10. Illustration - QR6 Turbine spacing (Reproduced with permission from Quiet Revolution)

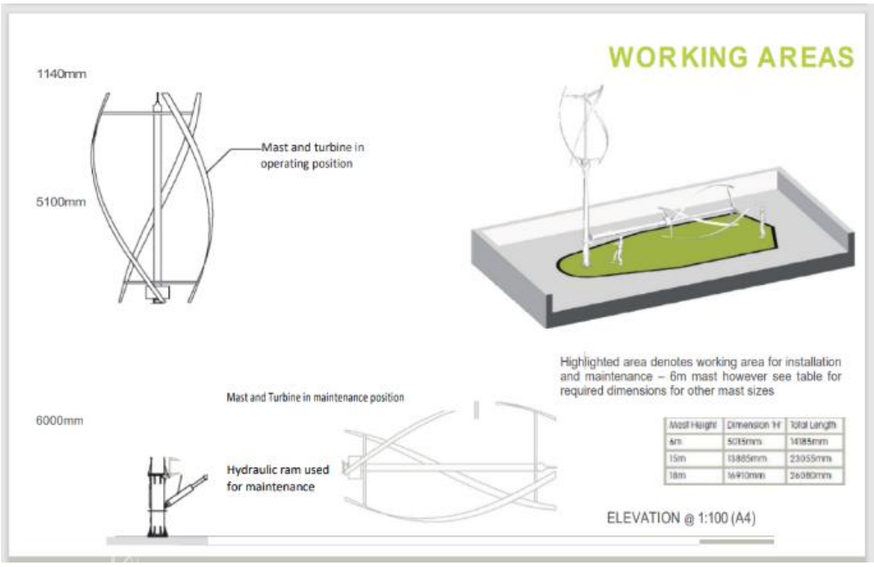

Figure 11. Illustration - QR6 Space Requirements maintenance (Reproduced with permission from Quiet Revolution)

Based on this manufacturer data, the QR6 turbines need to be spaced at a minimum 9.3 meters apart in any direction from each other.

Each turbine requires a footprint area of 86.5m². (9.3 x 9.3 m²)

Research question (b) Are there sufficient wind energy resources available in the Oslo study area to generate power using small wind turbines?

To determine if sufficient wind resources are available in the study area several sets of data were needed to determine firstly, the wind turbine power output at different wind speeds, secondly, the average wind speed above the study area and finally the calculated wind turbine power outputs based on these factors.

R6 Wind Turbine power curve

The manufacturer's power output generation data (Quiet Revolution, 2020) which was correlated to different wind speeds, was plotted, and used to estimate the potential power generation for the QR6 at different heights above the Oslo Study area. *(See Appendix 3 for the corresponding power generation table)*

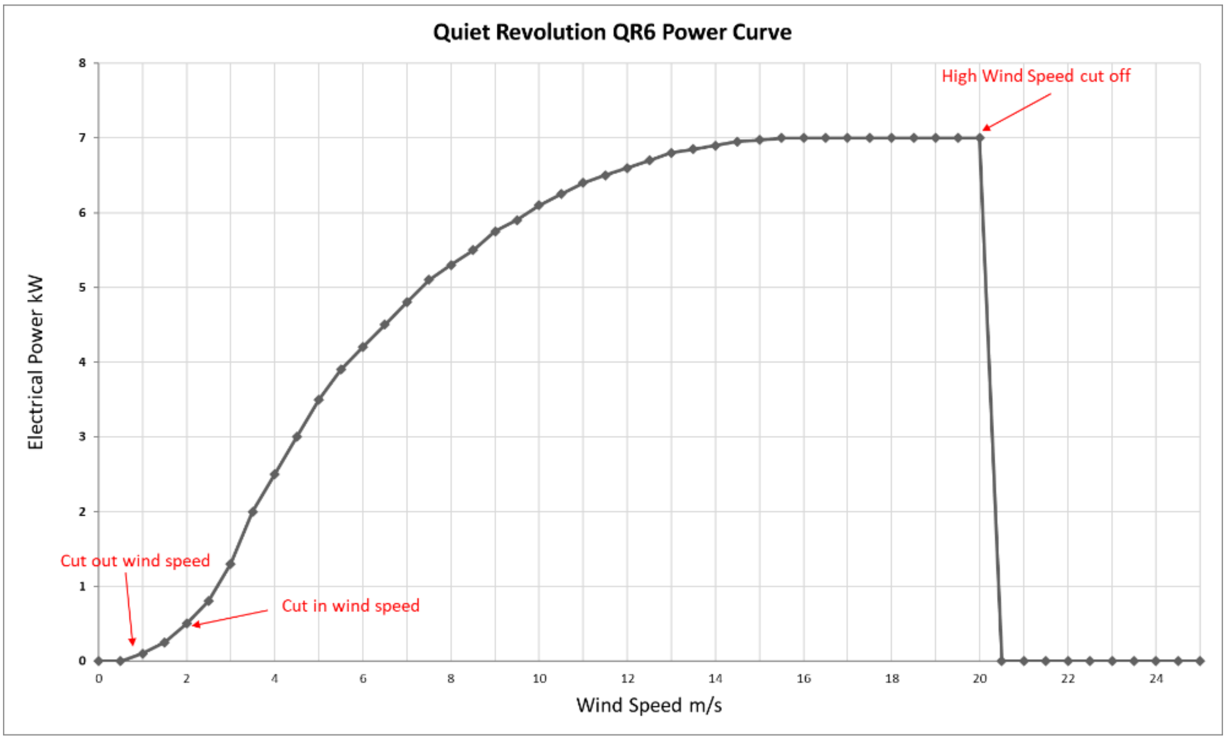

Figure 12. Graph - Quiet Revolution QR 6 Wind Turbine Power Curve

Average wind power above the study area

Available wind speeds above the study were obtained from the Global Wind Atlas (DTU 2021). The average wind speeds above the study area are;

10 meters AMSL = 2.5 m/s,
50 meters AMSL = 4.2 m/s
100 meters AMSL = 5.08 m/s

(See *Appendix 2* for the corresponding map images derived).

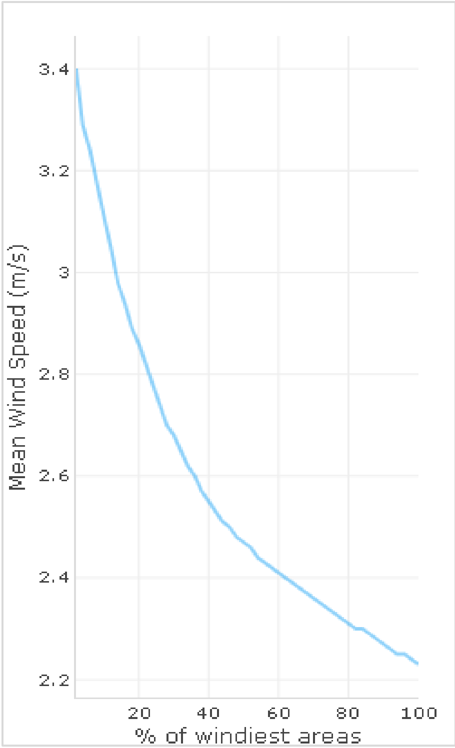

Figure 13. Graph - Average Wind speed Oslo 10 meters AMSL = 2.5 m/s

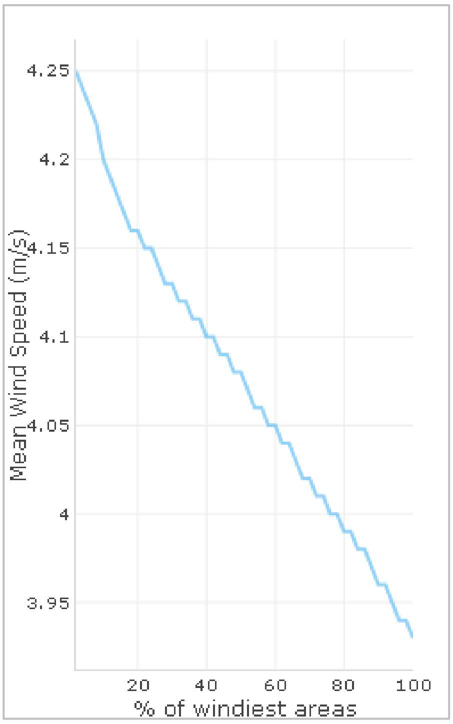

Figure 14. Graph - Average Wind speed Oslo 50 meters AMSL = 4.2 m/s

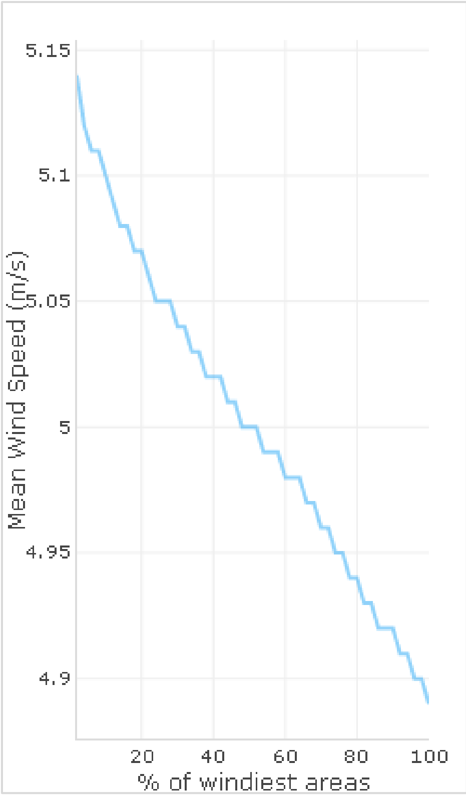

Figure 15. Graph - Average Wind speed Oslo 100 meters AMSL = 5.08 m/s

Table 2. Log law method - Table of heights and estimated wind speeds- Oslo

From height Meters AMSL	*To height Meters AMSL*	*Vref*	*Zref*	*Z*	*Final average speed m/s*
10	15	**2.55**	**10**	10	2.55
15	20			15	2.96
20	25			20	3.27
25	30			25	3.49
30	35			30	3.68
35	40			35	3.84
40	45			40	3.98
45	50			45	4.1
50	55	**4.14**	**50**	50	4.14
55	60			55	4.23
60	65			60	4.32
65	70			65	4.4
70	75			70	4.47
75	80			75	4.54
80	85			80	4.61
85	90			85	4.67
90	95			90	4.72
95	100			95	4.78
100	105	**5.09**	**100**	100	5.09
105	110			105	5.14
110	115			110	5.19
115	120			115	5.23
120	125			120	5.28
125	130			125	5.32
130	135			130	5.36
135	140			135	5.4
140	145			140	5.44
145	150			145	5.48
150	155	**5.96**	**150**	150	5.96

The average wind speeds ranged from 2.55 m/s at 10 meters AMSL (generating 0.8 kW output) to 5.96 m/s at 150 meters AMSL (generating 4.18 kW). (See *Table 2. Log law method - Table of heights and estimated wind speeds- Oslo* (above) and *Figure 12.* Graph - *QR6 Power Curve*, in the Oslo Study area)

<u>The wind speeds at a range of heights from 10 meters AMSL to 150 meters AMSL above the study area are sufficient to enable the QR6 turbine to generate electricity.</u>

Research question (c) What is the total surface area that is suitable and available to mount wind turbines located on top of existing urban buildings in the Oslo study area and how many small-scale wind turbines could theoretically be mounted on buildings in the Oslo study area and be effective?

Those buildings with roof heights greater than 10 meters AMSL in the Oslo study area are exposed to wind speeds that are sufficient to enable the QR6 turbine to generate power.

Table 3. Number of buildings and area m^2> 10 meters AMSL

Buildings- meters AMSL	*Number*	*Area m^2*
>100 m	2	1,728.04
90 - 100 m	7	5,011.90
80 - 90 m	41	31,646.93
70 - 80 m	124	42,284.84
60 - 70 m	294	123,574.48
50 - 60 m	454	295,949.84
40 - 50 m	546	375,879.21
30 - 40 m	787	498,744.18
20 - 30 m	572	437,596.14
10 - 20 m	27	20,550.06
Totals	**2854**	**1,832,965.6**

There are 2,854 buildings > 10 meters AMSL identified within the study areas with a total surface area of 1,832,965.6 m^2that is suitable and available to mount wind turbines *(see total Area m^2 and number in Table 3. above)*

This total area is equivalent to 256 football fields which is 14.6% of the study area and represents 89% of all buildings in the area.

Further refer to *Figure 16. Map - Buildings AMSL > 10 meters* for the general location of these buildings, which are evenly spread across the study area.

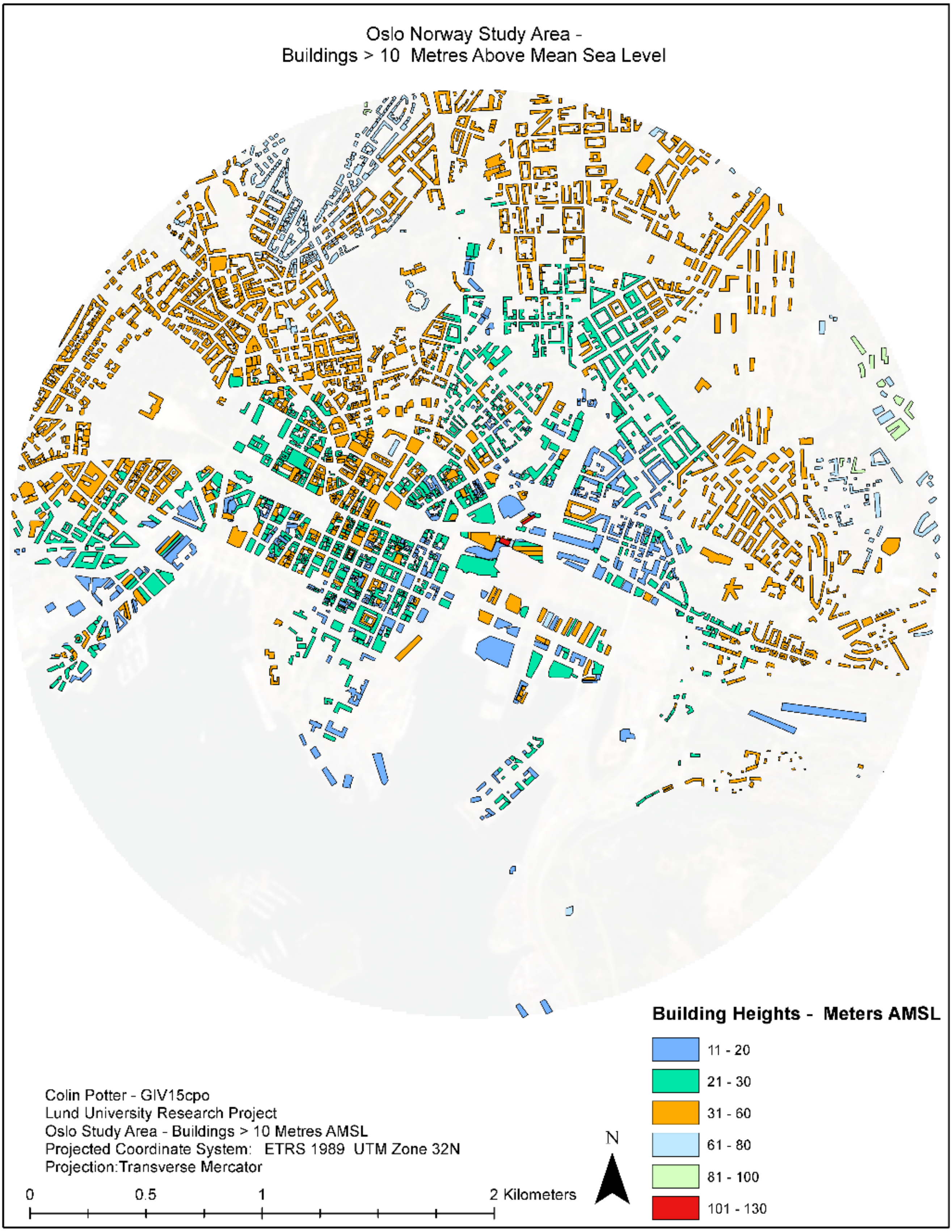

Figure 16. Map - Buildings > 10 meters AMSL– includes mast height of 6 meters – Oslo Study area

How many small-scale wind turbines could theoretically be mounted on buildings in the Oslo study area and be effective?

Table 4. Maximum number of QR6 turbines that could be installed by building heights > 10 meters

Buildings – meters AMSL	*No. buildings*	*No. of turbines*
>100 m	2	19
90 - 100 m	7	55
80 - 90 m	41	368
70 - 80 m	124	491
60 - 70 m	294	1439
50 - 60 m	454	3408
40 - 50 m	546	4375
30 - 40 m	787	5371
20 - 30 m	572	5080
10 - 20 m	27	239
Total	**2854**	**20845**

The maximum number of QR6 wind turbines that could be installed on suitable buildings within the Oslo study area is 20,845. *(See total turbines in Table 4 above)*

4.2 Sub hypothesis 2- Resource efficiency

"That small wind turbines located on top of existing urban buildings are more resource efficient than large scale open wind farms"

Research question (a)What is the total whole of life cycle costs for (1) acquiring, installing, and maintaining the small-scale wind turbines and (2) operating large scale turbines installed on wind farms (specifically Roan Wind farm Trøndelag County)?

The 20-year life cycle costs for acquiring, installing, and maintaining a single selected QR6 small scale wind turbine is USD$ 72,711.30

(See - *Table 10. All Costs 20 years – x 1 QR 6 Wind turbine*)

The costs related to establishing and operating the Roan Wind farm are USD $ 1,003,160,822 over a 20-year life cycle.

(See Tables 5 and 6, which details separate capital and operational costs that were used in the final calculations in *Table 7. All Costs 20 Years – Roan*)

These related itemized costs results are outlined below and broken down into capital and operational costs for both the Roan Wind farm and the Oslo study area. All values in U.S dollars (calculated conversion rate 25.10.21)

Roan Wind farm lifecycle costs

Table 5. Capital Costs 20 years – Roan Wind Farm

Capital Costs	*Kroner*	*USD$*
Foundation	270,000,000	$32,322,105
Turbines	2,400,000,000	$287,307,600
Groundwork	30,000,000	$3,591,345
Internal transmission lines	180,000,000	$21,548,070
Project Management	90,000,000	$10,774,035
Roads and construction	450,000,000	$53,870,175
On -costs/ depreciation/ replace	2,787,740,000	$333,724,537
Total	**6,207,740,000**	**$743,137,867**

Table 6. Operating Costs 20 years – Roan Wind farm

Operating costs - 20 Year Lifecycle	*Kroner*	*USD$*
Administration of plant	147,600,000	$17,669,417
Rent	37,180,000	$4,450,874
Annual compensation reindeer husbandry	3,040,000	$363,923
Property tax	111,000,000	$13,287,977
Maintenance turbines	1,043,100,000	$124,871,066
Maintenance Building and construction	15,800,000	$1,891,442
Maintenance costs for production radial	2,060,000	$246,606
Insurance buildings	2,200,000	$263,365
Insurance Turbines	18,100,000	$2,166,778
Balancing costs	252,000,000	$30,167,298
Grid rent	540,000,000	$64,644,210
Total	**2,172,080,000**	**$260,022,955**

Table 7. All Costs 20 Years – Roan

Total 20 Year Lifecycle Costs	*Kroner*	*USD$*
Capital costs	$6,207,740,000.00	$743,137,867
Operating costs	$2,172,080,000.00	$260,022,955
Total ALL	**$8,379,820,000.00**	**$1,003,160,822**

QR6 Wind turbine Lifecycle costs

The life cycle costs over 20 years in tables 8 to 10 below are based on one QR6 Turbine with a 6-meter mast installed with all controllers and connections.

Table 8.Total Capital Costs 20 years –x 1 QR6 Wind turbine

Capital costs	*Kroner*	*USD$*
1 X Wind turbine (QR6) (includes controllers)	407511.88	$47,680.50
Mast	69859.18	$8,173.80
Total	**477371.06**	**$55,854.30**

Table 9. Total Operational Costs 20 years – x1 QR6 Wind turbine

Operating costs	*Kroner*	*USD$*
Installation /connection to power mains and grid	23281.27	$2,724
Maintenance	52417.03	$6,133
Insurance	68373.76	$8,000
Total	**144072.06**	**$16,857**

Table 10. All Costs 20 years – x 1QR6 Wind turbine

Total 20-year Lifecycle costs	*Kroner*	*USD$*
Capital costs	477371.06	$55,854.30
Operational costs	144072.06	$16,857.00
Total	**621443.12**	**$72,711.30**

Research question (b) What is the potential annual energy output per m^2 land footprint of both existing large scale typical modern wind farms in Norway (Roan Wind farm Trøndelag County) and smaller wind turbines located on top of suitable existing urban buildings in the Oslo study area?

Table 11. Summary - Roan Wind Farm and Oslo Study area Energy output per m^2

Location	*kWh - Energy output per m^2*
Roan Wind farm	40
Oslo Study area	238.5

In reference to *Table 11. Summary - Roan Wind Farm and Oslo Study area Energy output per m^2* (above)

The potential annual energy outputs for the Roan Wind farm is 40 kWh per m^2

The potential annual energy outputs for the Oslo Study area is 238.5 kWh per m^2

The related results which contributed to the final calculation of this result for both the Roan Wind farm and the Oslo study area are summarised as follows.

Roan Wind farm

The digitization of this site was necessary to calculate the site area and using this value, calculate kWh outputs per m2 and profit per m2 to enable the comparison with the Oslo study area. This map includes substations which are required to transform the generated electricity from 132 kV to 420 kV to enable effective transmission across greater distances. *(See Figure 17. Site Map – Roan Wind farm)*

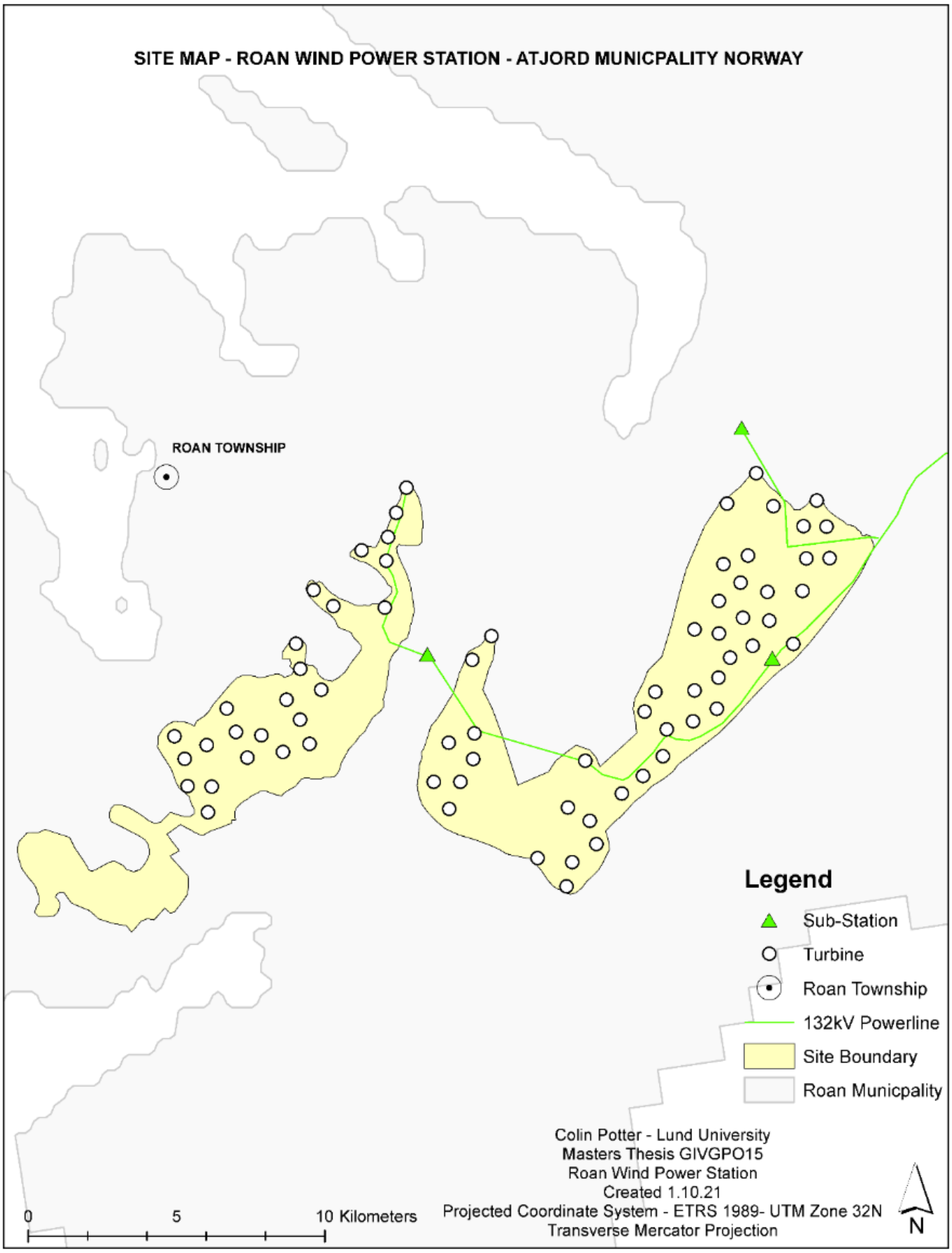

Figure 17. Site Map – Roan Wind farm

Table 12. Roan Wind farm kWh produced annually per m^2

Area of Roan Wind farm m^2	*Annual kWh production*	*kWh annually per m^2*
22,460,460.5	900,000,000	40

The total area of the Roan Wind Farm installation based on the site boundaries as 22,460,460.5 m^2 this is the equivalent of 3,145 football fields. With the total annual electricity produced by the wind farm estimated as 900,000,000 kWh. Based on this data the output is estimated as 40 kWh produced annually per m^2 across the wind farm site**.** (See *Table 12. Roan Wind farm kWh produced annually per m^2* above)

Oslo Study Area

The total roof area of all suitable buildings higher than 10 meters AMSL within the study area is 1,832,965.6 m^2 (2854 buildings). This suitable building roof area represents 14.6% of the total Oslo study area (12,566,370.6 m^2) (See *Table 3 . Number of buildings and area m^2 > 10 meters AMSL*)

Table 13.- Potential Energy Output of all suitable buildings Oslo Study Area

Buildings meters AMSL	*Annual kWh output*
>100 m	640,356
90-100 m	1,557,528
80 -90 m	10,089,326
70 - 80 m	12,765,072
60 -70 m	35,808,254
50-60 m	79,840,376
40-50 m	97,655,606
30 -40 m	114,170,396
20 -30 m	82,007,616
10 - 20 m	2,721,732
Total	437,256,262

Table 14. Heights> 10 meters AMSL - Oslo Wind turbines – kWh produced per m^2

Oslo Buildings m^2	*Annual kWh production*	*kWh annually produced per m^2*
1,832,965.6	437,256,262	238.5

This equates to a total annual energy output of 238.5 kWh per m^2 for the QR 6 turbines installed in the study area**.** (See *Table 14. Heights> 10 meters AMSL - Oslo Wind turbines – kWh produced per m^2* above).

The available surface area of the building roofs both on an individual building basis and within the height classes determines how many wind turbines can be installed on each building and within each height classification to generate power.

The number of turbines installed correlates more strongly to annual kWh production within the study area than the actual building heights. (See below – *Figure 18. Graph - Number of Turbines, Building Heights/ Annual kWh within the Oslo study area*)

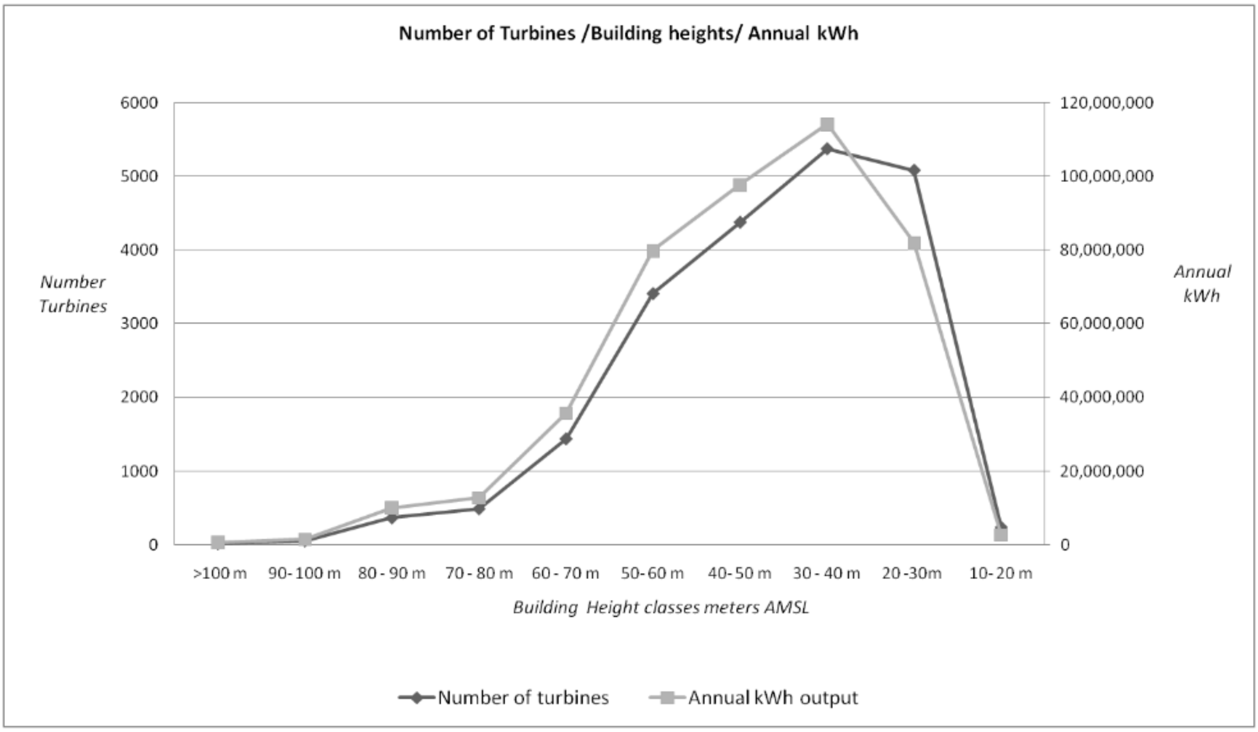

Figure 18. Graph - Number of Turbines, Building Heights/ Annual kWh within the Oslo Study area

The individual building roof area determines how many turbines can be installed on each building and the potential power generation; this is visualized on the next page in *Figure 19. Map - Oslo Study Area - Estimated kWh output annually per building.*

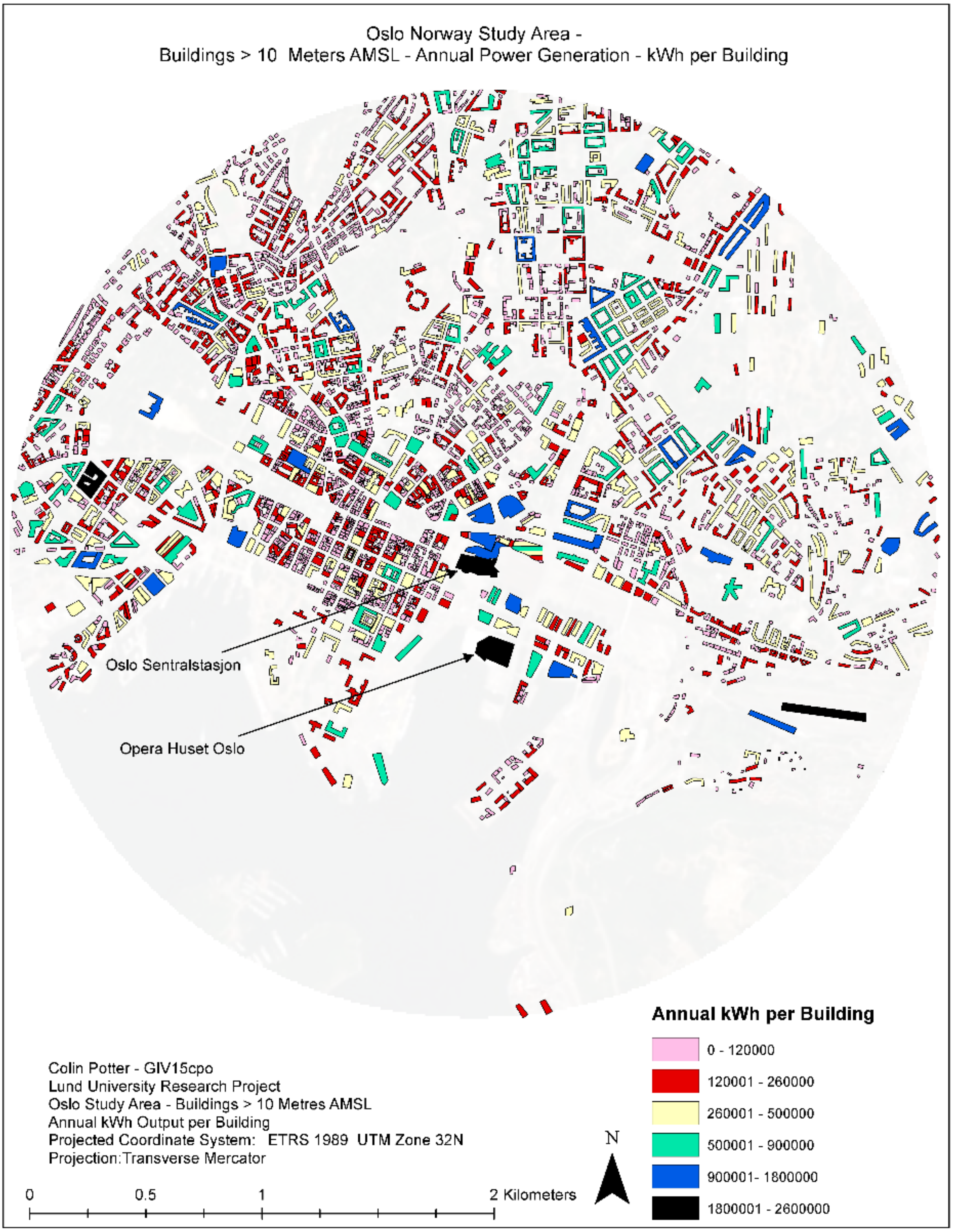

Figure 19. Map - Oslo Study Area - Estimated kWh output annually per building

Buildings with larger roof surface areas can have more turbines installed on them and consequently these have the highest per building energy outputs. For example, Oslo Sentralstasjon and Opera Huset Oslo as indicated on the map by arrows are buildings with large roof areas with are each classified as black in the legend (highest outputs) although they are not the highest buildings in the Oslo study area.

The power generation in kWh per m^2 of the Oslo Study area, to enable the energy effectiveness per m^2 comparison with the Roan wind farm is visualized in *Figure 20. Map - Oslo Study Area - Estimated kWh output annually per m^2* below.

Figure 20. Map - Oslo Study Area - Estimated kWh output annually per m^2

More detail is provided in *Figure 21. Map - Oslo – Detailed - Estimated kWh output annually- per m²* below. The detailed map also visualizes the number of turbines installed on each building. Height factors and related increased wind speeds could be influencing the per m^2 land use efficiency. Note in *Figure 21. Map - Oslo- Detailed* below Radisson Blu Plaza hotel and Biskop Gunnerus Gate, two of the highest building in Oslo that had relatively high per m^2 kWh annual outputs.

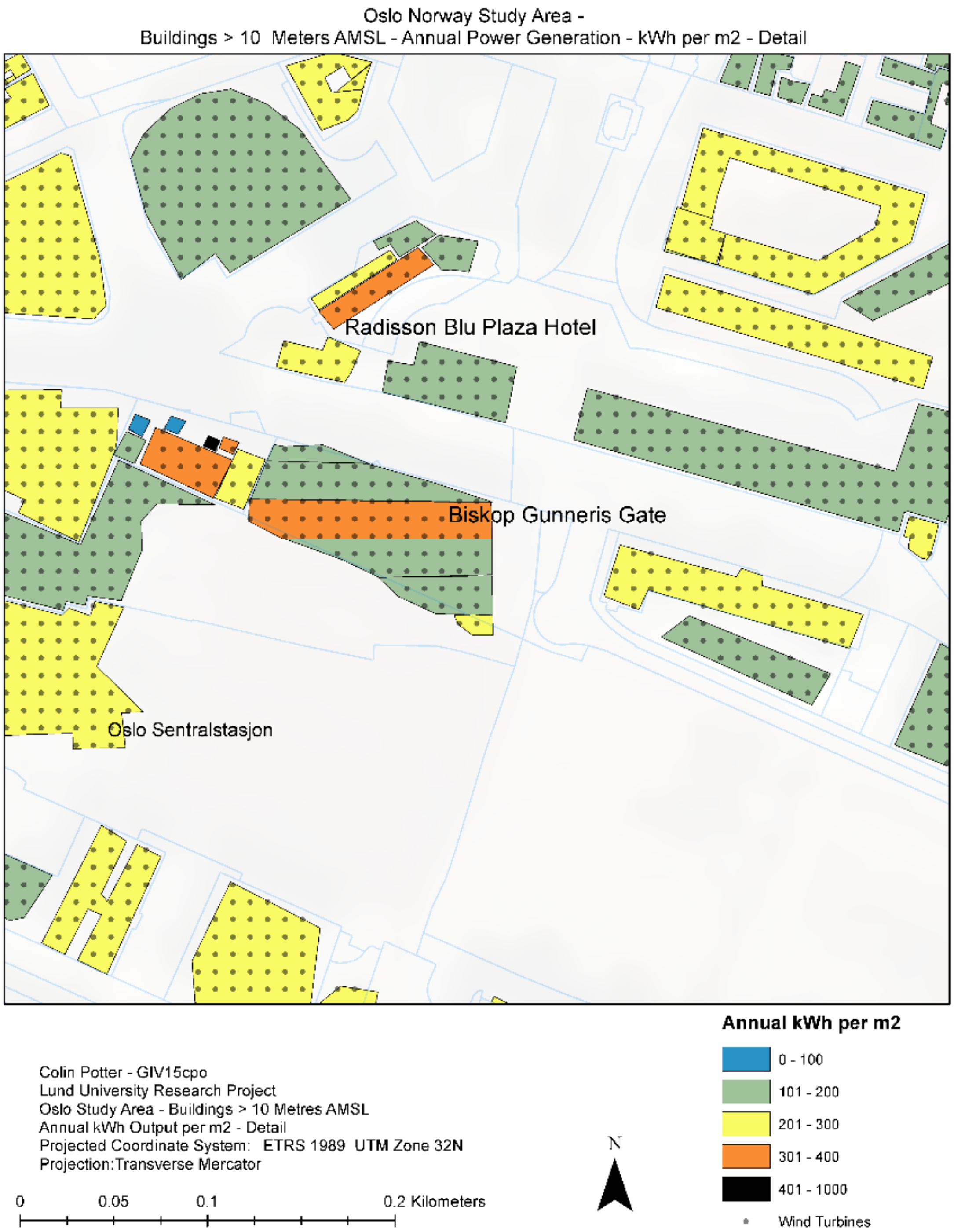

Figure 21. Map - Oslo – Detailed - Estimated kWh output annually - per m^2

This height factor is highlighted below in *Figure 22. Graph - Oslo Buildings by heights – Estimated kWh output annually per m²*. As the height of buildings increased within the Oslo Study Area, the effectiveness of land use per kWh power generated also increased. These increases ranged from 132.4 kWh per m^2 for buildings 10 – 20 meters AMSL high to 370.6 kWh per m^2 for buildings over 100 meters AMSL.

This is logical given that the wind speeds in the Oslo Study Area also increased with elevation, providing more energy to power the wind turbines.

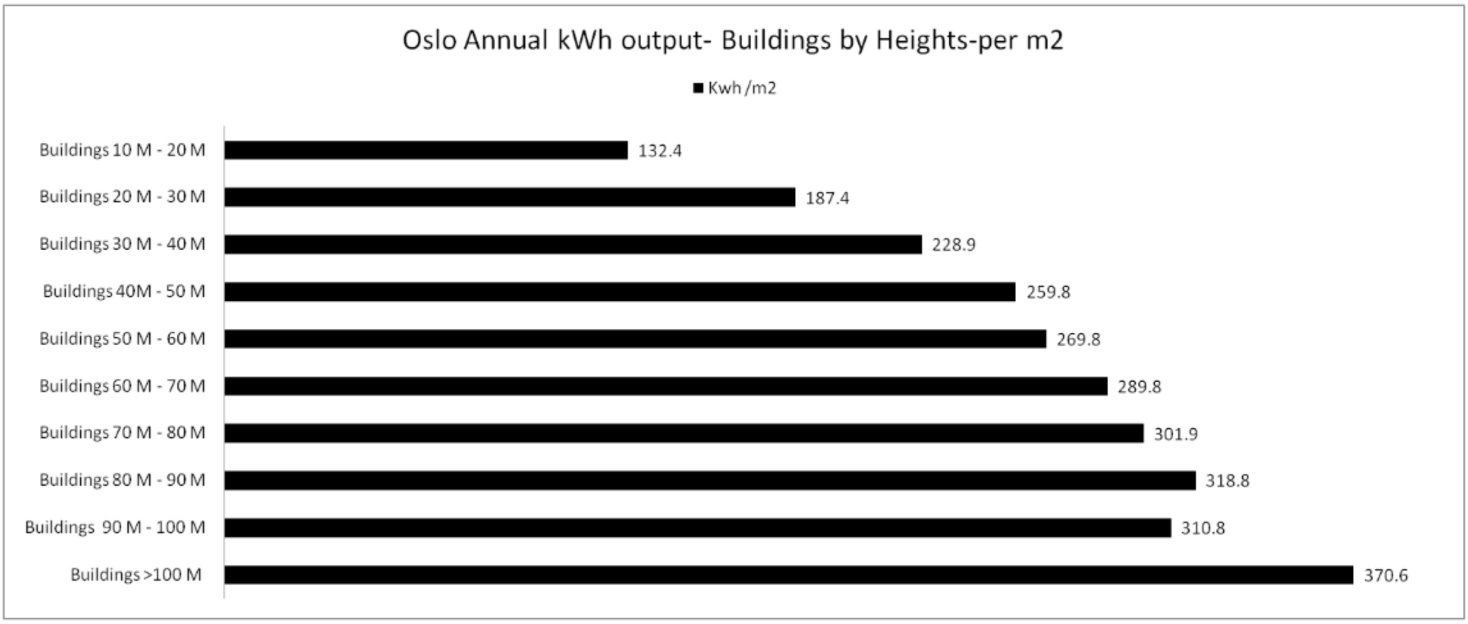

Figure 22. Graph - Oslo Buildings by heights – Estimated kWh output annually per m^2*

**Please note due to smaller individual rooftops areas of the buildings in the 90-100 meters AMSL height class, less wind turbines were able to be installed on them, resulting in a lower annual energy yield per m^2. This result was based on using the ArcGIS Fishnet tool/spatial join method (1 turbine per $91m^2$ for 90-100 meters compared to average across all building heights - 1 turbine per 87.93 m^2)*

Research question (c) Across a 20-year life cycle what is the net profit/loss $ value per kWh of the energy produced in total and per m^2 for both small wind turbines located on top of suitable urban buildings in the Oslo study area and large turbines on the Roan wind farm?

Table 15. Summary - Net loss / profit Roan Wind farm and Oslo Study area per kWh and per m^2

Location	*Net loss/profit per kwh*	*Net loss/profit per m^2*
Roan Wind farm	$0.0943 profit	$75.55 profit
Oslo Study Area	-$0.02 loss	-$111.24

In reference to *Table 15. Summary - Net loss / profit Roan Wind farm and Oslo Study area per kWh and per m^2* (above) .

<u>Over the 20-year life cycle the Roan wind farm delivers a net profit of USD$75.55 per m² and a net profit of USD$75.55 per kWh.</u>

<u>The Oslo Study Area over 20-year cycle delivers a net a loss of USD$111.24 per m² and a net loss of USD$0.02 per kWh</u>.

The related results which contributed to the total calculation for this result are summarised below for both the Roan Wind farm and the Oslo study area.

Roan Wind farm

Net Profit/loss per kWh energy produced

The total costs of generating power for the Roan Wind farm over a 20-year cycle were USD$0.557 per kWh. Delivering a net profit of USD$ 0.0943 per kWh generated. This value includes for comparative assessment purposes both capital (USD$0.0410) and operational costs (USD$0.0140) per kWh.

(See *Table 16. Profit/Loss USD$ per kWh and Table 17. Roan - Wind farm - Electricity Produced -Net Profit USD$ per m²* for profit/loss calculations)

Table 16. Roan - Wind farm - Electricity Produced – over 20-year cycle –Total Net Profit USD$ per kWh

Item	*USD$ Cost per kWh*	*Retail cost kWh/USD$*	*Profit/Loss USD$ per kWh*
Capital Costs	$0.0413	$0.15	
Operational Costs	$0.0144	$0.15	
Total costs	**$0.0557**	**$0.15**	**$0.0943**

The net profit/loss per m²

Table 17. Roan - Wind farm - Electricity Produced -Net Profit USD$ per m² over 20-year lifecycle

Item - 20 Year Lifecycle	*Value*
20 years Production of power (kWh)	18,000,000,000
Retail Value USD$	$2,699,999,999.79
Costs to generate USD$	$1,003,160,822.00
Profit USD$	$1,696,839,177.79
Area of wind farm	22,460,460.5
kWh output m²	801
Profit per m² /USD$	**$75.55**

Oslo Study Area

Net Profit/loss per kWh energy produced

The total costs to generate electricity across a 20-year cycle using QR6 wind turbines on top of all buildings over 10 meters AMSL is USD$0.1733 per kWh. This value includes for comparative assessment purposes both capital (USD$0.1396) and operational costs (USD$0.0337) per kWh.

(See *Table 18. Profit/Loss USD$ per kWh and Table 19. Oslo - Electricity Produced All Buildings*, for profit/loss calculations)

Table 18. Oslo - Electricity Produced All Buildings>10 meters AMSL – over 20-year lifecycle –Net Profit USD$ per kWh

Item	*USD$ Cost per kWh*	*Retail cost per kWh USD*	*Profit/Loss USD per kWh*
Capital Costs	$0.1396		
Operational Costs	$0.0337		
Total costs	**$0.1733**	**$0.15**	**-$0.02**

The net profit/loss per m^2

Table 19. Oslo - Electricity Produced All Buildings>10 meters AMSL – over 20-year cycle –Net Profit/loss USD$ per m^2)

Item - 20 Year Lifecycle	*Value*
20 years Production of power (kWh)	8,745,125,240.00
Retail Value USD$	$1,311,768,786.00
Costs to generate USD$	$1,515,667,048.50
Profit/Loss- USD$	-$203,898,262.50
Area of suitable buildings m2	1,832,965.6
kWh output m^2	238.5512624
Profit/loss per m^2	**-$111.24**

Research question (d) At what height do small wind turbines located on top of suitable urban buildings in the Oslo study area start to deliver a net profit per kWh and per m^2?

Only those buildings in the Oslo study area that are higher than 60 meters AMSL make a profit both per kWh and m^2, which progressively increases in relation to height

Profit per kWh – Oslo Study Area

The profit per kWh ranges from USD$0.0039 per kWh for the 60 -70-meter building class to USD $0.0436 per kWh for the 120 -130-meter building class. See *figure 23. Graph and Table 20. All Suitable Buildings Oslo by heights* below.

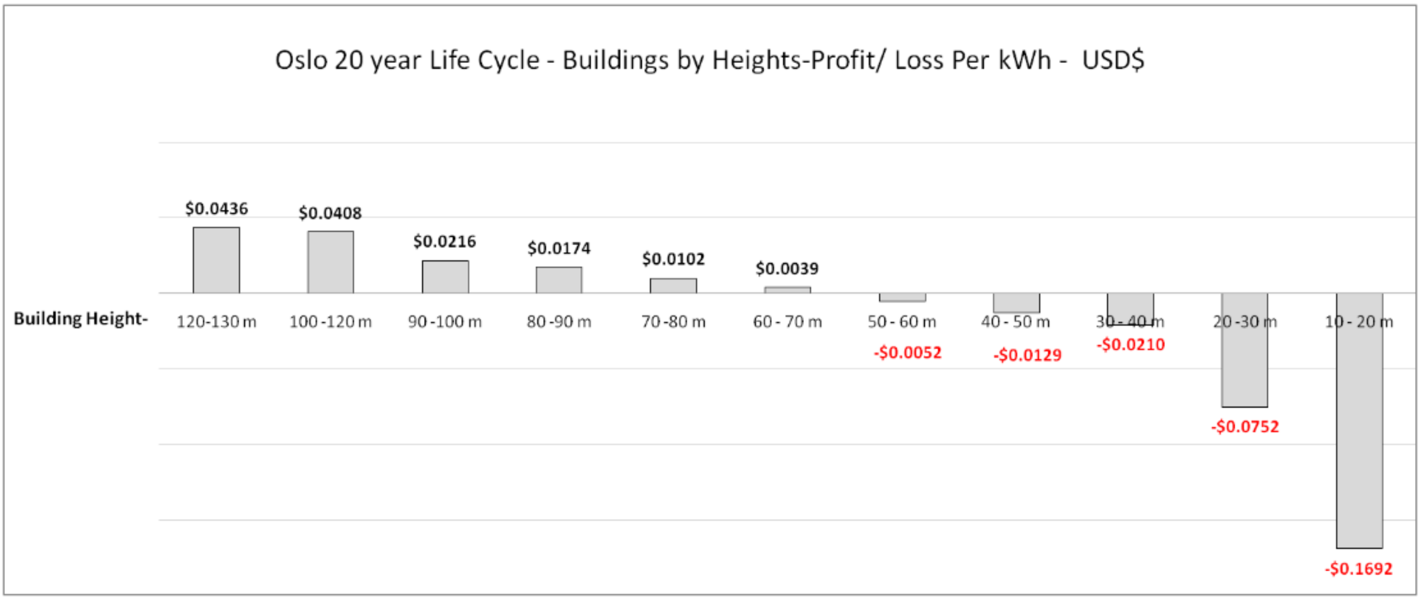

Figure 23. Graph - All Suitable Buildings Oslo by heights – Profit/Loss USD$ per kWh– 20-year life cycle

Table 20. All Suitable Buildings Oslo by heights – Profit/Loss USD$ per kWh– 20-year life cycle

Building Height - AMSL	*Profit/ Loss USD$ per kWh*
120 -130 m	$0.0436
100 - 120 m	$0.0408
90 - 100 m	$0.0216
80 - 90 m	$0.0174
70 - 80 m	$0.0102
60 - 70 m	**$0.0039**
50 - 60 m	-$0.0052
40 - 50 m	-$0.0129
30 - 40 m	-$0.0210
20 - 30 m	-$0.0752
10 - 20 m	-$0.1692

In reference to *Figure 24. Map - All buildings > 60 meters (including turbine height) locations - economically viable – Cost per kWh– 20-year cycle,* there were 468 buildings within this group with a combined surface area of 204,246.2 m^2, the equivalent of 28 football fields.

A couple of these buildings occupy a central CBD location these are the highest structures in Oslo; however, the majority (approximately 98%) are scattered to the Northeast and Western sides of the study area, these buildings are not high structures, (most are between 3-6 stories high) but they are located in areas of higher terrain elevation.

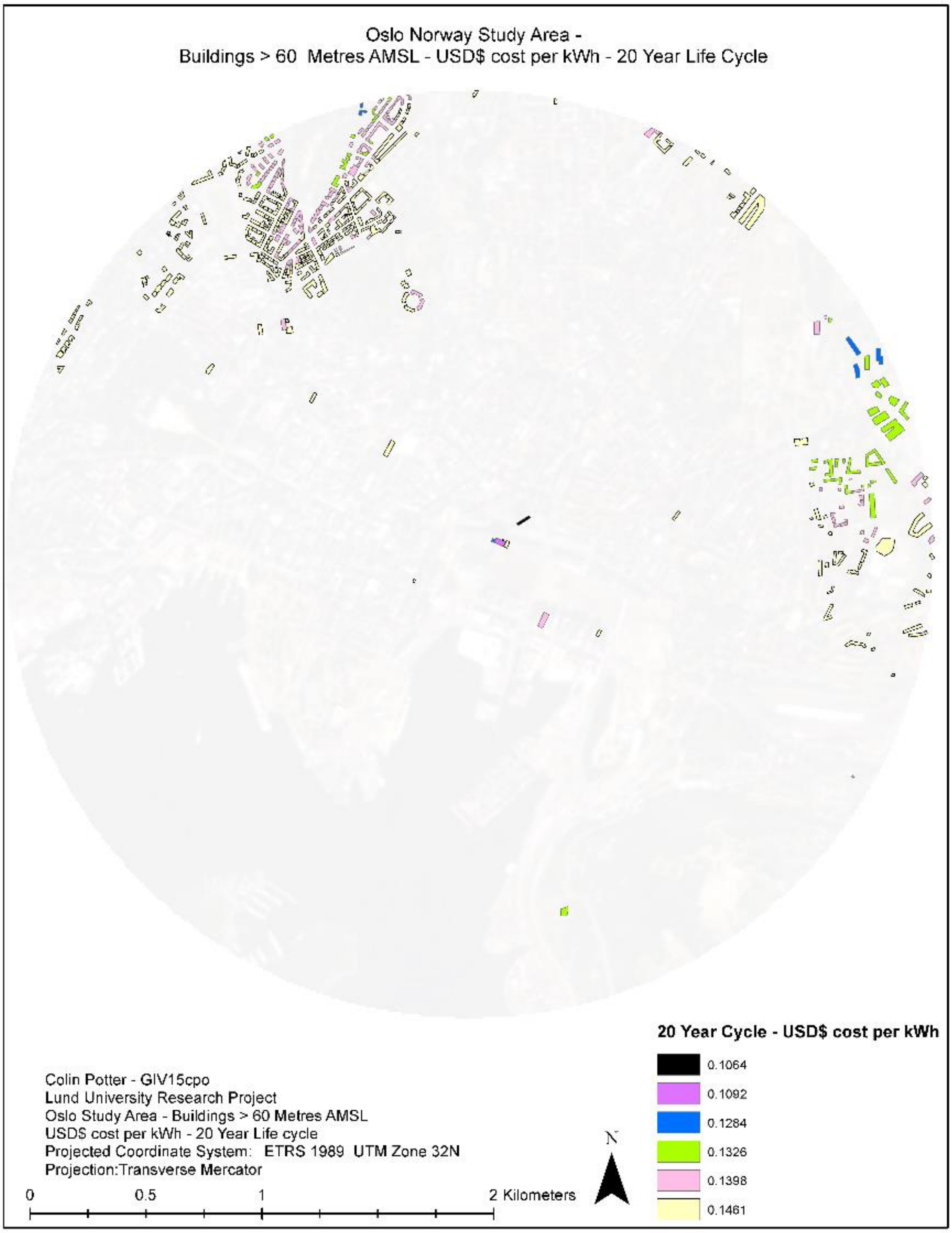

Figure 24. Map- All buildings >60 meters AMSL (including turbine height) locations - economically viable – Cost per kWh– 20-year cycle

The net profit/loss per m² – Oslo Study Area

In common with the profit per kWh height calculations, those buildings over 60 meters AMSL all make a profit per m² which progressively increases with building heights. These range from USD$22.60 per m² for the 60 -70-meter building class to USD$346.99 per m² for the 120 -130-meter building class. See *Figure 25. Graph - All Suitable Buildings Oslo by heights and Table 21. All Suitable Buildings Oslo by heights – Profit/Loss USD$ per m²* below.

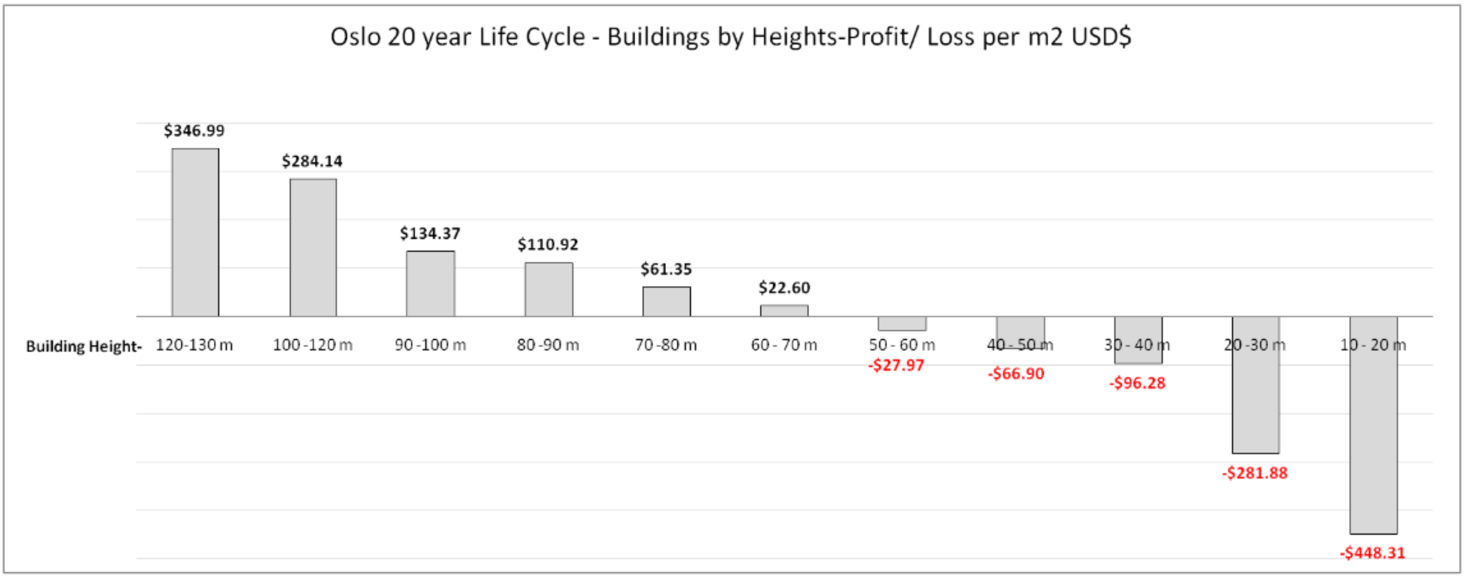

Figure 25. Graph - All Suitable Buildings Oslo by heights – Profit/Loss USD$ per m²– 20-year Lifecycle

Table 21. - All Suitable Buildings Oslo by heights – Profit/Loss USD$ per m²– 20-year life cycle

Building Height – meters AMSL	*Loss/ profit per m² – USD$*
120 -130 m	$346.99
100 - 120 m	$284.14
90 - 100 m	$134.37
80 - 90 m	$110.92
70 - 80 m	$61.35
60 -70 m	**$22.60**
50 - 60 m	-$27.97
40 - 50 m	-$66.90
30 - 40 m	-$96.28
20 - 30 m	-$281.88
10 - 20 m	-$448.31

Generally, Installing, and operating QR6 wind turbine on all buildings over 60 meters AMSL to generate power over a 20-year life cycle would result in a profit of USD$00.1 per kWh and a profit per m^2 of USD$49.50. (See - *Table 22. All buildings >60 meters (including turbine height) AMSL economically viable costs per kWh - 20-year cycle*).

Table 22. All buildings >60 meters (including turbine height) AMSL economically viable costs per kWh - 20-year cycle

Building Height - AMSL	*Cost per kWh USD$*	*Profit/ Loss USD$/ per kWh*	*Loss/ profit per m^2 USD$*
120 -130 m	0.106415086	0.043584914	$346.99
100 - 120 m	0.109215483	0.040784517	$284.14
90 -100 m	0.128380405	0.021619595	$134.37
80 - 90 m	0.132604291	0.017395709	$110.92
70 - 80 m	0.139839588	0.010160412	$61.35
60 -70 m	0.14609978	0.00390022	$22.60
Total	**$0.14**	**$0.01**	**$49.50**

5. Discussion

5.1 Data limitations

To test the major hypothesis, the research firstly required the modeling and investigation of the practicability of generating power using small turbines installed on the roofs of existing buildings in the hypothetical urban study area in Oslo Norway. If this was found to be feasible, a comparison was to be performed based on resource efficiency (financial and land utilization) between the modeled urban study area and an existing operating large scale wind farm in Roan, Norway. In conducting the processing required to answer the related research questions several data limitations were identified which could impact on the validity of the results.

In relation to the QR 6 turbine maintenance and spacing specifications there is a reliance on the manufacturer's specifications for the area required for each turbine to enable maintenance and effective performances. In addition to this, a fishnet GIS process was applied to locate the turbines onto the roof tops which assigned turbine points to every available area of the roof tops, when this in reality may not be possible or practical.

In relation to the estimations of wind speeds at different heights above the study area obtained from the Global Wind Atlas (DTU Wind Energy, 2021). These maps of wind strengths and directions were of relatively low resolution (250 meters) and because of this were not highly suitable for high resolution studies of this type. In addition to this only 3 relevant heights average annual wind speeds were available through the Atlas; 10, 50 and 100-meters AMSL, with other values extrapolated/interpolated for the range of building heights in the study area through the application of the log law algorithm. These factors make this method of obtaining accurate wind speeds problematic.

Furthermore, the use of annual average speeds to estimate the power output at heights for the QR 6 turbine is inherently inaccurate. The QR power curve provided by the manufacturer is based on constant wind flow, which is a highly unlikely scenario in reality, there would be most probably short and long period and seasonal fluctuations in speed effecting turbine power output characteristics in reality (McIntosh, 2009). The average wind speed data represents and is calculated from all wind speeds over the year which may range from no wind (<1 m/s) when the QR 6 turbine will not generate electricity to high winds (>20 /s) in which the QR 6 turbine will cut out to minimize damage (Quiet Revolution, 2020).

These inherent inaccuracies in average wind speeds and turbine performance are compounded by the added complexity of modeling these dynamics in the urban context with no accepted single accurate method for modeling wind strength in this environment. Although it is noted that the impacts of surface roughness of the urban terrain are accounted for in the calculation of the wind speeds (DTU Wind Energy, 2021). It is difficult to determine if the modeling used in the Wind Atlas accurately accounts for the high variable in roughness and drag impacts on surface objects and the effect of adjacent buildings on wind flow strength and consistency in the study area. (Stathopoulos et al, 2018). These factors can impact accurate estimations of urban wind strength.

In relation to identifying the buildings that was suitable for the turbine installations, the only consideration for selection was the height of the buildings, which needed to be over 10 meters AMSL (Although parliament, royal palaces, churches, cathedrals, or historic protected buildings were excluded from the digitization). Some of the individual buildings identified as suitable, may with further individual analysis be found to be unsuitable for turbine installations because of other factors that were not within the scope of the study. For example, Individual building construction, roof load capacities, roof shape and contour, roof material, harmonics, and building codes and regulations.

Furthermore, the base layer for these buildings was manually created from relatively coarse data (10 meters resolution) and consequently there are unaccountable inherent inaccuracies that could impact the building size and height and as a result the final efficiency measures. For example, the data used was not of a sufficient resolution to replicate small changes in building roof heights or profiles changes. This inaccuracy was compounded using a "spatial join", a GIS process which assigned a single mean elevation value from a 10-meter resolution points dataset to a single building polygon even though in most cases there were multiple points within these polygons, this process assigned flat roofs to all building polygons, when in reality this may have not been the case.

In relation to the 20-year life cycle costs for a single QR 6 turbine, specifically that the turbine will last at least 20 years and related purchase, installation and maintenance costs and intervals, there is a reliance on the manufacturer's claims. It is assumed in the study that the company representations regarding these factors are reliable and accurate. However, this may not be the case, and future costs could change. This could result in errors in the economic modeling, for example, when the value per turbine is multiplied by the number of turbines to measure the costs for the installation and operating of numerous turbines within the study area.

Furthermore, the economic modeling data for the Roan wind farm 20-year life cycle costing was based on the work of Skorstad (2014), for accuracy this data was cross checked and verified against a later commercial consultancy report from the Thema Consulting Group (2019). However, this modelling is only a projection in which it is assumed that the costs of production will not change markedly from the projected values from year to year. Other factors including future government taxes and excises, changes in available wind power at the site, turbine performance or the market price for electricity could result in errors in the future projected life cycle economic and energy modeling for the wind farm. Although several limitations relating to data sources and methods have been identified, the following observations are noted.

5.2 General discussion

Specifically in relation to Sub-hypothesis 1, that small wind turbines located on top of existing urban buildings are a practical option for the generation of wind power,
it appears from the results that the installation of turbines on the roof top is possible and practical. However as noted the results, the numbers of turbines installed was somewhat extreme, with the entire area of every single building over 10 meters AMSL, regardless of individual characteristics was taken up by wind turbines. This is an entirely unrealistic scenario; it is difficult to imagine communities accepting the saturation of a city skyline with thousands of turbines and related noise and construction issues. I could not find any references in the literature to incidences of the mass installation of wind turbines on buildings in cities.

Furthermore, due to data limitation as noted earlier it is highly likely that a significant number of these turbines would not work effectively in the first place. This is in part due the uncertainty of measuring wind strengths in the urban environment. For example, of relevance is the actual wind turbine installation site research conducted by Haase (2014) within the Oslo Study area that found that the monthly average strength of the wind recorded on-site at the top of the Biskop Gunnerus Gate 14 building (110 meters AMSL) was considerably lower than the average speeds recorded at the nearby Blindern and Alna weather stations, which were at a much lower elevation. Also, the digitization process did not account for individual building characteristics in the estimation of wind speeds including roof shapes. Ledo et al, (2011), concluded that roof profiles can influence the speed of wind and that turbines mounted on flat roofs are likely to yield more consistent and higher power than turbines mounted at the same height on other roof profiles. Perhaps the most dependable method is to directly measure the wind speed at the site and height of the wind turbine installation (Stathopoulos et al, 2018) (Kassem et al, 2019). However, for the purposes of this study, this method was impracticable and beyond the scope of this research.

Specifically in relation to Sub-hypothesis 2 - That smaller wind turbines located on top of existing urban buildings are more resource efficient than large scale open wind farms, it was found that the modeled Oslo study area on the basis of energy output per m^2 (238.5 kWh per $m^{2)}$ was significantly more land use efficient than the Roan Wind farm (40 kWh per $m^{2)}$ but on the basis of costs per kWh energy produced it was substantially less efficient than the Roan Wind farm.

However, if only all buildings above 60 meters AMSL were used to generate power in the study area, this would generate a profit of USD$0.01 per kWh produced. Although this modeled scenario delivers a profit and is economically viable, it is not more economically viable than the Roan wind farm, which operates at a greater profit per kWh over the 20-year life cycle. Even if as noted earlier in the results section, only buildings above 100 meters AMSL in the study area were used to generate power using the QR6 turbines these would only deliver a profit of USD$0.042 per kWh. This is considerably less than the Roan wind farm profit per kWh.

It is also important to note that in the results it was established that the number of turbines installed within building height classes *did not impact* the profit/loss value per kWh per class. Eeach individual turbine within the study area has a constant 20-year life cycle cost of $72,711.30 and as the number of turbines is decreased or increased within each height class the kWh output and cost per turbine is also increased or decreased by this same factor, the ratio remains constant. Therefore, if only a couple of turbines were installed on each building, instead of the maximum number possible, the same profits or losses would still be maintained. In relation to at what height do turbines installed in the study area start to deliver a profit, those buildings with heights between 60 and 70 meters AMSL offer only the most marginal financial benefits, economic viability could be sustained more easily if only the highest buildings had wind turbines installed on them.

The Roan Wind farm appears to be the better overall option for generating power from the wind mainly because it is significantly more profitable, being designed and built specifically to achieve this economic efficiency. Furthermore, the financial analysis for the Oslo Study area didn’t allow for the likely costs of excessive modifications of buildings required to retrofit turbines within the Oslo Study area, this could be very expensive and problematic and result in significantly increased costs. Although it is noted that the land use efficiency of the Oslo study area is substantially better than the Roan Wind farm, this type of efficiency does not out-weight these financial shortcomings. For the installation of turbines in the Oslo study area to be financially viable, the Norwegian Government would need to provide significant financial support. Finally, although it is noted that there are negative impacts on people living around the large-scale wind farm at Roan, the amount of people who are directly impacted would be significantly less than the number of people impacted through the mass urban installation of turbines within the Oslo CBD, with these turbines installed much closer to a denser population.

6. Conclusions and recommendations for further research

In the first instance, the research indicates that installation of small turbines in the study area is practically possible. Even noting the limitations of the modeling process, if only half of these 2,854 buildings that were over 10 meters AMSL were determined through field studies to be suitable, the QR 6 turbines could still be considered as a practical option for the generation of power in the study area. These turbines could be installed, and they could generate power from the wind from at least some roof top sites. From this confirmation of suitability, progressing to the land and economic effectiveness comparison between the wind farm and the Oslo study area, based on the outputs and cost modelling, it is possible to conclude in relation to the major hypotheses.

Smaller wind turbines located on top of existing urban buildings in the study area

1. DO use space more effectively than large scale open wind farms

They generate significantly more power per m^2 than the Roan Wind farm

However, they are

2. NOT more economically viable than large scale open wind farms

The major hypothesis is partially disproven, but the results regardless of this outcome are relevant and informing.

Although smaller wind turbines located on top of existing urban buildings are less economically viable than large scale open wind farms, a profit can be realized if only those buildings above 60 meters AMSL use QR 6 wind turbines to generate power.

An important facet of this research is its land use aspects because there are land equity, environmental and social rights issues and challenges related to take up of vast areas for the installation and operating of large-scale wind farms, not only in Norway, but in numerous countries across the world. It is also important to note, that most roof tops in the Oslo study area are probably underutilized pieces of land and activating these areas to generate power is not only a highly land resource efficient process but would also result in minimal environmental and social impacts. However, whether the social and environmental benefits of the using these roof tops in the Oslo study area to mount small scale turbines outweighs the economic costs of these installations is yet to be established, as this would be a variable that is dependent on the specific number of turbines installed and where they are located. Such an installation would also require considerable public and government support to be economically and socially realizable.

The research has revealed opportunities for further research that could utilize, build on, refine, or fill gaps in these findings and generate further knowledge in this field.

A study using a high resolution digital 3-dimensional model of the buildings within the Oslo study area to simulate wind speeds and strengths within the actual buildings could provide more accurate data to estimate wind turbine outputs and overcome some of the digitization and GIS process limitations on this modeling and research. Although this technology and methodology is still in its infancy, there has been some robust development in this area and the application of virtual reality in this field (Piepereit et al, 2019).

In addition to this, research could be conducted using a more accurate and intense remote digitization process that was focused on the most economically viable installation sites in the study, for example, those buildings above 60 meters AMSL. A more concentrated approach could provide more accurate results for these installations.

On–site research also focusing on these most economically viable buildings could be considered. The installation of wind speed and direction monitors on each building roof could result in more accurate and reliable estimations of high-resolution wind speeds and more reliable estimations of wind turbine performance. These factors once established could lead the way for on-site testing/ trialing of single wind turbines on the actual buildings. This would be economically viable because according to this research a single QR 6 turbine at a height above 100 meters AMSL could deliver a profit over 20 years of USD$0.0421 per kWh generated or a net profit of USD$28,397.57.

Of note also is the considerable recent research that has been conducted in using small scale wind turbines coupled to and directly powering heat pumps, which can be used to cool or heat buildings instead of providing a more general electricity supply to the building. Heat pumps are characterized by a high co-efficiency of performance level (COP). The COP which is defined as the watt energy produced by the heat pump divided by the energy consumed by the heat pump (Mix, 2006) is generally approximated as 4 for heating and 3 for cooling (Bilir et al, 2016). A recent study conducted by Hailong et al (2018) concluded that in an urban study area in Turkey, 68.9% of the heat pump electrical energy needs on an annual basis can be covered by a small-scale wind turbine installed on top of a building. Therefore, the use of wind turbines to directly power heat pumps in urban installations is of worthy consideration for furthermore detailed research. This application shows great promise as it could result in 3 to 4 times greater economic efficiency and could make the installation of small wind turbines in this study area and other urban applications highly economically viable.

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Appendix 1. Methodology

The methodology is comprised of the following stages in the research investigation.

GIS operations are indicated by *italics.*

1. Creation of the buildings with heights polygon layer for the Oslo Study area.
2. Finalizing the actual heights of turbines when installed on buildings
3. Calculating wind speeds at different building heights within the study area
4. Calculating the total roof area within the study area suitable for mounting/installing wind turbines
5. Calculating how many QR6 turbines could be installed on buildings with heights between 10 and 130 meters AMSL within the study area.
6. Determining the QR6 turbine power output in kWhs at different building heights
7. Calculating land usage and m^2 output per kWh for the study area
8. Determining the 20-year lifecycle costs and economic effectiveness of the study area
9. Calculating over a 20-year lifecycle the profitability of installing the turbines in the study area
10. Creating the Roan Wind farm map to estimate the site area
11. Determining the costs per kWh for the Roan wind farm over a 20-year life cycle
12. Calculating land usage and m^2 output per kWh for the Roan Wind farm

<u>1. Creation of the buildings with heights polygon layer for the Oslo Study area.</u>

The DOM surface and DTM terrain model tiles for UTM zone 32, which covered the city of Oslo were downloaded from the Geonorge Katlalog service operated by the Norwegian Mapping Authority.

A number of raster data sets were produced which represented the range of mosaic tiles covering the area.

- A *merge* using processing tools was performed to combine separately the numerous coverage tiles for both the DOM and DTM datasets that covered the Oslo area.

Two separate raster datasets; were produced.

(1) DOM (heights of objects from the surface) and
(2) DTM (heights of land in meters AMSL)

- Using the raster algebra tool, the new DTM dataset was *subtracted* from the new DOM dataset to create a new raster data set which featured only the elevation values of buildings and other man-made infrastructures across the city of Oslo.

A new digital raster model of "building heights" was created.

- This new "Building Heights" raster layer was *converted* to a vector point dataset.

- All building heights below 10 meters ASL were *deleted* from the dataset.

There were 2 reasons why these buildings were deleted.

(1) Wind speed data available for heights below 10 meters for the Oslo city area were not available to calculate energy generation and

(2) For aesthetic purposes, if wind turbines were installed on the roofs of buildings below 10 meters in height, people walking and cars driving past these buildings would be able to see and hear the bank of turbines and this would detract from the amenity of an area.

- The DTM dataset, which featured only the natural terrain for the Oslo area was *converted* to a vector point dataset.

It is important to note that the buildings heights dataset has the Z values of heights of buildings only from the surface of the land (ASL) and the DTM point dataset has the Z values of land height in relation to meters AMSL. These two data sets had to be added together to create a dataset for the actual heights of the buildings above sea level. Furthermore, the wind speed data sources used in this analysis calculate wind speeds at meters AMSL.

- To determine the actual building height at meters AMSL, a *spatial join* was executed using a one-to-one process between "Building Heights Points

DOM” dataset and the” DTM Point” dataset for the Oslo area to create the final building heights point dataset.

In the “Final building heights point” dataset the attribute table of this dataset, included both a column for both the actual “Building Height Meters ASL” in meters and “Height of the Land” on which the building is located in meters AMSL.

- A new column in table was created; “Building Height meters AMSL”. Using the field calculator, the values for this new column were calculated by *adding* the value of the “Building Height Meters ASL” and “Height of the Land” to calculate the building heights above sea level.

- The study area was created by executing a *buffer zone operation* which constructed a circular zone based on a 2000-meter radius using the Oslo Sentralstasjon as the central point.

The size and shape of the study area was selected to make the research and datasets more manageable and minimize the amount of manual digitization. In addition to this, this location was selected because the area represented an identifiable CBD for the urban centre of Oslo and was centered on a major transport hub, enabling future comparative research with other urban areas. Another factor confirmed in initial investigations was that this area contained the highest buildings in Oslo.

- The new “Final Building Heights” point’s dataset was *clipped* to the 2000-meter radius buffer zone.

- To commence the digitization of the building within the study area, a new polygon dataset; “Buildings” was created.

- To define and guide the process of manually digitizing all buildings within the study area this dataset was *overlaid* with the following.

a) Oslo Cadastre (for property boundaries) layer
b) Ortofoto Oslo County dataset layer to determine building shapes and dimensions
c) ESRI world street map of Oslo as a final check of building outlines

Only those building polygons which contained the final building heights points were digitized. Parliament, royal palaces, churches, cathedrals or historic protected buildings were excluded from the study area. 2,854 buildings within the study area were digitized.

- A *spatial join* was executed between the" Buildings" polygon dataset and the "Final Building Heights" point dataset to assign heights to the building polygons from the points dataset.

This process was implemented using a *one-to-one join,* the polygon dataset "Buildings " was selected as the target dataset and the "Final Building Heights "point layer as the join features dataset, all target features were kept. A single average points value was assigned to each building polygon.

A new "Final Buildings" polygon layer was created which included the final building heights in meters AMSL.

2. Finalizing the actual heights of turbines when installed on buildings

The QR6 turbine being used for this research study is mounted onto a mast which is installed on top of a building. The mast is 6 meters high (Quiet Revolution, 2020). This additional height of the turbine needed to be accounted for when calculating wind speeds, energy outputs and economic factors.

- To accomplish this, within the "Final Buildings" polygon layer (which included heights of buildings meters AMSL) attribute table a new column was added; "Turbine Heights". Using the *field calculator* within this column, 6 meters was added to the "Building heights Meters AMS" value to create a new final turbine height value to use in calculations.

3, Calculating wind speeds at different building heights within the study area

The calculation of average wind speeds at different building heights within the study area was critical to this research, because from this the potential wind energy generation of the QR6 wind turbines can be calculated. This value is a key factor in this research and will be combined with other metrics to model costs per kWh and energy output per m^2 using a range of scenarios to enable the modeling.

Note the power curve for the QR6 wind turbine (Quiet Revolution, 2020) which was used for power outputs estimations is based only on wind speeds and not wind density; therefore, only wind speeds were used in this analysis.

- Using the Global Wind Atlas (DTU Wind Energy, 2021) the study area was selected and visualized based on the wind's speeds in m/s at 3 different available heights in meters AMSL 10, 50 and 100 through the map interface.

- The graphs of average wind speeds at 3 heights were downloaded (meters AMSL 10, 50 and 100) and also the corresponding raster data sets maps were *re-projected* and *transformed* from WGS 1984 Mercator to UTM Euref89. (See *Appendix 2 – Wind Speeds – Study area*)

To estimate potential wind power at building heights other than 10, 50 and 100 meters and to enable the calculation of power generation, the values of wind speeds at other heights were calculated using the known average wind speeds at 10, 50 and 100 meters.

- Using an Excel spreadsheet, the average wind speed for heights between 10 – 100 meters AMSL based on 5-meter intervals were interpolated and for heights between 100- 150 meters AMSL extrapolated using the Log law method (UC Santa Cruz-School of Earth and Planetary Sciences, n.d)applying the following logarithmic expression.

$$v \approx v_{ref} \cdot \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

where:

- V = velocity to be calculated at height z
- Z = height above ground level for velocity v
- V_{ref} = known velocity at height z_{ref}
- Z_{ref} = reference height where v_{ref} is known
- Z_0 = roughness length in the current wind direction

Surface roughness length, which is a factor used in the calculation of average wind speeds at different height, with rougher surfaces such as urban terrains having the effect of reducing the wind speeds was factored in the calculation derived through the Global W*in*d Atlas (DTU Wind Energy, 2021). An urban roughness length of .85 was applied to the other interpolated wind speed calculations (UC Santa Cruz-School of Earth and Planetary Sciences, n.d) to account for the increased surface roughness in the final wind speed estimation.

- Within the “Final Buildings” polygon layer attribute table a new column; “Wind Speed” was created. The closest fit derived average wind speeds based on the different heights for the building polygons based on the 5-meter classification interval used in the wind speed interpolation were then added against the corresponding row for that turbine height.

4. Calculating the total roof area within the study area suitable for mounting/installing wind turbines

- In the "Final Buildings" polygon layer, heights of buildings were *classified* based on 10-meter Turbine Height intervals classes between 10 and 130 meters AMSL.

- Using the "Final Buildings" polygon layer column "Area" the total roof area available was calculated across the whole study area for all heights between 10 and 130 meters AMSL with the roof area based on different turbines height interval classes.

5. Calculating how many QR6 turbines could be installed on buildings with heights between 10 and 130 meters AMSL within the study area.

From the QR 6 turbine data (Quiet Revolution, 2020), each turbine required a minimum area of 9.3 m^2 for both effective operation and installation.

- The *fishnet tool* operation was used to create a "Grid and Label Points" layer with a specification that the points should be evenly spaced 9.3 meters apart using the "Final Buildings" polygon layer as the extent.

- The "Grid and Label Points" layer was *clipped* to the "Final Buildings" polygon layer with only those points within the final buildings polygon and study area kept.

- A "one to one" *spatial join* was made between "Final Buildings" layer as the target layer and "Grid and Label Points" as the join feature, with a specification that all target features were to be kept.

Through the process a new "Final Building Turbine" polygon layer was created with a new attribute column; "Turbines" which had a numerical value for how many points or turbines could theoretically be installed on top of each building polygon.

6. Determining the QR6 turbine power output in kWs at different building heights

The QR6 wind turbine power curve spreadsheet was used to plot and map the output in kWs of the turbine at different wind speeds in .1 increments from 2.1 to 20 m/s. (See *Appendix 3 – Wind Speeds and Power Curve*).

The wind speed range finally selected was from the spreadsheet was 2.1 to 5.3 m/s as this range represented the minimum and maximum average wind speed value that was derived through the wind speed heights calculations based on the building height ranges of 10 to 130 meters AMSL.

- In the “Final Building Turbine” polygon layer a new column was created in the attribute table; “Turbine output” with the corresponding kw value inputted for a single turbine in relation to the wind speed value from the spreadsheet was based on the final height of the building polygon which included the mast structure.

- A new column in the “Final Building Turbine” polygon layer was created; “Final Turbine Output”. The field calculator was used to execute a *multiplication* operation between values in the “Turbine Output” column with the value in the “Turbines” column (number of turbines that could be fitted on each building roof) to calculate a final all turbine output value in kW for each building polygon.

- A new column in the” Final Buildings Turbine” polygon layer was created; “Turbine’s kWh”. Using the field calculator, the values in the Final Turbine Output column was multiplied by the number of hours in a year (8,760) to calculate the total kWh output for each building polygon, which could then be applied based on the 10-meter building classifications or on a per buildings basis as needed across the study area.

<u>7. Calculating land usage and m^2 output per kWh for the study area</u>

- a new column was created in “Final Building Turbine” polygon layer “kWh– per m^2 Yearly”, using the *field calculator* the “Final Turbine Output” value was divided by the “Area” of the corresponding polygon building to calculate the Kwh output per m^{2}of individual building polygons, classes of building heights and the total study area per year.

<u>8. Determining the 20-year lifecycle costs and economic effectiveness of the study area</u>

Using 20-year lifecycle costing data obtained from the manufacturer. (Potter, 2021)

- An excel spreadsheet (See *Appendix 4 - Cost Life cycle Turbines*) was used to calculate all costs for turbines over 20 years, installed on different building heights based on 10-meter interval building classification (10-20 meters etc) and all buildings up to and above the 10-meter interval classes (>10 meters etc). This spreadsheet also included all costs over the lifecycle for the QR6 turbines including per turbine initial purchase costs (including mast cost and connection, insurance, maintenance, and installation) with all values in USD$.

A spreadsheet was used to for these costing calculations rather than the attribute table in the “Final Building Turbine” polygon layer because this method was flexible and enabled easier analysis and movement of data. In addition to this, the application of a 20-year cost cycle to the evaluation and many of these costs across this time were easier to derive and manipulate using a spreadsheet. In retrospect it could be worth considering using the attribute table for this operation.

- Within the attribute table for the “Final Building Turbine” polygon layer a selection based on the 10-meter interval building classifications was derived. The “Turbine’s kWh” column was selected, and the statistics option was used to identify the sum annual output in kWh for all turbines within the selected building height interval class.

- kWh values were copied over to the Cost Lifecycle Turbines spreadsheet to enable the 20-year kWh yields. Also copied over to the spreadsheet in the same operation was the number of turbines (attribute column; “Turbines”) from within each selected classification, this was used to calculating the costs of the installations across the same time frame.

- Using the Cost Life cycle Turbines spreadsheet, the 20-year cost to generate power per kWh in USD$. Was calculated within each height interval.

- For map visualization purposes a new column was created in the attribute table for the “Final Building Turbine” polygon layer- “Costs 20-year cycle in kWh”. A select *by attributes* operation was conducted within the attribute table with a selection based on the 10-meter interval building classifications.

Based on these selections and applying the relevant final turbine height classification the cost per kWh for the 20-year lifecycle period was applied from the Cost Life cycle Turbines spreadsheet to the appropriate height classification.

<u>9. Calculating over a 20-year lifecycle the profitability of installing the turbines in the study area</u>

- Identified the current retail domestic cost of electricity in Norway and converted to USD$

- Using the “Cost Life cycle Turbines” spreadsheet calculated for each height classification a profit or loss based on the costs to generate power using this method. This was achieved by subtracting the costs per kWh over the 20-year lifecycle for each classification from the retail domestic costs to purchase this power.

- Divided the total profit/loss per height classification over 20 years by the area of each height classification and for the total study area to calculate profit/loss per m^2

10. Creating the Roan Wind farm map – to estimate the site area

- A new vector layer "Roan Wind Farm" was created using the same standard projected coordinate system; UTM Euref89 (EPSG 25832)

- The Tostendalen (Trondelag County) cadastre of the boundaries of the Roan wind farm was imported and used to delineate and enable the initial digitization and calculate site area.

- For visualization purposes only, Google maps and also the ESRI World Imagery mapping layer were over-laid, these were used as guides to digitize features within the wind farm area (location of turbines and connective infrastructure). A map of the site from Tronderenergi (2016) was also used to confirm locations and details.

11. Determining the costs per kWh for the Roan wind farm over a 20-year life cycle

- The data within the costs table from Skorstad, Mona (2014) which included both operating and capital costs per kWh over a 20-year period was used as the reference for costs. These were already calculated and required no processing.

- These values were converted to $USD to enable the comparison between the Roan Wind farm and the study area in Oslo.

- For profit/loss - total costs per kWh was subtracted from the retail domestic costs to purchase this power

- Profit loss per m^2over 20 years was calculated by dividing the total profit by the area of the Roan wind farm.

12. Calculatingland usage and m^2 output per kWh for the Roan Wind farm

- In the "Roan Wind Farm" map layer the area of the wind farm was determined by referencing the area of the boundary polygon in the layer attribute table (Area = 22460460.49 m^2).

The total kWh annual output of the Roan Wind farm was identified and cross verified by confirming an identical corresponding value within 2 sources (899999999.93 kWh);

(1) Roan Wind farm Norway (The Windpower, 2021) and

(2) Roan Wind Park- fact sheet (Tronderenergi, 2016).

- The total energy produced annually in kWh was divided by the total polygon area of the wind farm boundary in m^2 to calculate the output in kWh per m^2 for the site.

Appendix 2. Wind Speeds – Study area

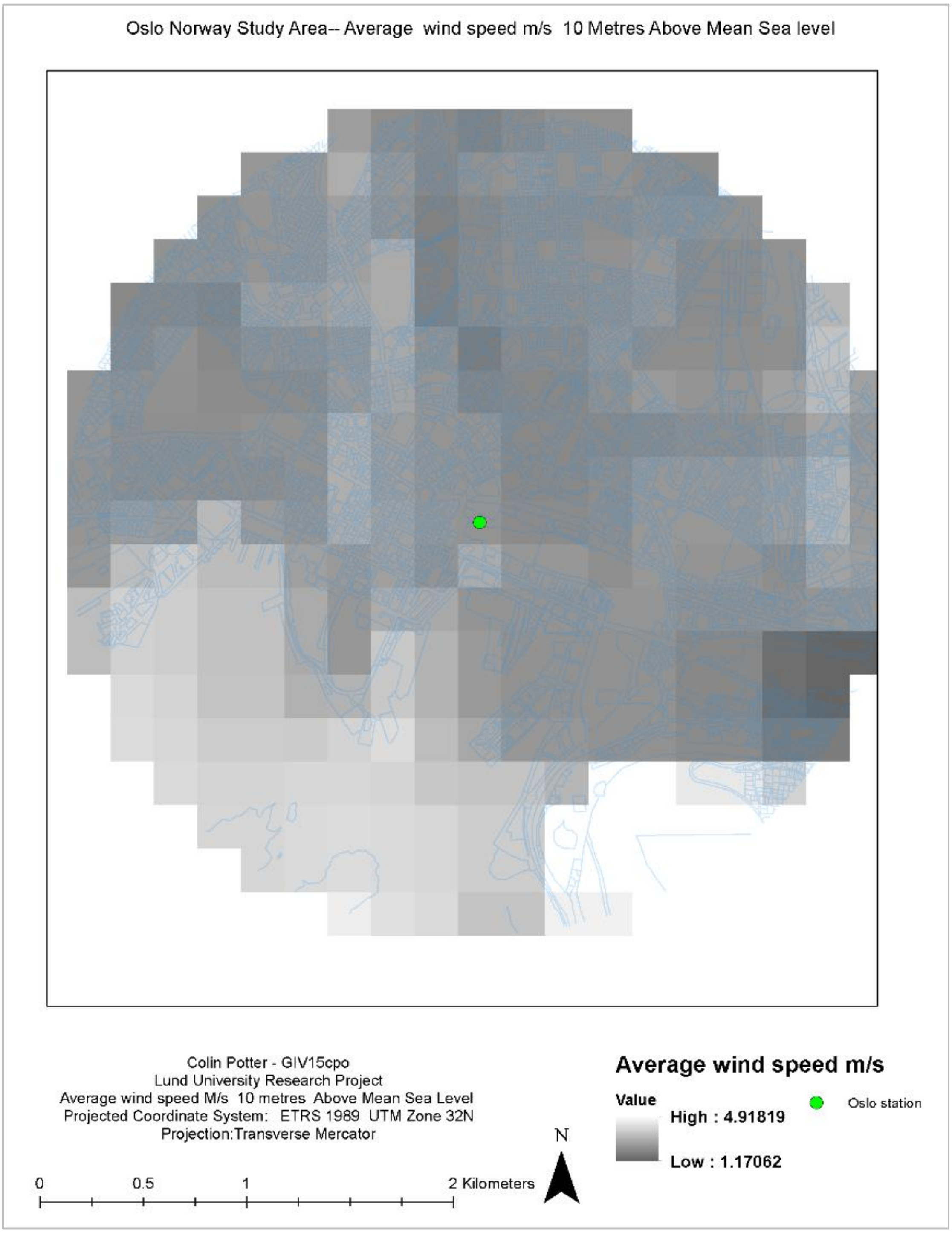

Figure 26. Map - Average Wind speed Oslo 10 meters AMSL

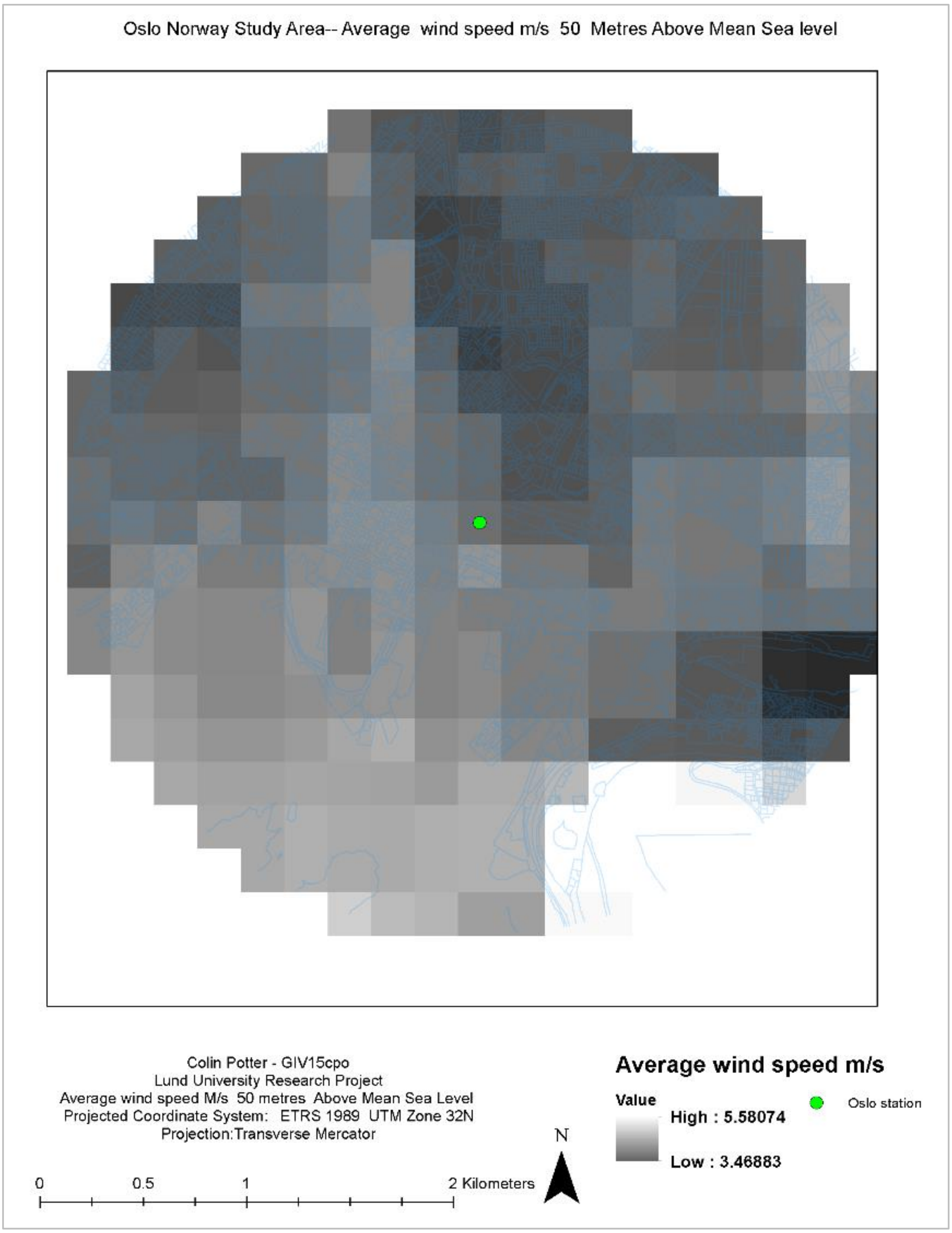

Figure 27. Map - Average Wind speed Oslo 50 meters AMSL

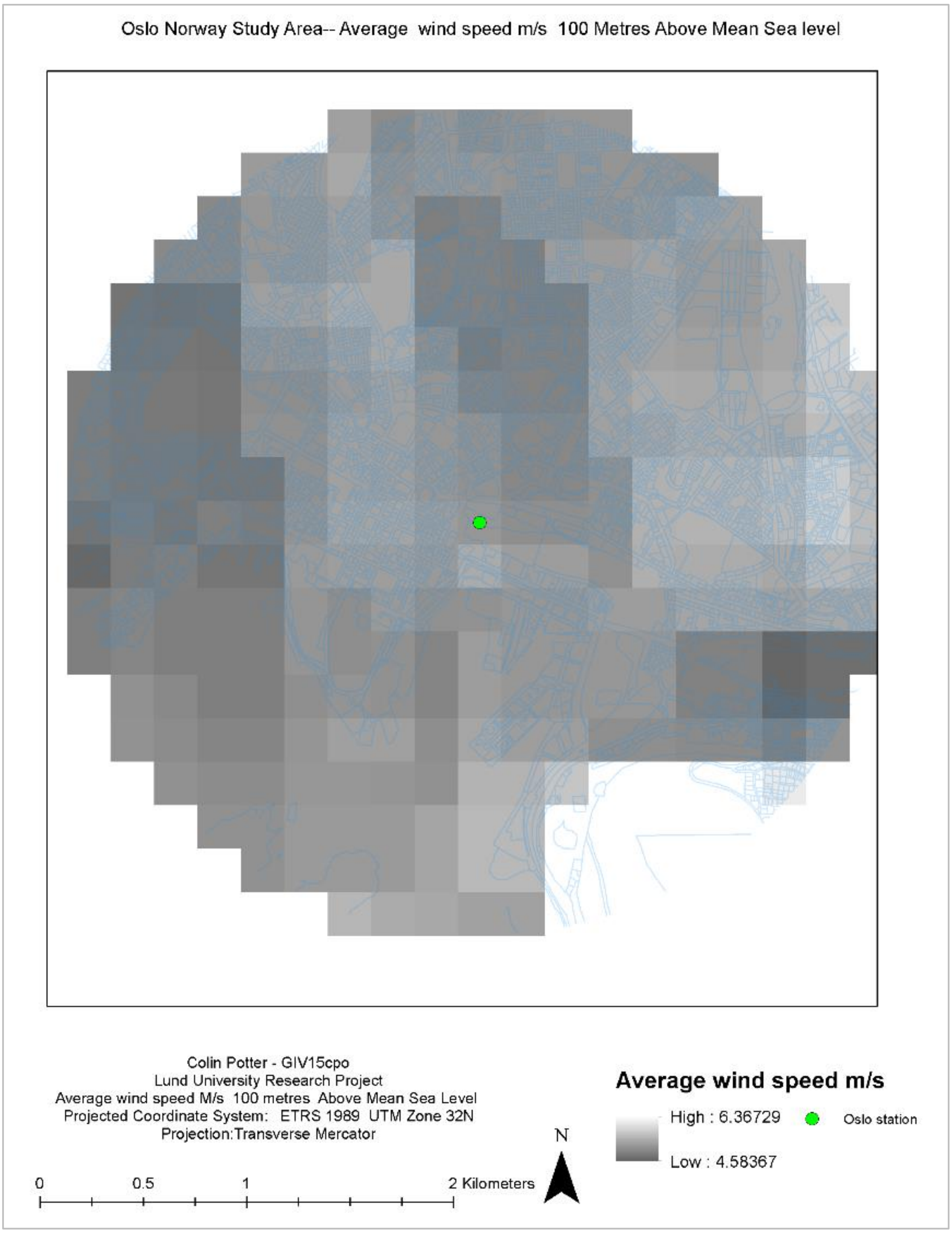

Figure 28. Map - Average Wind speed Oslo 100 Meters AMSL

Appendix 3. Wind Speeds and Power Curve

Table 23.Wind speed- m/s and energy generated kW– Power Curve QR6 Turbine

Wind Speed m/s	*Electrical Power kW*	*Notes*
0	0	
0.5	0	
1	0.1	
1.5	0.25	
2	0.5	Cut in speed
2.5	0.8	
3	1.3	
3.5	2	
4	2.5	
4.5	3	
5	3.5	
5.5	3.9	
6	4.2	
6.5	4.5	
7	4.8	
7.5	5.1	
8	5.3	
8.5	5.5	
9	5.75	
9.5	5.9	
10	6.1	
10.5	6.25	
11	6.4	
11.5	6.5	
12	6.6	
12.5	6.7	
13	6.8	
13.5	6.85	
14	6.9	
14.5	6.95	
15	6.975	Throttle back threshold
15.5	7	
16	7	
16.5	7	
17	7	
17.5	7	
18	7	
18.5	7	
19	7	
19.5	7	
20	7	Shut Off
20.5	0	
21	0	
21.5	0	
22	0	
22.5	0	
23	0	
23.5	0	
24	0	
24.5	0	
25	0	

Appendix 4. Cost Life cycle Turbines

Table 24 - 20-year cost cycle– Buildings> heights meters AMSL

20 years costings - all Buildings >100 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	19	$905,929.50	$155,302.20	$51,756	$11,652.70	$7,600	$1,132,240.40	640356.0000	$1.77
2	19					$7,600	$7,600.00	640356.0000	$0.01
3	19					$7,600	$7,600.00	640356.0000	$0.01
4	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
5	19					$7,600	$7,600.00	640356.0000	$0.01
6	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
7	19					$7,600	$7,600.00	640356.0000	$0.01
8	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
9	19					$7,600	$7,600.00	640356.0000	$0.01
10	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
11	19					$7,600	$7,600.00	640356.0000	$0.01
12	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
13	19					$7,600	$7,600.00	640356.0000	$0.01
14	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
15	19					$7,600	$7,600.00	640356.0000	$0.01
16	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
17	19					$7,600	$7,600.00	640356.0000	$0.01
18	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
19	19					$7,600	$7,600.00	640356.0000	$0.01
20	19				$11,652.70	$7,600	$19,252.70	640356.0000	$0.03
total		$905,929.50	$155,302.20	$51,756.00	$116,527.00	$152,000.00	$1,381,514.70	12,807,120.00	$0.11

20 years costings - all Buildings >90 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	74	$3,528,357.00	$604,861.20	$201,576	$45,384.20	$29,600	$4,409,778.40	2197884	$2.01
2	74					$29,600	$29,600.00	2197884	$0.01
3	74					$29,600	$29,600.00	2197884	$0.01
4	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
5	74					$29,600	$29,600.00	2197884	$0.01
6	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
7	74					$29,600	$29,600.00	2197884	$0.01
8	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
9	74					$29,600	$29,600.00	2197884	$0.01
10	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
11	74					$29,600	$29,600.00	2197884	$0.01
12	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
13	74					$29,600	$29,600.00	2197884	$0.01
14	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
15	74					$29,600	$29,600.00	2197884	$0.01
16	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
17	74					$29,600	$29,600.00	2197884	$0.01
18	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
19	74					$29,600	$29,600.00	2197884	$0.01
20	74				$45,384.20	$29,600	$74,984.20	2197884	$0.03
total		$3,528,357.00	$604,861.20	$201,576.00	$453,842.00	$592,000.00	$5,380,636.20	43,957,680.00	$0.12

20 years costings - all Buildings >80 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	442	$21,074,781.00	$3,612,819.60	$1,204,008	$271,078.60	$176,800	$26,339,487.20	12927566	$2.04
2	442					$176,800	$176,800.00	12927566	$0.01
3	442					$176,800	$176,800.00	12927566	$0.01
4	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
5	442					$176,800	$176,800.00	12927566	$0.01
6	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
7	442					$176,800	$176,800.00	12927566	$0.01
8	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
9	442					$176,800	$176,800.00	12927566	$0.01
10	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
11	442					$176,800	$176,800.00	12927566	$0.01
12	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
13	442					$176,800	$176,800.00	12927566	$0.01
14	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
15	442					$176,800	$176,800.00	12927566	$0.01
16	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
17	442					$176,800	$176,800.00	12927566	$0.01
18	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
19	442					$176,800	$176,800.00	12927566	$0.01
20	442				$271,078.60	$176,800	$447,878.60	12927566	$0.03
total		$21,074,781.00	$3,612,819.60	$1,204,008.00	$2,710,786.00	$3,536,000.00	$32,138,394.60	258,551,320.00	$0.12

20 years costings - all Buildings >70 metres

year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	933	$44,485,906.50	$7,626,155.40	$2,541,492	$572,208.90	$373,200	$55,598,962.80	25052282	$2.22
2	933					$373,200	$373,200.00	25052282	$0.01
3	933					$373,200	$373,200.00	25052282	$0.01
4	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
5	933					$373,200	$373,200.00	25052282	$0.01
6	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
7	933					$373,200	$373,200.00	25052282	$0.01
8	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
9	933					$373,200	$373,200.00	25052282	$0.01
10	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
11	933					$373,200	$373,200.00	25052282	$0.01
12	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
13	933					$373,200	$373,200.00	25052282	$0.01
14	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
15	933					$373,200	$373,200.00	25052282	$0.01
16	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
17	933					$373,200	$373,200.00	25052282	$0.01
18	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
19	933					$373,200	$373,200.00	25052282	$0.01
20	933				$572,208.90	$373,200	$945,408.90	25052282	$0.04
total		$44,485,906.50	$7,626,155.40	$2,541,492.00	$5,722,089.00	$7,464,000.00	$67,839,642.90	501,045,640.00	$0.14

20 years costings - all Buildings >60 metres

year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	2372	$113,098,146.00	$19,388,253.60	$6,461,328	$1,454,747.60	$948,800	$141,351,275.20	60860536	$2.32
2	2372					$948,800	$948,800.00	60860536	$0.02
3	2372					$948,800	$948,800.00	60860536	$0.02
4	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
5	2372					$948,800	$948,800.00	60860536	$0.02
6	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
7	2372					$948,800	$948,800.00	60860536	$0.02
8	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
9	2372					$948,800	$948,800.00	60860536	$0.02
10	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
11	2372					$948,800	$948,800.00	60860536	$0.02
12	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
13	2372					$948,800	$948,800.00	60860536	$0.02
14	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
15	2372					$948,800	$948,800.00	60860536	$0.02
16	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
17	2372					$948,800	$948,800.00	60860536	$0.02
18	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
19	2372					$948,800	$948,800.00	60860536	$0.02
20	2372				$1,454,747.60	$948,800	$2,403,547.60	60860536	$0.04
total		$113,098,146.00	$19,388,253.60	$6,461,328.00	$14,547,476.00	$18,976,000.00	$172,471,203.60	1,217,210,720.00	$0.14

20 years costings - all Buildings >50 metres

year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	5780	$275,593,290.00	$47,244,564.00	$15,744,720	$3,544,874.00	$2,312,000	$344,439,448.00	140700912	$2.45
2	5780					$2,312,000	$2,312,000.00	140700912	$0.02
3	5780					$2,312,000	$2,312,000.00	140700912	$0.02
4	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
5	5780					$2,312,000	$2,312,000.00	140700912	$0.02
6	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
7	5780					$2,312,000	$2,312,000.00	140700912	$0.02
8	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
9	5780					$2,312,000	$2,312,000.00	140700912	$0.02
10	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
11	5780					$2,312,000	$2,312,000.00	140700912	$0.02
12	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
13	5780					$2,312,000	$2,312,000.00	140700912	$0.02
14	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
15	5780					$2,312,000	$2,312,000.00	140700912	$0.02
16	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
17	5780					$2,312,000	$2,312,000.00	140700912	$0.02
18	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
19	5780					$2,312,000	$2,312,000.00	140700912	$0.02
20	5780				$3,544,874.00	$2,312,000	$5,856,874.00	140700912	$0.04
total		$275,593,290.00	$47,244,564.00	$15,744,720.00	$35,448,740.00	$46,240,000.00	$420,271,314.00	2,814,018,240.00	$0.1493

20 years costings - all Buildings >40 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	10155	$484,195,477.50	$83,004,939.00	$27,662,220	$6,228,061.50	$4,062,000	$605,152,698.00	238356518	$2.54
2	10155					$4,062,000	$4,062,000.00	238356518	$0.02
3	10155					$4,062,000	$4,062,000.00	238356518	$0.02
4	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
5	10155					$4,062,000	$4,062,000.00	238356518	$0.02
6	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
7	10155					$4,062,000	$4,062,000.00	238356518	$0.02
8	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
9	10155					$4,062,000	$4,062,000.00	238356518	$0.02
10	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
11	10155					$4,062,000	$4,062,000.00	238356518	$0.02
12	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
13	10155					$4,062,000	$4,062,000.00	238356518	$0.02
14	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
15	10155					$4,062,000	$4,062,000.00	238356518	$0.02
16	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
17	10155					$4,062,000	$4,062,000.00	238356518	$0.02
18	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
19	10155					$4,062,000	$4,062,000.00	238356518	$0.02
20	10155				$6,228,061.50	$4,062,000	$10,290,061.50	238356518	$0.04
total		$484,195,477.50	$83,004,939.00	$27,662,220.00	$62,280,615.00	$81,240,000.00	$738,383,251.50	4,767,130,360.00	$0.1549

20 years costings - all Buildings >30 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	15526	$740,287,443.00	$126,906,418.80	$42,292,824	$9,522,095.80	$6,210,400	$925,219,181.60	352526914	$2.62
2	15526					$6,210,400	$6,210,400.00	352526914	$0.02
3	15526					$6,210,400	$6,210,400.00	352526914	$0.02
4	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
5	15526					$6,210,400	$6,210,400.00	352526914	$0.02
6	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
7	15526					$6,210,400	$6,210,400.00	352526914	$0.02
8	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
9	15526					$6,210,400	$6,210,400.00	352526914	$0.02
10	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
11	15526					$6,210,400	$6,210,400.00	352526914	$0.02
12	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
13	15526					$6,210,400	$6,210,400.00	352526914	$0.02
14	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
15	15526					$6,210,400	$6,210,400.00	352526914	$0.02
16	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
17	15526					$6,210,400	$6,210,400.00	352526914	$0.02
18	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
19	15526					$6,210,400	$6,210,400.00	352526914	$0.02
20	15526				$9,522,095.80	$6,210,400	$15,732,495.80	352526914	$0.04
total		$740,287,443.00	$126,906,418.80	$42,292,824.00	$95,220,958.00	$124,208,000.00	$1,128,915,643.80	7,050,538,280.00	$0.16

20 years costings - all Buildings >20 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	20606	$982,504,383.00	$168,429,322.80	$56,130,744	$12,637,659.80	$8,242,400	$1,227,944,509.60	434534530	$2.83
2	20606					$8,242,400	$8,242,400.00	434534530	$0.02
3	20606					$8,242,400	$8,242,400.00	434534530	$0.02
4	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
5	20606					$8,242,400	$8,242,400.00	434534530	$0.02
6	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
7	20606					$8,242,400	$8,242,400.00	434534530	$0.02
8	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
9	20606					$8,242,400	$8,242,400.00	434534530	$0.02
10	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
11	20606					$8,242,400	$8,242,400.00	434534530	$0.02
12	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
13	20606					$8,242,400	$8,242,400.00	434534530	$0.02
14	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
15	20606					$8,242,400	$8,242,400.00	434534530	$0.02
16	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
17	20606					$8,242,400	$8,242,400.00	434534530	$0.02
18	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
19	20606					$8,242,400	$8,242,400.00	434534530	$0.02
20	20606				$12,637,659.80	$8,242,400	$20,880,059.80	434534530	$0.05
total		$982,504,383.00	$168,429,322.80	$56,130,744.00	$126,376,598.00	$164,848,000.00	$1,498,289,047.80	8,690,690,600.00	$0.1724

20 years costings - all Buildings >10 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	20845	$993,900,022.50	$170,382,861.00	$56,781,780	$12,784,238.50	$8,338,000	$1,242,186,902.00	437256262	$2.84
2	20845					$8,338,000	$8,338,000.00	437256262	$0.02
3	20845					$8,338,000	$8,338,000.00	437256262	$0.02
4	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
5	20845					$8,338,000	$8,338,000.00	437256262	$0.02
6	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
7	20845					$8,338,000	$8,338,000.00	437256262	$0.02
8	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
9	20845					$8,338,000	$8,338,000.00	437256262	$0.02
10	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
11	20845					$8,338,000	$8,338,000.00	437256262	$0.02
12	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
13	20845					$8,338,000	$8,338,000.00	437256262	$0.02
14	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
15	20845					$8,338,000	$8,338,000.00	437256262	$0.02
16	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
17	20845					$8,338,000	$8,338,000.00	437256262	$0.02
18	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
19	20845					$8,338,000	$8,338,000.00	437256262	$0.02
20	20845				$12,784,238.50	$8,338,000	$21,122,238.50	437256262	$0.05
total		$993,900,022.50	$170,382,861.00	$56,781,780.00	$127,842,385.00	$166,760,000.00	$1,515,667,048.50	8,745,125,240.00	$0.1733

Table 25. 20-year cost cycle– Buildings - based on 10-meter AMSL classes

20 years costings - all Buildings 80 metres - 90 metres

year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	368.00	$17,546,424.00	$3,007,958.40	$1,002,432	$225,694.40	$147,200	$21,929,708.80	10089326	$2.17
2	368.00					$147,200	$147,200.00	10089326	$0.01
3	368.00					$147,200	$147,200.00	10089326	$0.01
4	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
5	368.00					$147,200	$147,200.00	10089326	$0.01
6	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
7	368.00					$147,200	$147,200.00	10089326	$0.01
8	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
9	368.00					$147,200	$147,200.00	10089326	$0.01
10	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
11	368.00					$147,200	$147,200.00	10089326	$0.01
12	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
13	368.00					$147,200	$147,200.00	10089326	$0.01
14	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
15	368.00					$147,200	$147,200.00	10089326	$0.01
16	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
17	368.00					$147,200	$147,200.00	10089326	$0.01
18	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
19	368.00					$147,200	$147,200.00	10089326	$0.01
20	368.00				$225,694.40	$147,200	$372,894.40	10089326	$0.04
total		$17,546,424.00	$3,007,958.40	$1,002,432.00	$2,256,944.00	$2,944,000.00	$26,757,758.40	201,786,520.00	$0.1326

20 years costings - all Buildings 70 metres -80 metres

year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	491.00	$23,411,125.50	$4,013,335.80	$1,337,484	$301,130.30	$196,400	$29,259,475.60	12765072	$2.29
2	491.00					$196,400	$196,400.00	12765072	$0.02
3	491.00					$196,400	$196,400.00	12765072	$0.02
4	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
5	491.00					$196,400	$196,400.00	12765072	$0.02
6	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
7	491.00					$196,400	$196,400.00	12765072	$0.02
8	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
9	491.00					$196,400	$196,400.00	12765072	$0.02
10	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
11	491.00					$196,400	$196,400.00	12765072	$0.02
12	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
13	491.00					$196,400	$196,400.00	12765072	$0.02
14	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
15	491.00					$196,400	$196,400.00	12765072	$0.02
16	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
17	491.00					$196,400	$196,400.00	12765072	$0.02
18	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
19	491.00					$196,400	$196,400.00	12765072	$0.02
20	491.00				$301,130.30	$196,400	$497,530.30	12765072	$0.04
total		$23,411,125.50	$4,013,335.80	$1,337,484.00	$3,011,303.00	$3,928,000.00	$35,701,248.30	255,301,440.00	$0.1398

20 years costings - all Buildings 60 metres -70 metres

year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	1439.00	$68,612,239.50	$11,762,098.20	$3,919,836	$882,538.70	$575,600	$85,752,312.40	35808254	$2.39
2	1439.00					$575,600	$575,600.00	35808254	$0.02
3	1439.00					$575,600	$575,600.00	35808254	$0.02
4	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
5	1439.00					$575,600	$575,600.00	35808254	$0.02
6	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
7	1439.00					$575,600	$575,600.00	35808254	$0.02
8	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
9	1439.00					$575,600	$575,600.00	35808254	$0.02
10	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
11	1439.00					$575,600	$575,600.00	35808254	$0.02
12	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
13	1439.00					$575,600	$575,600.00	35808254	$0.02
14	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
15	1439.00					$575,600	$575,600.00	35808254	$0.02
16	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
17	1439.00					$575,600	$575,600.00	35808254	$0.02
18	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
19	1439.00					$575,600	$575,600.00	35808254	$0.02
20	1439.00				$882,538.70	$575,600	$1,458,138.70	35808254	$0.04
total		$68,612,239.50	$11,762,098.20	$3,919,836.00	$8,825,387.00	$11,512,000.00	$104,631,560.70	716,165,080.00	$0.1461

20 years costings - all Buildings 50 metres -60 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	3408.00	$162,495,144.00	$27,856,310.40	$9,283,392	$2,090,126.40	$1,363,200	$203,088,172.80	79840376	$2.54
2	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
3	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
4	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
5	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
6	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
7	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
8	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
9	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
10	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
11	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
12	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
13	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
14	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
15	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
16	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
17	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
18	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
19	3408.00					$1,363,200	$1,363,200.00	79840376	$0.02
20	3408.00				$2,090,126.40	$1,363,200	$3,453,326.40	79840376	$0.04
total		$162,495,144.00	$27,856,310.40	$9,283,392.00	$20,901,264.00	$27,264,000.00	$247,800,110.40	1,596,807,520.00	$0.1552

20 years costings - all Buildings 40 metres -50 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	4375.00	$208,602,187.50	$35,760,375.00	$11,917,500	$2,683,187.50	$1,750,000	$260,713,250.00	97655606	$2.67
2	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
3	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
4	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
5	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
6	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
7	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
8	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
9	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
10	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
11	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
12	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
13	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
14	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
15	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
16	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
17	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
18	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
19	4375.00					$1,750,000	$1,750,000.00	97655606	$0.02
20	4375.00				$2,683,187.50	$1,750,000	$4,433,187.50	97655606	$0.05
total		$208,602,187.50	$35,760,375.00	$11,917,500.00	$26,831,875.00	$35,000,000.00	$318,111,937.50	1,953,112,120.00	$0.1629

20 years costings - all Buildings 30 metres -40 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	5371.00	$256,091,965.50	$43,901,479.80	$14,630,604	$3,294,034.30	$2,148,400	$320,066,483.60	114170396	$2.80
2	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
3	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
4	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
5	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
6	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
7	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
8	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
9	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
10	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
11	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
12	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
13	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
14	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
15	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
16	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
17	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
18	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
19	5371.00					$2,148,400	$2,148,400.00	114170396	$0.02
20	5371.00				$3,294,034.30	$2,148,400	$5,442,434.30	114170396	$0.05
total		$256,091,965.50	$43,901,479.80	$14,630,604.00	$32,940,343.00	$42,968,000.00	$390,532,392.30	2,283,407,920.00	$0.1710

20 years costings - all Buildings 20 metres -30 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	5080.00	$242,216,940.00	$41,522,904.00	$13,837,920	$3,115,564.00	$2,032,000	$302,725,328.00	82007616	$3.69
2	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
3	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
4	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
5	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
6	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
7	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
8	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
9	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
10	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
11	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
12	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
13	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
14	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
15	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
16	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
17	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
18	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
19	5080.00					$2,032,000	$2,032,000.00	82007616	$0.02
20	5080.00				$3,115,564.00	$2,032,000	$5,147,564.00	82007616	$0.06
total		$242,216,940.00	$41,522,904.00	$13,837,920.00	$31,155,640.00	$40,640,000.00	$369,373,404.00	1,640,152,320.00	$0.2252

20 years costings - all Buildings 10 metres -20 metres									
year	Number turbines	Turbine costs	Mast	Installation	Maintenance	Insurance	Total	Kwh	Cost per Kwh
		$47,680.50	$8,173.80	$2,724	$613.30	$400			
1	239.00	$11,395,639.50	$1,953,538.20	$651,036	$146,578.70	$95,600	$14,242,392.40	2721732	$5.23
2	239.00					$95,600	$95,600.00	2721732	$0.04
3	239.00					$95,600	$95,600.00	2721732	$0.04
4	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
5	239.00					$95,600	$95,600.00	2721732	$0.04
6	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
7	239.00					$95,600	$95,600.00	2721732	$0.04
8	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
9	239.00					$95,600	$95,600.00	2721732	$0.04
10	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
11	239.00					$95,600	$95,600.00	2721732	$0.04
12	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
13	239.00					$95,600	$95,600.00	2721732	$0.04
14	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
15	239.00					$95,600	$95,600.00	2721732	$0.04
16	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
17	239.00					$95,600	$95,600.00	2721732	$0.04
18	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
19	239.00					$95,600	$95,600.00	2721732	$0.04
20	239.00				$146,578.70	$95,600	$242,178.70	2721732	$0.09
total		$11,395,639.50	$1,953,538.20	$651,036.00	$1,465,787.00	$1,912,000.00	$17,378,000.70	54,434,640.00	$0.3192

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