Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Social and Educational Sciences
Department of Geography

Malin Bergset

Assessing the Feasibility of Implementing of Ground- Mounted Photovoltaics in Combination with Agriculture at High Latitudes

A GIS- Based Multi-Parameter Analysis of Oppdal, Norway

Bachelor's thesis in Geography
Supervisor: Jan Ketil Rød
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Oppdal. Malin Bergset

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Preface

In October 2022 I participated in *URSA MAJOR*, an autumn school organized by NTNU and SINTEF, where I met students from all over the world to work on citizen participation in the development of sustainable and smart cities. During this week, I was introduced to the *Helios*-project at the Department of Civil and Environmental Engineering, which is a multidisciplinary project with aim to break the paradigm of solar energy use in Nordic climates by accelerating the use of solar energy in the built environment. I found the theme very engaging, and together with Astrid Seland I had the opportunity to collaborate with Helios in the writing of my bachelor thesis.

During the work with this thesis, I have gained a lot of insight on the potential for solar energy in high latitudes and the importance to accelerate the implementation of renewable energy sources to achieve climate goals. Furthermore, it has become clear to me that it requires more than just development in the technology, but also social acceptance and effective incentives for making such investments. Furthermore, working with solar radiation analyses have made me more experienced in working with ArcGIS Pro, and I have learned a lot from the struggles I experienced while analysing my data.

I would like to thank my supervisor at the Department of Geography, Jan Ketil Rød, for excellent guidance and support, especially during the process of working with spatial data and ArcGIS Pro. I would also like to thank Gabriele Lobaccaro, Tahmineh Akbarinejad and Matteo Formolli from the Helios-project for helping me write this paper and providing me with valuable knowledge and perspectives along the way.

Malin Bergset
Trondheim, May 13, 2023

Abstract

There is a projected increase in energy demand all over the world, at the same time as carbon footprint must be reduced in order to preserve our planet and achieve climate goals. Solar energy is gaining attention as a renewable energy source, but there is still scepticism towards the technology in Nordic climates due to seasonal variations in insolation and production potential. Consequently, solar energy has not been implemented in Norway in large scale compared to other European countries. To cover future energy needs it is important to exploit all possibilities.

This thesis presents an assessment of the feasibility of implementing land-based photovoltaic modules and combining energy production with agricultural activities. Mapping of solar radiation for a study area in Oppdal was done using geographical information system. The results from this analysis were made to estimate electrical power production potential for selected agricultural patches in the area. Furthermore, potential and central challenges for implementation of land-based photovoltaic modules and other renewable energy sources considering transitioning into new energies are discussed.

Samandrag

Det er ei anslått auke i energietterspurnaden over heile verda, samstundes som karbonavtrykket må reduserast for å bevare planeten vår og nå klimamåla. Solenergi får mykje merksemd som ei fornybar energikjelde, men det er framleis skepsis til teknologien i nordisk klima på grunn av sesongvariasjonar i solinnstråling og produksjonspotensial. Solenergi har følgeleg ikkje blitt implementert i Noreg i stor skala samanlikna med andre europeiske land. For å dekke fremtidens energibehov er det dog viktig å utnytte alle mogelegheiter.

Denne oppgåva presenterer ei vurdering av gjennomførbarheita av å implementere landbaserte solcellemoduler og kombinere energiproduksjon med landbruksaktivitetar. Kartlegging av solinnstråling for eit studieområde i Oppdal vart gjort med hjelp av geografiske informasjonssystem. Resultata frå denne analysen ble nytta for å estimere produksjonspotensialet for elektrisk kraft for utvalde landbruksområder i studieområdet. Vidare diskuterast potensialet og sentrale utfordringar knytt til implementering av landbaserte solcellemoduler og andre fornybare energikilder ved overgang til eit nytt energilandskap.

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Abbreviations and Nomenclature

Table 1: Abbreviations and Nomenclature

Digital Surface Model (DSM)	Model of the earth’s surface containing terrain, vegetation and other building-related facilities.
European Union (EU)	Regional cooperation organization in Europe consisting of 27 member countries with headquarters in Brussel.
Felles Kartdatabase (FKB)	The most detailed vector data available in Norway. Kartverket and other parties update data directly in a common database.
Greenhouse Gases (GHG)	Gases in the atmosphere that absorb long-wave radiation, which contributes to climate change.
Geographical Information System (GIS)	Tools to collect, organize, store, analyse and visualize geographical information.
Intergovernmental Panel on Climate Change (IPCC)	The Climate Panel compiles the latest knowledge on climate change. Reports from the UN Climate Panel are the most important scientific basis on climate change for international negotiations.
Light Detection and Ranging (LiDAR)	Lidar is a remote sensing technique based on the backscattering of light. By comparing time delays and frequency shifts in transmitted and reflected light, the distance to objects can be determined.
Norges Offentlige Utredninger (NOU)	Reports published by committees or working groups set up by the government or a ministry.
Photovoltaic (PV)	Conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect.
Renewable Energy Sources (RES)	A natural energy resource that will be replenished to replace the part depleted by use and consumption, either by natural reproduction or other recurring processes.
Sustainable Development Goals (SDG)	The United Nation’s joint work plan to eradicate poverty, fight inequality and stop climate change by 2030 – consisting of 17 main goals and 169 sub-goals.
United Nations (UN)	UN is a global international organization founded in 1945. The most important job is to ensure peace and security in the world.
CO_2-equivalents	A unit that adds up emissions of different GHG to the global warming effect that emissions of one tonne of CO_2 will have over 100 years.

AF	Area factor indicating fraction of calculated area that can be covered by PV panels
CA	Calculated area of suitable land
EGP	Electricity power generation potential
h	Hours
k	Kilo
m^2	Square meters
SR	Annual solar radiation received per unit horizontal area
W	Watt
$\boldsymbol{\eta}$	PV system efficiency

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1. Introduction

It is no longer doubt that anthropogenic activities have resulted in fast and fatal changes in the atmosphere, cryosphere, ocean and biosphere. Global surface temperatures have increased faster since 1970 than in any other 50-year period over the past 2.000 years, and global surface temperatures is expected to continue to increase – no matter what emission scenario (IPCC, 2021, p.14). Due to rapid climate changes and gloomy predictions for future generations, it is urgent to decrease greenhouse gas emissions (GHG) into the atmosphere. This was agreed upon by 189 countries in the Paris Agreement in 2015 (UN, n.d.), and the main goal is to keep global heating under 2 degrees Celsius, preferably under 1.5 degrees. Unless significant changes are made to how we organize society, the world will experience a 2-degree heating or more before the end of this century (IPCC, 2021, p.14).

The European Union (EU) made a growth strategy for the future called the *European Green Deal*, with goals of creating a European society where economic growth is decoupled from resource use whilst being competitive, effective and with zero net emissions by 2050 (EU, 2019, p.2). The Green Deal has several focus areas, energy-use being one of them (EU, 2019, p.3). The energy sector accounts for 73% of the GHG emissions worldwide and is a significant contributor to changes in climate conditions (Ritchie, Roser & Rosado, 2020). To achieve climate goals, a more efficient and flexible use of energy must be established, in addition to increased investments in renewable energy sources (RES) and expansion of the power grid capacity.

Agriculture is a significant contributor to GHG emissions and could reduce its carbon footprint by increasing its use of RES. Converting from fossil fuels to RES for heating, powering machines and food production could contribute to achieving a more climate neutral and sustainable industry (Norges Bondelag, 2019, p.8). Agriculture being heavily district based, increased electrification would require considerable investments in the electricity grid to ensure sufficient capacity. Private investments in local energy production will therefore be important to facilitate the green energy-transition (Noregs Bondelag, 2019, p.23).

Solar energy is a RES that international framework for green transitions focuses heavily on. The interest for solar energy has steadily increased in Norway over recent years, but there still seems to be a general scepticism towards the usefulness of the technology due to the country's geographical location at high latitudes – and to the fact that Norway gets considerable amounts of green energy from hydroelectric power (Manni, Nocente, Bellmann & Lobaccaro, 2023, p.1).

In February 2023, the Norwegian Energy Commission – appointed by the Ministry of Petroleum and Energy, presented a public investigation (NOU) stating the need for increased electrification, increased power consumption and more renewable power production – and concluded that solar energy can be implemented quickly and has great potential (NOU, 2023:3, p.20). There has so far been made relatively little effort to implement solar energy in the energy mix on a larger scale in Norway.

There seems to have been a lack of effort to provide relevant actors with information, intensives and capital to invest in solar energy. This thesis aims to assess the potential of using land based photovoltaic (PV) modules to generate solar energy in combination with agricultural activities at high latitudes, using geospatial techniques to map solar insolation in Oppdal Municipality. The result can thereby provide both local and national farmers, policy makers and investors with insight of the potential for adopting solar energy. The result of this analysis will be used to answer the following research questions:

> *What is the potential for solar energy in combination with agriculture in northern latitudes?*
>
> *Which criteria should be considered when implementing land-based PV modules?*

The first chapter of this thesis consider the background for the analysis, with a brief introduction to solar energy, national and international trends for the technology, sustainable development in agriculture and competing use of land. Furthermore, modelling solar radiation with geographical information systems (GIS) and estimating electricity production potential is explained. Results from the calculations are thereafter presented and discussed, before concluding the thesis and providing directions for further research.

2. Background

In this chapter the concept of solar energy is presented, in addition to European and Norwegian trends for the technology. Furthermore, challenges coupled to solar- and RES in general will be presented, as well as its relevance for Norwegian conditions and agriculture industries. Lastly, modelling of solar radiation using GIS is explained.

2.1 Solar Energy

Being a renewable and continuous resource there are numerous reasons to increase the exploitation of solar energy. There are several ways of utilizing energy from the sun, but this will focus on PV technology. The word *photovoltaic* implies the conversion of “photo” (light) into “volts” (electricity) (Jieb & Hossain, 2022, p.3). This is a relatively simple technology without complicated systems. It uses semiconductor materials fabricated from Silicon or Germanium to directly convert sunlight into electricity in direct current. The electricity generated from PV modules does not emit any GHG, it is noise free can and can be installed in any part of the world (Jieb & Hossain, 2022, p.5).

The technology works just as well in developing countries as industrialised ones, in both urban and rural areas. In addition to being an investment with long life span (minimum 30 years) that requires little maintenance, there has also been a considerate drop of cost for the electronics the past years. Production cost of large-scale solar power dropped with an average of 85% from 2010 – 2020 (NOU, 2023, p.105).

2.2 European and Norwegian Trends for Solar Energy

UN has presented 17 sustainable development goals (SDG), that provides a blueprint for future development. SDG 7 – *Affordable and Clean Energy*, aims to secure reliable and modern energy for everyone, while also being sustainable. This goes well together with SDG 13 – *Climate Action*, about taking urgent actions to combat climate change and its impact. Energy-related CO_2 emissions increased globally by 6% in 2021 and reached its highest level ever (UN, 2023). This implies that progress in energy efficiency and investments in RES needs to accelerate to achieve global climate goals and tackle environmental consequences (EU, 2022 a, p.16).

Based on the SDGs from UN, EU has presented the Green Deal. REPower EU, a subproject of Green Deal, aims for a renewable energy share that reaches 69% by 2030. A sustainable future will rely on several RES, but it is though expected that solar energy will be the largest electricity source in terms of capacity by 2030 – with more than 50% expected to be solar-rooftop capacities (EU, 2022 a, p.24). This will be a significant increase from the 5% solar energy accounted for in EUs electricity mix in 2020 (EU, 2022 b, p.1). This development requires incentives for people to play an active role and make private investments in order for power generation to happen at several scales (EU, 2022 b, p.2).

Norway is highly reliant and self-sufficient on hydroelectric power, but there is still projected a need for increased electrification, power consumption and more renewable power production. In the NOU “*Mer av alt – raskere”* (*More of everything – faster*) from 2023, the Energy Commission states an urgent need for more efficient and flexible use of energy, in addition to investments in RES and higher power grid capacity (NOU, 2023:3, p.11). The report emphasizes that all opportunities must be exploited, and highlights ground-mounted solar energy as a technology with high potential (NOU, 2023:3, p.20).

2.3 Sustainable Development in Norwegian Agriculture

In 2019, *Norges Bondelag* and *Norges Bonde- og Småbrukarlag*, together with the Norwegian government, agreed on a plan to reduce GHG emissions and increase absorption of carbon in agriculture from 2021 to 2030 (*Landbrukets Klimaplan*). The main goal is to reduce GHG emissions with 5 million tonnes CO_2-equivalents, and to work towards a more climate neutral and sustainable industry (Norges Bondelag, 2019, p.8).

In *Landbrukets Klimaplan* there is presented eight focus areas to reach these goals. Amongst them are *Fossil Free Machine Park* and *Fossil Free Heating*, that aims to decouple agricultural activities from the use of fossil fuels to power machines and tractors, heating of greenhouses and use of diesel generators – among others. In 2020, emissions from agriculture in Norway was estimated to be approximately 343.000 tonnes of CO_2-equivalents, most of them from the tractor (Norges Bondelag, 2019, p.20). Heating accounted for 56.000 CO_2-equivalents in the same period (Norges Bondelag, 2019, p.24).

2.4 Competing Use of Land

A central challenge coupled to solar- and RES in general, is that it has significantly lower power density than fossil fuels. Power density describes the flow of power from a given area, and is a measure of concentration that describes the rate at which energy is transferred (Watts/m^2). If two unequally sized areas of land generate the same amount of power, the smallest area has higher power density (Bridge, Barr, Bouzarovski, Bradshaw, Brown, Bulkeley, & Walker, 2018, p.21). All landscapes have potential power densities depending on what energy resource landscape it is part of. Energy resource landscapes are where societies take in energy and turn it into the task of satisfying needs and desires in society, and largely deals with the land use required to utilize energy sources (Brigde et al., p.36).

Fossil energy sources has a higher energy density and rely mostly on subterranean stocks of energy which requires relatively little surface land to harness. Consequentially, a transition to RES will require harnessing large quantities of land (Huber & McCarthy, 2017, p.2).

2.5 Food Security

In Norway, only 3% of land areal accounts for agricultural land, and one third of this area is suited as topsoil for food production (NIBIO, 2023). The topsoil in Norway is young and originates from the last ice age 10.000 – 12.000 years ago. Most of Norway's current bedrock is resistant to the erosion and decomposition that creates weathering soil, and therefore has small amounts of it (Sulebak, 2015, p.340). Given the time it takes for soils to become suitable to grow foods on, caution should be exercised when it comes to development in these areas.

Topsoil is under pressure. Large areas suitable for food production has been subject for construction and infrastructure purposes (Sulebak 2015, p.347). One main challenge is that high quality soil often is located close to urban areas, and are subject for *urban sprawl* – where urban areas expand more than the population growth indicates it should (Vinge, 2020, p.2) This, and the fact that climate change likely will alter the preconditions for food production, points to how preservation of topsoil must be a priority in the green transition (NIBIO, 2023).

2.6 Modelling Solar Radiation with Geographical Information Systems

At global scale, the Earth's geometry of rotation and revolution around the sun causes latitudinal gradients of insolation. At local scale, topography is the major factor modifying the distribution of insolation (Fu & Rich, 1999, p.1). Variability in seasons, elevation, slope, aspect, and shadows cast by topographic features creates local gradients of insolation, and spatial and temporal heterogeneity in energy balance (Rød, 2015, p.233). For most geographical areas, accurate information about insolation is not available. Spatial solar radiation models provide cost-efficient means for understanding spatial and temporal variation of insolation and are easily made available with GIS where insolation maps can be generated and related to other digital map layers (Fu & Rich, 1999, p.2).

2.6.1 Geographical Information Systems

GIS are tools that can create, manage, analyse and map spatial- and attribute data (Rød, 2015, p.14). The system connects data to a map and integrates location data with descriptive data which helps users understand patterns, relationships and geographical contexts – and to solve geographical related problems (Rød, 2015, p.17).

When representing spatial data, one could either use discrete objects or continuous data – also referred to as vector- and raster data (Rød, 2015, p.19). Vector data occur in three geometrical shapes: point, line and polygon represented with x-, y-, and z-coordinates in a map (Rød, 2015, p.14). Raster data is represented by a matrix of pixels (cells) with individual values, whereas size and resolution vary depending on their purpose (Rød, 2015, p.41). Higher resolutions would provide more details but requires more storage and processing capacity. A coarser resolution requires less processing but is less detailed (Rød, 2015, p.191).

2.6.2 Solar Radiation Analysis

Solar radiation analysis calculates insolation from raster data for specific time periods based on methods from the hemispherical viewshed algorithm, developed by Paul M. Rich and his colleagues (Fu & Rich, 1999, p.3). The total amount of radiation calculated for a particular area is given as global radiation: the sum of direct (Dir_{tot}) and diffuse (Dif_{tot}) radiation. Direct radiation generally accounts for the largest component. As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by atmospheric components such as air molecules, clouds, dust, pollutants, and water vapour. This is diffuse radiation (Rød, 2015, p.234).

$$Global_{tot} = Dir_{tot} + Dif_{tot}$$

The calculation involves three steps: (i) calculation of an upward-looking hemispherical viewshed based on topography, (ii) overlaying the viewshed on a sun map to estimate direct radiation, (iii) overlaying the viewshed on a sky map to estimate diffuse radiation, as shown in figure 1. The process is repeated for each location in the study area (Esri, n.d, a).

2.6.3 Hemispherical Viewshed

The viewshed is an upward-looking view from one specific point based on lines of sight, where the sky is either visible or obstructed (Rød, 2015, p.228). Lines of sight are drawn from a base point to several measure points, depending on calculation directions. If the line is undisturbed by terrain or infrastructure, the areas of measure are coded as *visible*. Else, they are coded *not-visible*, as shown in figure 1 and 2 (Rød, 2015, p.228). For all unsearched directions horizon angles are interpolated (Esri, n.d., a). The horizon angles are then converted into a hemispherical coordinate system.

2.6.4 Sun Map

Direct radiation originating from each sky direction is calculated using a sun map in the same hemispherical projection as the viewshed (Esri, n.d., a). A sun map is a raster displaying the sun’s position as it changes over time. The sun map contains discrete sectors that are defined by the sun’s position at particular intervals and is calculated based on latitude and time configuration that defines the sectors in the sun map (Esri, n.d., a). For each sector in the sun map, a unique identification value is specified along with its centroid zenith and azimuth angle. Direct radiation is then calculated from the visible sectors (Esri, n.d., a).

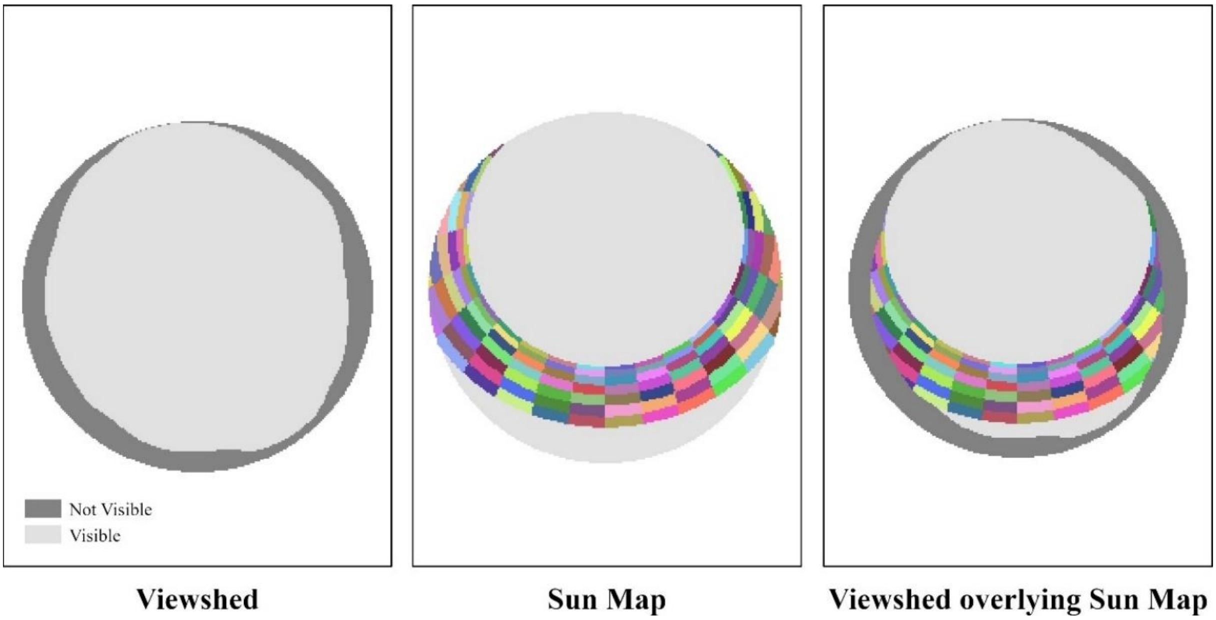

Figure 1: Viewshed and Sun Map from Oppdal, each 14th day from March 1st to June 1st

2.6.5 Sky Map Calculation

Diffuse radiation originates from all sky directions due to scattering by atmospheric components. To calculate the diffuse radiation for specific locations, a sky map is created to represent a hemispherical view of the entire sky – divided into a series of sky sectors defined by zenith and azimuth angles. Each sector is assigned a unique identifier value, along with the centroid zenith and azimuth angles. Diffuse radiation is calculated for each sky sector based on direction (zenith and azimuth) (Esri, n.d., a).

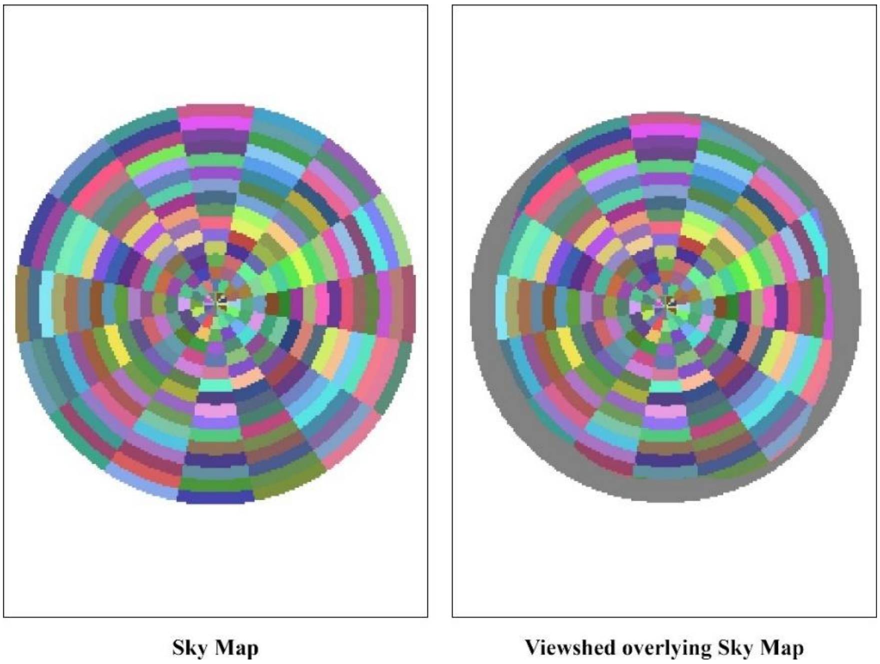

Figure 2: Sky Map and Viewshed Overlying Sky Map to Calculate Diffuse Radiation

3. Materials and Methods

The methods chapter is divided into six parts: (i) presentation of study area, (ii) collection of spatial data and literature, (iii) preparation of data, (iv) solar radiation analysis, and (v) selection of sub-areas to (vi) calculate potential electric power generation, as shown in figure 3.

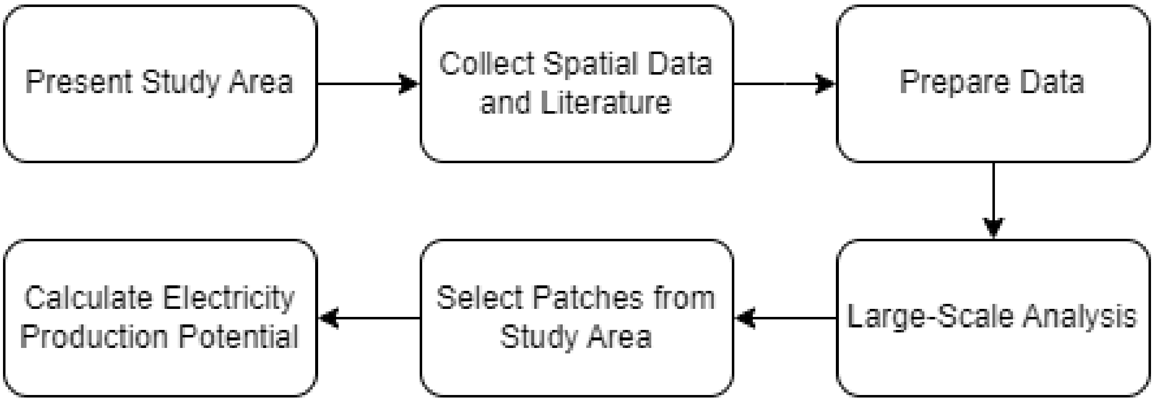

Figure 3: Workflow of the Study

3.1 Study Area: Oppdal

The study is conducted in Oppdal municipality over an area covering about 790 km^2, displayed in figure 4. Oppdal lies in the southernmost part of Trøndelag county in Norway, at latitude 62,5 degrees north. The municipality covers a total of 2 274 km^2 and house about 7 250 people (SSB, n.d.). Primary industries have traditionally had a strong position in Oppdal, and according to Statistics Norway (SSB) 256 people were employed in the primary industries in 2020, including forestry and fishing (SSB, n.d.).

79.3 km^2 of the municipality is regarded as agricultural area (3,5%), whereas 41.6 km^2 is fully cultivated – meaning that it has been cultivated to normal ploughing depth. These can be used for crops or meadows. 1.8 km^2 is surface cultivated agricultural areas, where land is mostly cleared and smooth on the surface, making mechanical harvesting is possible. More than 35.8 km^2 is regarded as infield grazing areas (NIBIO, 2023). Agricultural areas are located in the valley below the mountains and extends in three different directions from the city centre. Surrounding mountain areas are included in the analysis because topography affects insolation by casting shadows and creating microclimates.

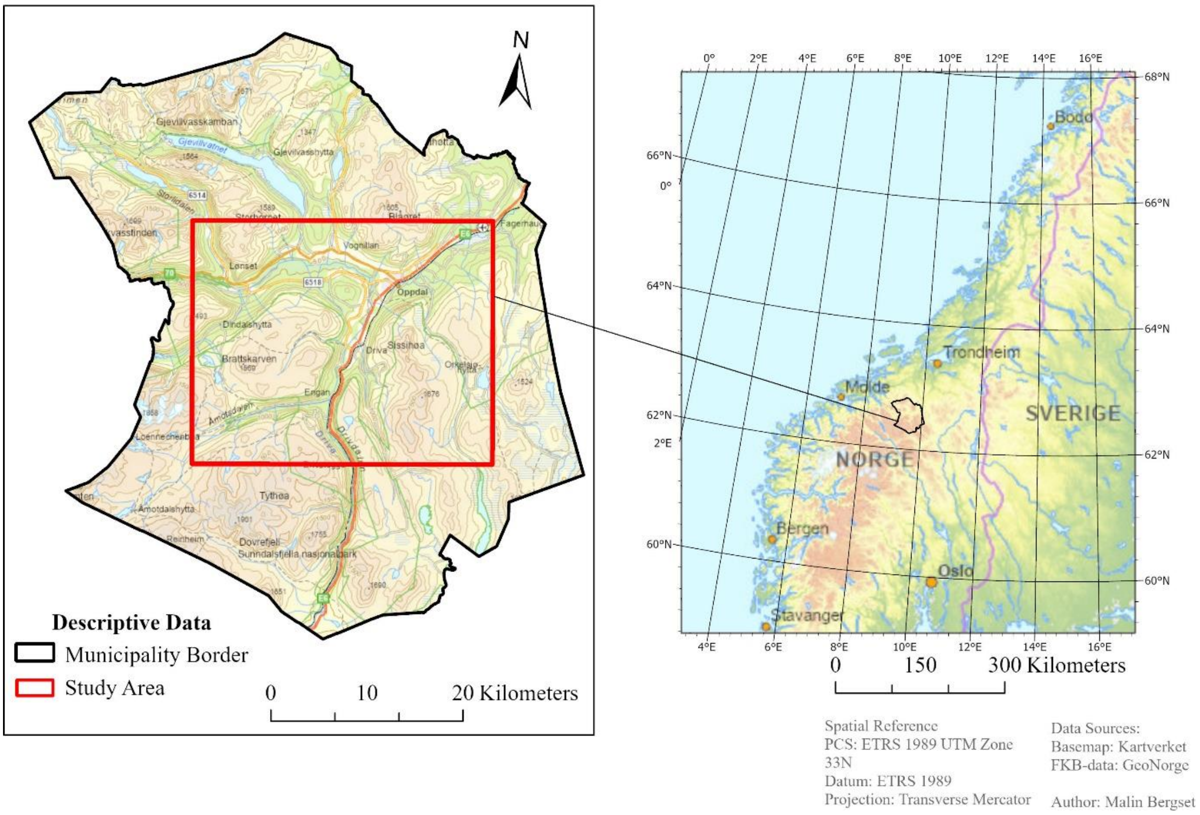

Figure 4: Study Area

Oppdal was selected as study area because of its location in higher latitudes and its long-lasting tradition for agriculture, which still is a central industry. In Oppdal's *Climate- and Energy Plan for 2019 – 2030*, the municipality presents how they want agriculture to adapt to climate change and become a more environmentally friendly industry. Three main measures are presented in the plan to reduce GHG emissions from agriculture: (i) *reduce own emissions of climate gasses and the use of fossil energy sources,* (ii) *bind carbon in soil, woods and other biomasses,* (iii) *produce bioenergy to reduce emissions of fossil carbon* (Oppdal Kommune, 2019, p.14). It is emphasized that a key to success will be to tailor the measures to individual farms.

The Climate- and Energy Plan mentions solar energy as a potential RES once in the entire report, in combination with new constructions and restoration of buildings (Oppdal Kommune, 2019, p. 7). The thesis will investigate the potential for solar energy production in higher latitudes and assess areas where land-based PV-modules could be mounted, to increase the energy production from RES.

3.2 Data Collection

3.2.1 Literature Review

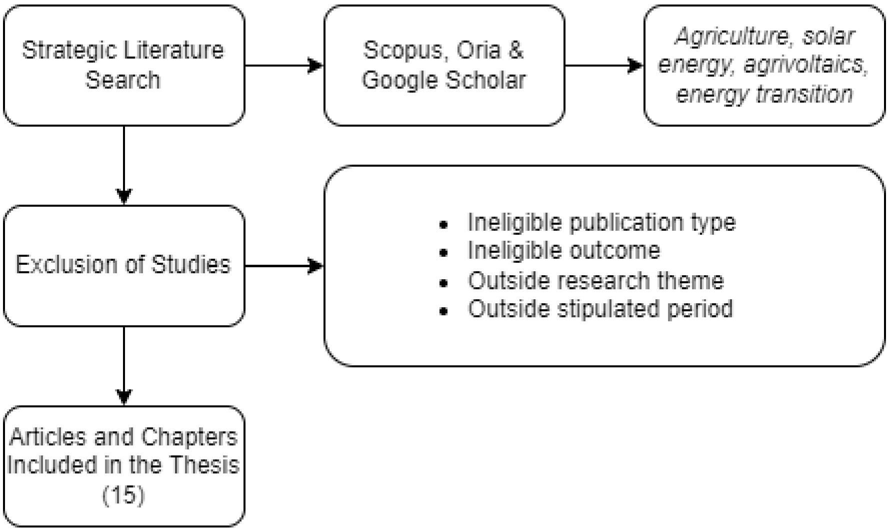

Figure 5: Collecting Literature for the Thesis

Several studies on solar energy have been reviewed for this thesis. Figure 5 shows the process of selecting literature for the thesis. Scientific databases such as Scopus, Oria and Google Scholar was used to obtain papers with high degree of reliability. Strategic words, such as *solar energy* + *agriculture*, *agrivoltaics* and *energy transition* was used to find relevant papers. When selecting on papers to include or gather inspiration from, assessing where and when the paper was published was two main criteria. Peer reviewed articles are preferred, in addition to being up to date with the technology's development. Furthermore, selecting articles with the most relevant themes after reading abstracts was decisive for the final selection. In addition, relevant reports and plans at local, national and international scales were frequently used to find information.

3.2.2 Collecting Spatial Data

To execute a solar radiation analysis, a digital surface model (DSM) is required. A DSM with 10-meter resolution was downloaded from Høydedata. Høydedata is a data portal making elevation data for Norway, down to 1 meter resolution, available for everyone (Høydedata, n.d.).

Furthermore, area type data is used. AR5 is a highly detailed areal resource map that shows land resources with an emphasis on the production base for agriculture and forestry. Land areas are categorized according to area type, forest quality, tree species and soil conditions (NIBIO, n.d.). Unproductive areas and areas over the forest border is registered as *not mapped*. The condition of the areas decides classification type (NIBIO, n.d.). This dataset was obtained from

GeoNorge. Lastly, FKB data of Oppdal's administrative zones were also gathered from GeoNorge. Table 2 gives an overview of the data.

Table 2: Data Types and -Sources

Data	Source	Data Type	Data Year
Areal Resources Map	NIBIO, AR5	Vector - polygon	2023
DSM, 10 meters	Høydedata	Raster	2017
Boundary of Oppdal	FKB	Polygon - polygon	2023

3.2.3 Additional Resources

Esri is the supplier of ArcGIS Pro, which is the software used for the analysis. During the work with this analysis, explanations, and guidance from Esri was used while running tools and processes in GIS.

3.3 Digital Surface Model: Downloading and Preparing the Data

Figure 6: Preparation of Data.

The DSM was ordered from *Høydedata*, downloaded and imported to GIS. A DSM is a two-dimensional raster data which reflects the elevation of the earth's surface with all external objects on top of it (Zhou, Mi, Chen, Geng, 2013, p.1). It is product of Light Detection and Ranging (LiDAR), a remote sensing technique that send out beams of light that reflects when hitting the surface. By comparing delays and frequency shifts in emitted and reflected light, distance to objects at the ground reflecting the light are determined (Gallay, 2013, p.1). The elevation information is used to create hemispherical viewsheds for the analysis.

Figure 6 shows how the data was prepared for the analysis. The data was imported to GIS. In its original form, the data consists of partly overlapping tiles in TIFF-format (Tag Image File Format). The raster tiles were mosaicked into one raster. In terms of the overlapping areas of the individual files, the method *First* was used to determine the priority in which images are displayed – meaning that the colour map from the first raster dataset in the list will be applied to the output raster (Esri, n.d, b).

After mosaicking the files into one single raster, a polygon of the study area was created. The DSM was clipped to fit the study area, using the study area polygon as output extent (Esri, n.d, c). In *Environments* the original DSM was set to *Snap Raster*, meaning that the output DSM will match the cell alignment of the specified snap raster (Esri, n.d, d).

3.4 Area Solar Radiation using a Multi-Parameter Analysis

Incoming solar radiation is modelled using a multi-parameter analysis tool in ArcGIS Pro. This section will present the parameters and values used for the analysis.

3.4.1 Defining the Parameters for Calculation

From the *Solar Radiation*-toolbox, *Area Solar Radiation* is used to model solar insolation for the DSM. 13 parameters must be assigned values before running the analysis. Table 3 shows an overview of the parameters and inputs used in the analysis, which are explained further in this section.

Table 3: Parameters and Inputs for the Area Solar Radiation Tool

Parameter	**Value**
Input Raster	DSM with 10 m resolution
Latitude	62,5
Sky Size	200
Time Configuration	One year (2022)
Day Interval	14 days
Hour Interval	1 hour
Z-factor	1
Slope and Aspect	From the input surface raster
Calculation Directions	32
Zenith Divisions	16
Azimuth Divisions	16
Diffuse Model Type	Uniform overcast sky
Diffuse Proportion	0.3
Transmittivity	0.6

Because of the Earth’s tilt, solar insolation will be different across the globe and *latitude* is considered when calculating solar radiation. The same value is set for the whole DSM, as the study area covers a relatively small geographical area where variations are insignificant (Esri, n.d., e). The DSM contains a spatial reference, which automatically calculates the mean latitude to 62.559.

Resolution refers to the sky size for the hemispherical viewshed, sky map and sun map raster. The default size is a raster of 200 by 200 cells, which are sufficient for whole DSMs with large day intervals (> 14 days). The default value is accepted (Esri, n.d., e). Increasing the sky size makes calculations more accurate, but also increases calculation time significantly.

The analysis will be run for one year (2022), with 14-day intervals and 1 hour interval, meaning that for each 14th day, every hour of the day will be calculated for incoming solar insolation.

The *Z-factor* is a converting factor that adjusts measuring units for the vertical units (z) when they differ from the horizontal coordinates (x, y). It is the numbers of ground x, y-units in a surface z-unit. If the vertical units are not corrected to the horizontal units, the results from the surface-tools will not be correct. Setting 1 as the Z-factor is default, and is accepted for this analysis (Esri, n.d., f).

Aspect refers to the compass direction that downhill slopes face for each location. *Slope* represents the rate of change in elevation for each pixel in the digital surface model, measured in degrees (Esri, n.d., g). *Slope and Aspect Input Type* specifies how slope and aspect will be derived for the analysis. *From the Input Surface Raster* is default, and the slope and aspect will be calculated from the DSM (Esri, n.d., e).

Calculation directions specifies the number of horizons angles the viewshed will trace. Valid values must be multiplies of 8 (Esri, n.d., e). The number of calculation directions needed is related to the DSMs resolution. The default input value is 32 directions, which is adequate for complex topography. A higher number increases accuracy, but also calculation time (Esri, n.d., e).

The numbers of zenith and azimuth divisions defines the resolution of the sky map. *Zenith* is the centre in the sun- and sky map and is used as a reference to measure zenith divisions (Rød, 2015, p.237). Zenith value is set to 16. *Azimuth* divisions are used to create sky sectors, and is also set to 16 (relative to north) (Esri, n.d., e). More sectors give higher accuracy, but requires more processing.

Diffuse proportion refers to the proportion of diffuse radiation as a fraction of total radiation. Shortwave solar radiation is not much absorbed by gases in the atmosphere, but reflected and diffused by clouds (Huang, Rich, Crabtree, Potter & Fu, 2008, p.6). The value is set according to atmospheric conditions, and ranges from 0 to 1. Default value is 0.3 for generally clear conditions, and accepted for the analysis (Esri, n.d., e).

Atmospheric transmittivity is the fraction of total radiation that passes through the atmosphere (averaged overall wavelengths) (Huang et al., 2008, p.7). The value ranges from 0 (no transmission) to 1 (all transmission). Default is 0.5 for a generally clear sky. According to Yr.no, Oppdal had 91 days with rainfall over the past 13 months (March 2022 – April 2023) (Yr, n.d.). It is therefore anticipated that Oppdal has a considerate number of days with cloud coverage. The value used is 0.6 – somewhat higher than the default because Oppdal is a rural area with relatively little air pollution that could block insolation (Esri, n.d., e).

3.4.2 Running the Finished Model

The running of the model with all the values above gives one output – a raster showing the global radiation for one year. The output has units of kilowatt-hours per square meter (kWh/m^2). In addition, the same analysis was run for each month with the same parameters, except the time interval is set to 5 days instead of 14 – to get monthly global radiation.

3.5 Selecting Sub-Areas from the AR5 Dataset

To find suitable areas for implementation of PV modules, the AR5-dataset is used. Areas used for agricultural purposes were extracted from the dataset using the *Select*-tool. Area type 21 (*Fully Cultivated Areas*), 22 (*Surface Cultivated Areas*) and 23 (*Infield Grazing Areas)* are the categories containing land utilized for agricultural purposes, but fully cultivated areas being the ones with highest quality was excluded from further analysis in order to protect high quality topsoil for food production. Area type 22 and 23 were therefore copied into a new dataset.

For the selected area types, *Zonal Statistics as Table* was used to sum annual radiation within the individual patches (Esri, n.d., h). The polygons of area types define the zones for calculation. The insolation map contains the values on which to calculate statistics. Lastly, the *Statistics Type* wanted for this purpose is *SUM*, to find the total value of all cells in the value raster within the individual zones (Esri, n.d., h). The output is a standalone table showing total annual insolation for each of the polygons, given in WH/m^2. Using *Add Join*, the *SUM*-field from the table was joined to the feature layer containing the patches of topsoil (Esri, n.d.,). The attribute table of the topsoil patches now consists of information on how much solar insolation each patch has.

A sub-selection of five agricultural patches will be subject for further discussion. Figure 8 shows where the five different patches are located. These patches were selected to investigate electricity production potential between the five selected patches according to size, annual insolation, localization in the study area, and quality of soil. This way, energy need can be evaluated and compared to potential electricity production from different sizes.

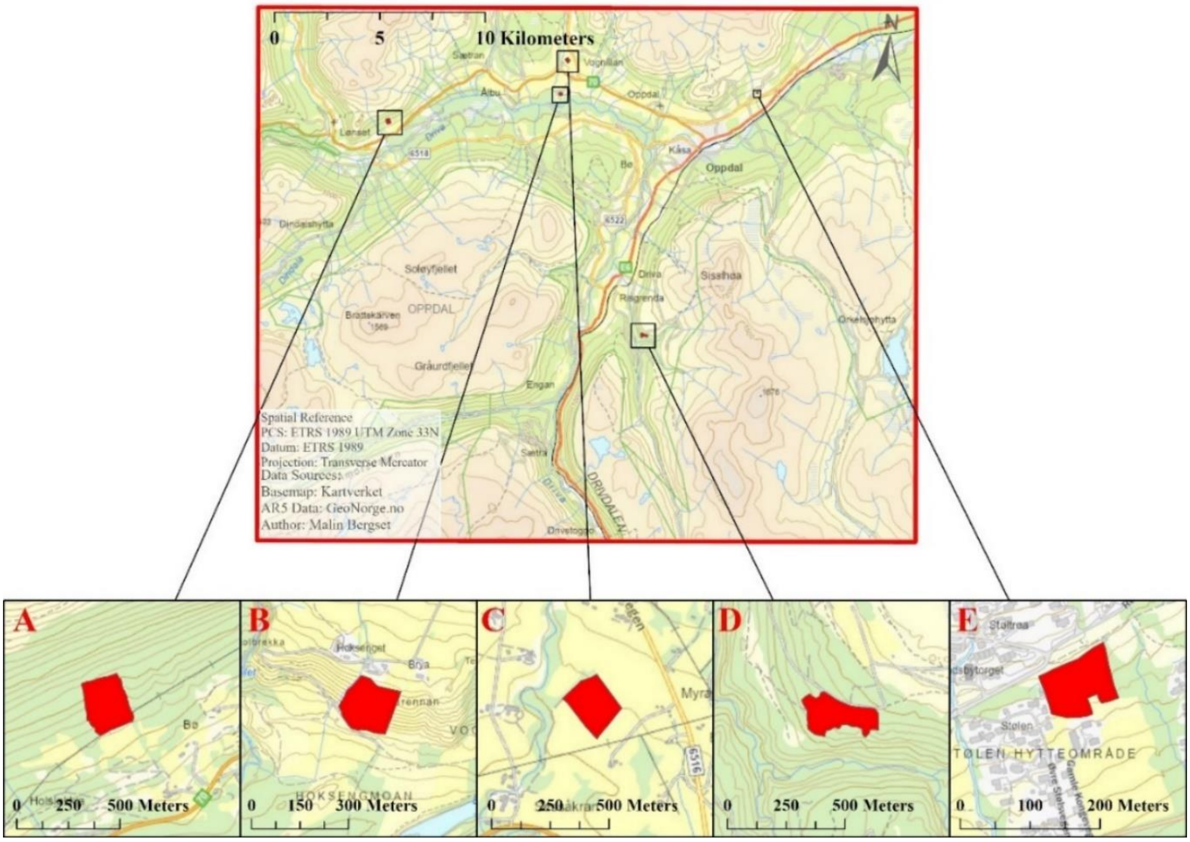

Figure 7: Sub-Selection of Patches for Calculations

3.6 Calculating Electric Power Generation Potential

To find insolation statistics for each of the patches, *Zonal Statistics as Table* was used to find total and mean annual and monthly insolation (Esri, n.d., h). In order to estimate how much energy can be produced at the respective patches, the following electric power generation potential-equation was used (Gastli & Charabi, 2011, p.5):

$$EGP = SR \times CA \times AF \times \eta$$

where:

EGP	Electric power generation potential per year (Wh/year)
SR	Annual solar radiation received per unit horizontal area (Wh/m^2/year)
CA	Calculated total area of suitable land (m^2)
AF	Area factor indicating what fraction of the calculated areas that can be covered by solar panels
η	PV system efficiency

4. Results

To decide on suitable areas for ground mounted PV modules in Oppdal, incoming solar radiation was assessed for the area of interest using GIS and a 10-meter resolution DSM. Areas with topsoil of high quality was excluded for further analysis with aim to preserve topsoil for agriculture and food production, while five areas of lower top soil quality with different size and amounts of radiation was selected for estimating potential electricity production. This section will first present spatial and temporal variation of solar radiation for the whole study area, before focusing on the five selected agricultural patches.

4.1 Spatial Distribution and Temporal Variation of Insolation in the Study Area

In relation to the annual basis analysis, the most radiated areas receive 1 337.4 kWh/m^2/year, while the least radiated areas receive 89.8 kWh/m^2 annually, as shown in figure 9. From this, it is clear which areas that receive less radiation from the sun and which receives more.

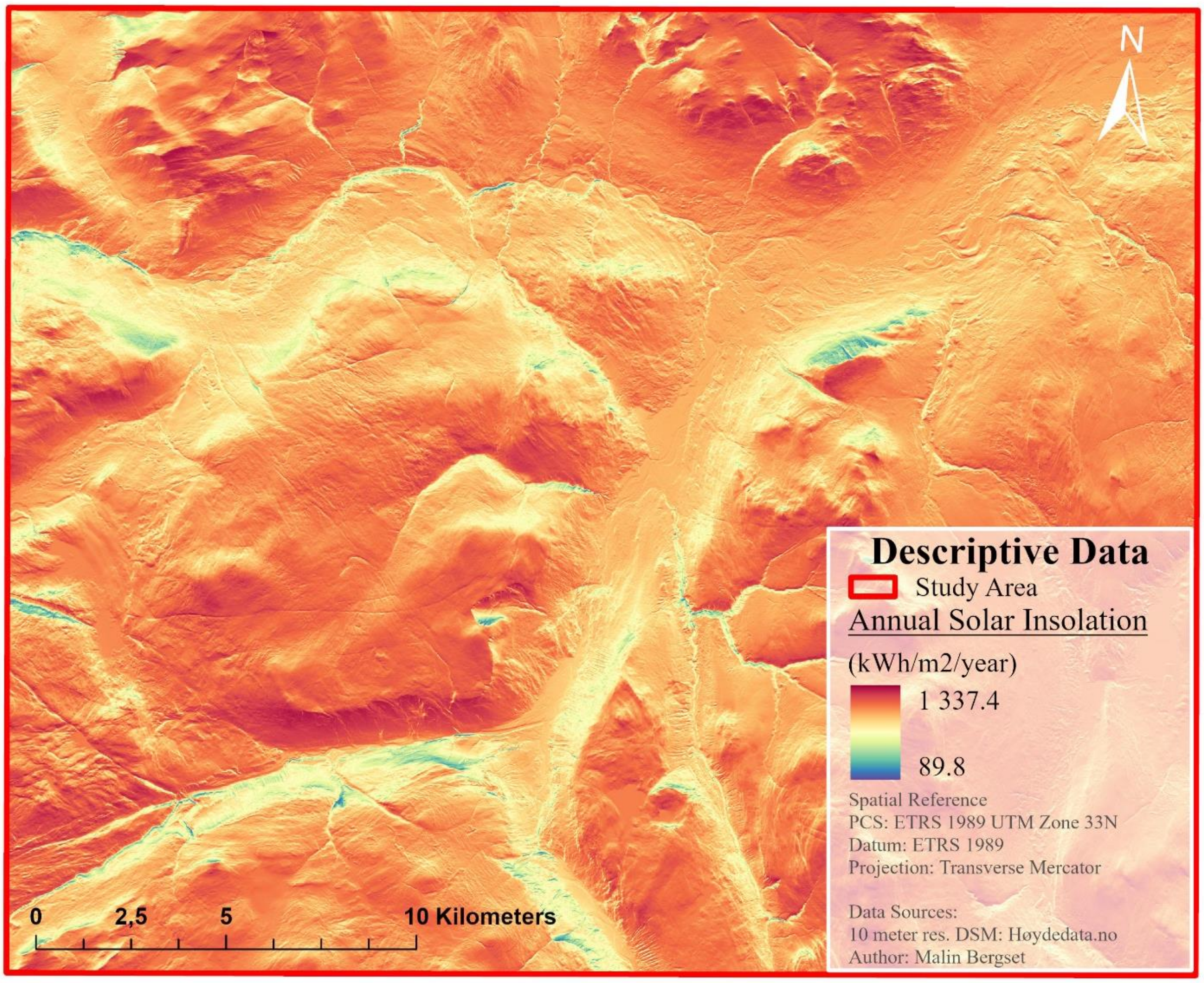

Figure 8: Annual Solar Insolation in Study Area

Over the course of a year, seasonal variation is significant. Figure 10 shows temporal variations between January, April, July and October. Insolation is at its lowest in January, with only 0.146 kWh/m^2, while July received at most 226.9 kWh/m^2.

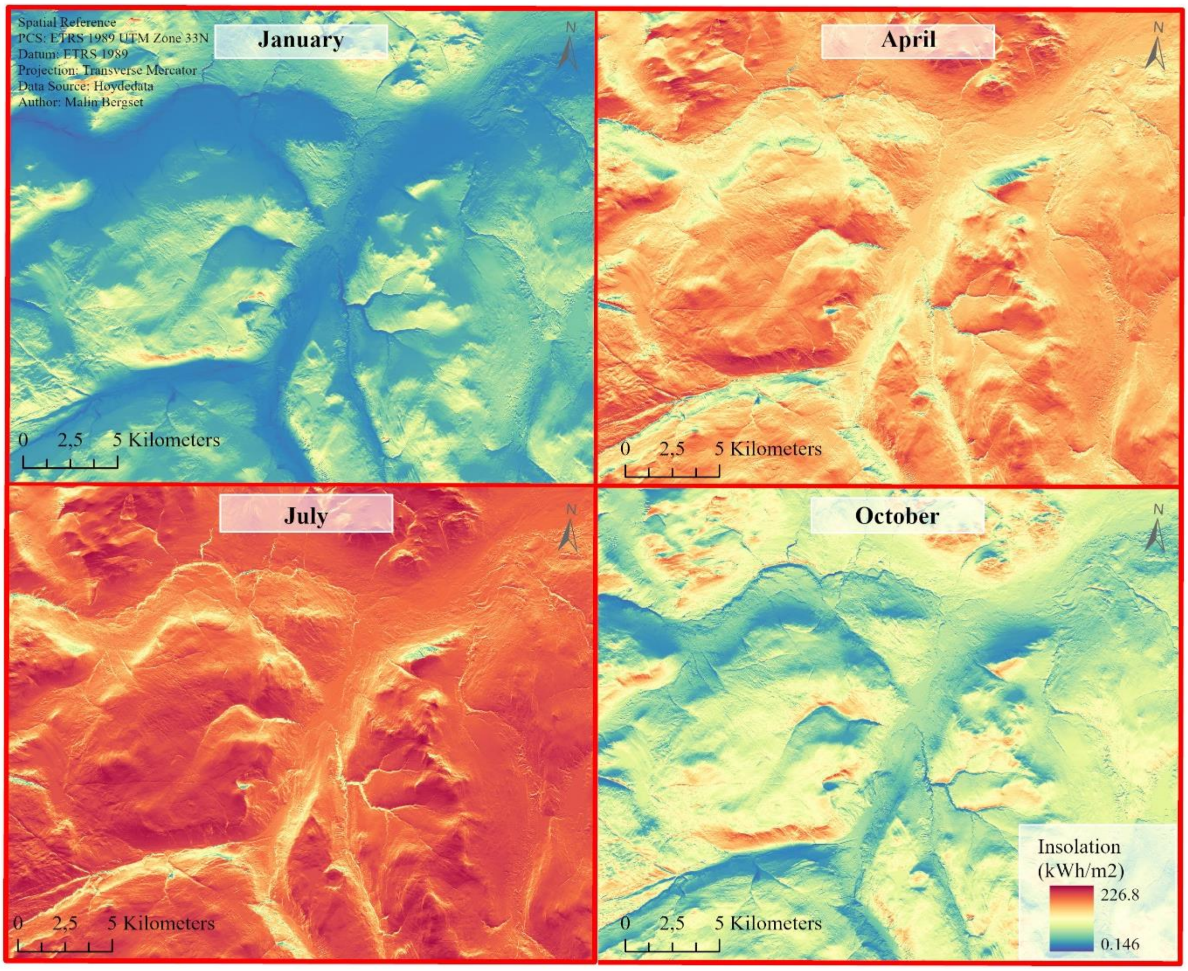

Figure 9: Temporal Variations of Insolation in the Study Area

Table 4 and figure 11 show the minimum, maximum and mean global solar radiation as kWh/m^2 for each month over the course of a year. The results from the analysis underlines that the insolation is received in May, June and July with an average of 185.4 kWh/m^2/month. June has the largest maximum insolation with 231.4 kWh/m^2. During the winter months, the study area receives considerably less insolation. As Oppdal is located in high latitude, the sun is low on the horizon at this time of year. In December, the study area receives 0.5 kWh/m^2 at most, according to the analysis.

Table 4: Total Solar Radiation in the Study Area (kWh/m2/month)

Global Solar Radiation (kWh/m^2/month)	**Month**	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**	**July**	**August**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
	Min.	0.1	1.3	5.2	10.2	14.8	16.1	15.7	12.2	6.7	2.4	0.3	0
	Max.	4.1	30.4	98.9	159.2	214	231.4	226.8	183.6	117.5	51.8	8	0.5
	Mean	0.9	10.6	50.7	109.7	173.3	195.5	187.5	135	67.6	20.7	2.1	0

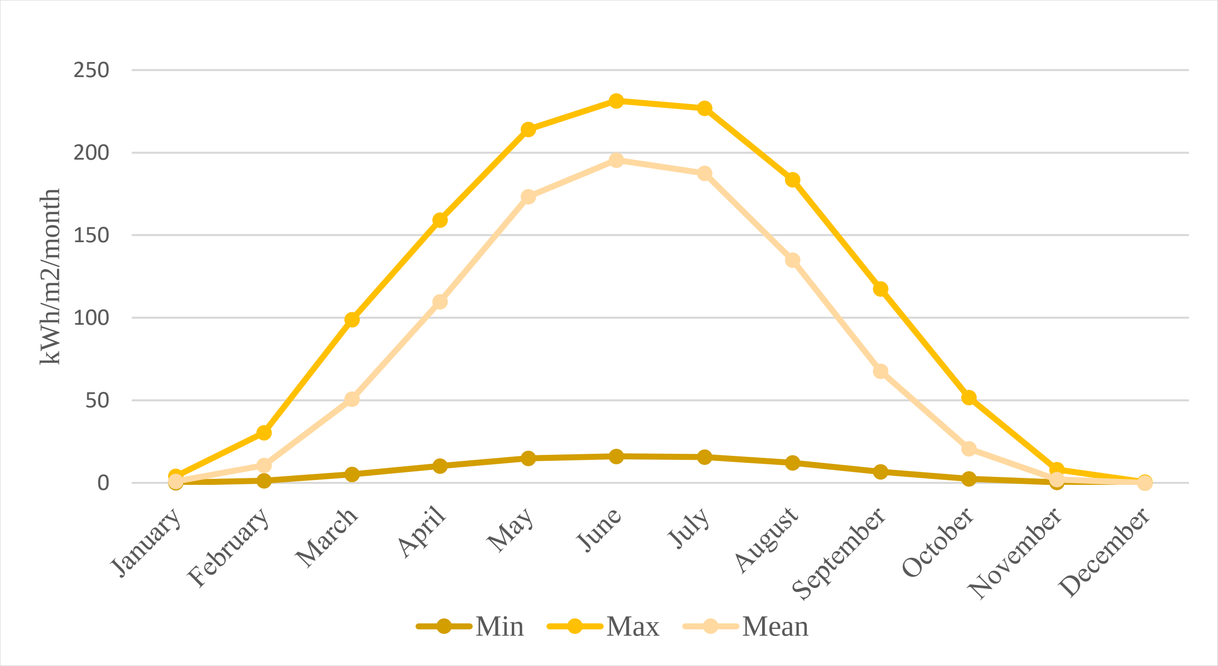

Figure 10: Total Monthly Insolation in the Study Area (kWh/m^2/month)

4.2 Spatial Distribution and Temporal Variation of Solar Radiation in the Selected Patches

The five selected patches have different size, topsoil quality and insolation values, displayed in table 5. The following sections is going to compare solar radiation in the different patches and calculate electric power generation potential for each of them, using the electric power generation potential equation.

Table 5: Selected Patches for Calculation

Patch	**Soil Category**	**Area (m^2)**	**Annual Solar Radiation (kWh)**
A	23	51 046	573 679
B	22	22 763	252 916
C	23	36 262	367 844
D	23	48 962	544 626
E	22	7 326	80 123

Total annual global radiation for the 5 patches in the study area is 1 819 188 kWh. Patch A being the largest one, naturally receives the most insolation, followed by patch D, C, B and E as shown in figure 12.

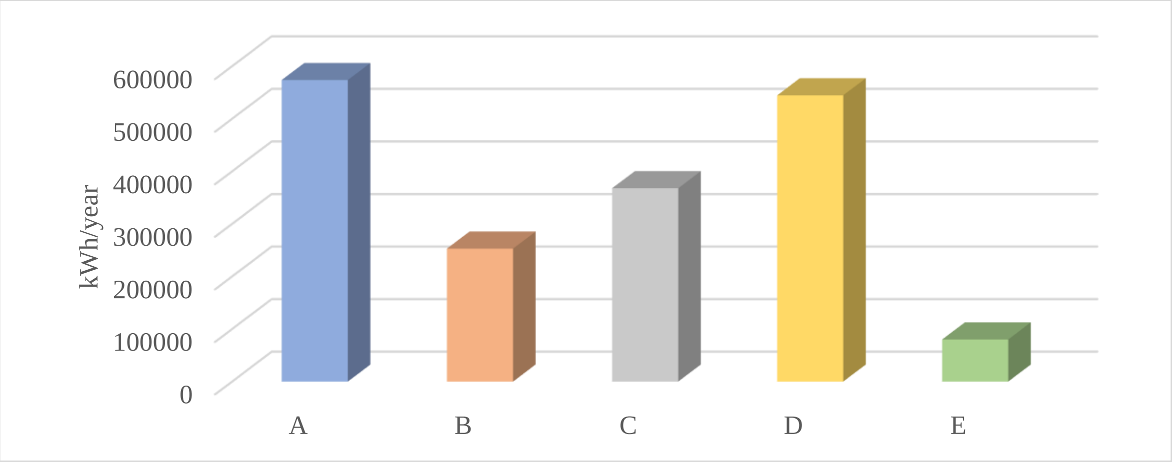

Figure 11: Annual Global Total Radiation for Each Patch (kWh/year)

Breaking it down to monthly insolation, shows how much each patch receives throughout the year and highlights temporal variations. Table 6 and figure 13 shows total monthly global radiation as kWh, while table 7 and figure 14 shows mean monthly insolation as kWh/m^2/month.

Table 6: Total Monthly Insolation (kWh/month)

Patch	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
A	658	8111.3	34265.8	66347.9	96994.5	106078.4	103417.7	79230.6	43875.2	15199.8	1620.9	34.1
B	231.7	3486.9	15012.9	29270.8	42886.4	46942.3	45738.7	34993.8	19281	6591.8	625.3	12.1
C	359.8	4115.6	19412	41298.1	64344.1	73222.8	69543.5	50559	25716.5	7975	796.1	28.1
D	645.7	7230.2	31731.2	62581.1	92852.6	102264.2	99335.7	75153.3	40899.5	13777.8	1461.8	45.8
E	90.2	1028.8	4532.5	9138.7	13756.2	15238.2	14762.7	11036.4	5890.6	1948.2	7.4	5.8

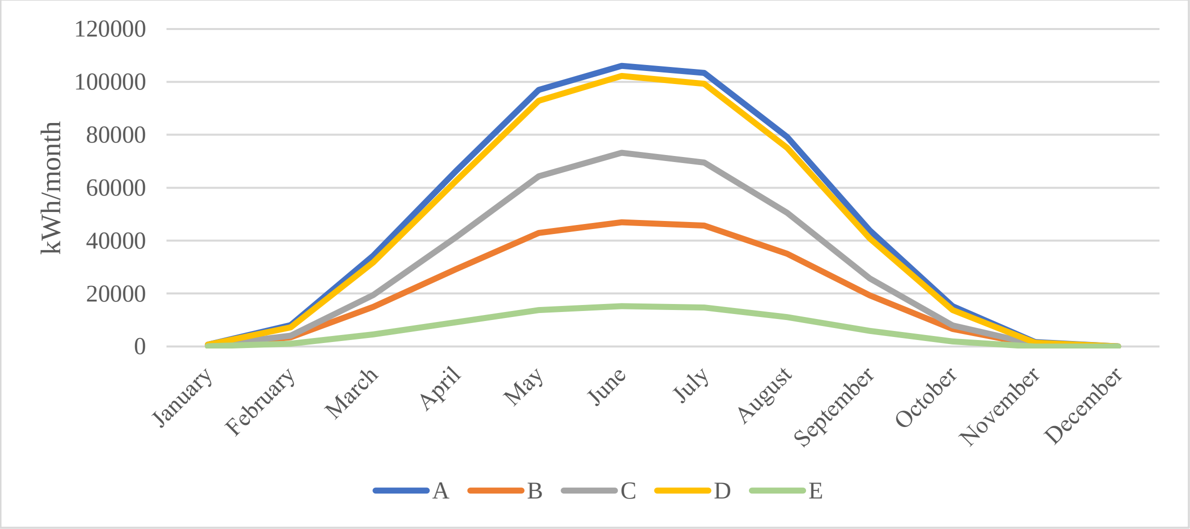

Figure 12: Total Monthly Insolation (kWh/month)

Table 7: Mean Monthly Insolation in Each Patch (kWh/m2/month)

Patch	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
A	1.3	15.8	66.9	129.5	189.4	207.1	201.9	154.7	85.6	29.6	3.1	0.06
B	1	15.1	65.2	127.2	186.4	204	198.8	152.1	83.8	28.6	2.7	0.05
C	0.9	11.3	53.3	113.4	176.7	198.6	191	138.8	70.6	21.9	2.1	0.07
D	1.3	14.6	64.1	126.4	187.5	207.1	200.6	151.8	82.6	27.8	2.9	0.09
E	1.2	13.9	61.2	123.4	185.8	205.9	199.4	149.1	79.6	26.3	2.7	0.07

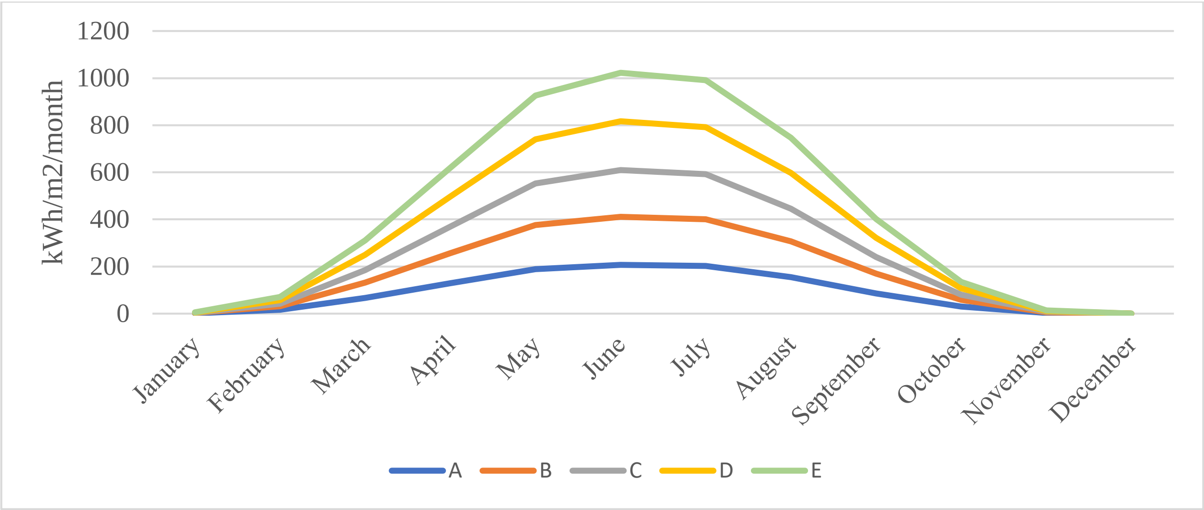

Figure 13: Mean Monthly Insolation for Each Patch (kWh/m^2/month)

4.3 Estimating Electricity Generation Potential

An aim with this analysis is to estimate energy generation for the five selected patches of topsoil. This is done using the electric power generation (EGP) potential-equation.

$$\text{EGP} = \text{SR x CA x AF x } \eta$$

SR is the annual solar radiation received per unit horizontal area (kWh/m^2/year), CA is calculated area of suitable land (m^2), AF is the area factor indicating what factor of the calculated areas that can be covered by solar panels and η is the PV system efficiency.

The study area with the five selected patches of agriculture land receives a total of 1 819 188 kWh each year (SR), distributed over an area of 166 323 m^2 (CA). According to Scognamiglio, area factor (AF) should be set to 33% to open for movements of big vehicles such as trucks and tractors (Scognamiglio, 2015, p.4). Different types of PV technologies have different module efficiency (η). First generation *Monocrystalline* type has an efficiency between 14-17.5%, second generation *Amorphous Silicon* has an efficiency between 4-8% while third generation

Cadmium Tellurium (CdTe) type solar cell lies between 9-11% efficiency (Parthiban & Ponnambalam, 2022, p.3). For this purpose, calculations for three levels of efficiency are done: 16%, 11% and 8%, as shown in table 8.

Table 8: Electricity Generation Potential for Each Patch

Patch	**PV-Technology**	**Efficiency (%) η**	**Mean annual solar radiation (kWh/m^2/year) SR**	**Total area of suitable land (m^2) AC x AF**	**Generation potential (kWh/year) EGP**
A	Monocrystalline	16	1 120.4	16 845	3 019 702.0
	Amorphous Silicon	11			2 076 045.1
	CdTe	8			1 509 851.0
B	Monocrystalline	16	1 099.6	7 551	1 328 492.7
	Amorphous Silicon	11			913 338.7
	CdTe	8			664 246.3
C	Monocrystalline	16	1 010.5	11 966	1 934 662.8
	Amorphous Silicon	11			1 330 080.7
	CdTe	8			967 331.4
D	Monocrystalline	16	1 100.2	16 157	2 844 149.0
	Amorphous Silicon	11			1 955 352.4
	CdTe	8			1 422 074.5
E	Monocrystalline	16	1 082.7	2 417	418 701.7
	Amorphous Silicon	11			287 857.4
	CdTe	8			209 350.8

According to these calculations, the largest patch (A) could potentially produce 3 019 702 kWh of green electricity over the course of a year, using the first-generation Monocrystalline type with 16% efficiency. The smallest patch (E) could potentially produce 418 701.7 kWh annually, using the same technology. Using third generation Cadmium Tellurium technology, patch A could potentially produce 1 509 851 kWh annually, while patch E could produce 209 350.8 kWh.

5. Discussion

The analysis shows how GIS could be used to model and estimate global solar radiation and calculate electricity production potential for land-based PV modules on agricultural land.

Through a solar radiation analysis combined with requirements for the quality of the topsoil modules can be situated on, five patches of agricultural land from the study area were selected, where annual solar radiation and potential energy conversion was estimated. Based on results from the calculations, land-based PV modules could contribute with large amounts of electricity, without occupying land solely for energy generation. The following chapter discuss potential and challenges by implementing land-based solar energy in combination with agriculture in northern latitudes, and what social and ecological criteria that should be considered during the process.

5.1 Potential for Solar Energy in Agriculture in Oppdal

Using patch C and PV modules with 16% efficiency as an example – the patch could potentially produce 1 873 722 kWh annually when 33% of the area is utilized for land-based PV modules. Figure 15 shows the patch and its location in Oppdal.

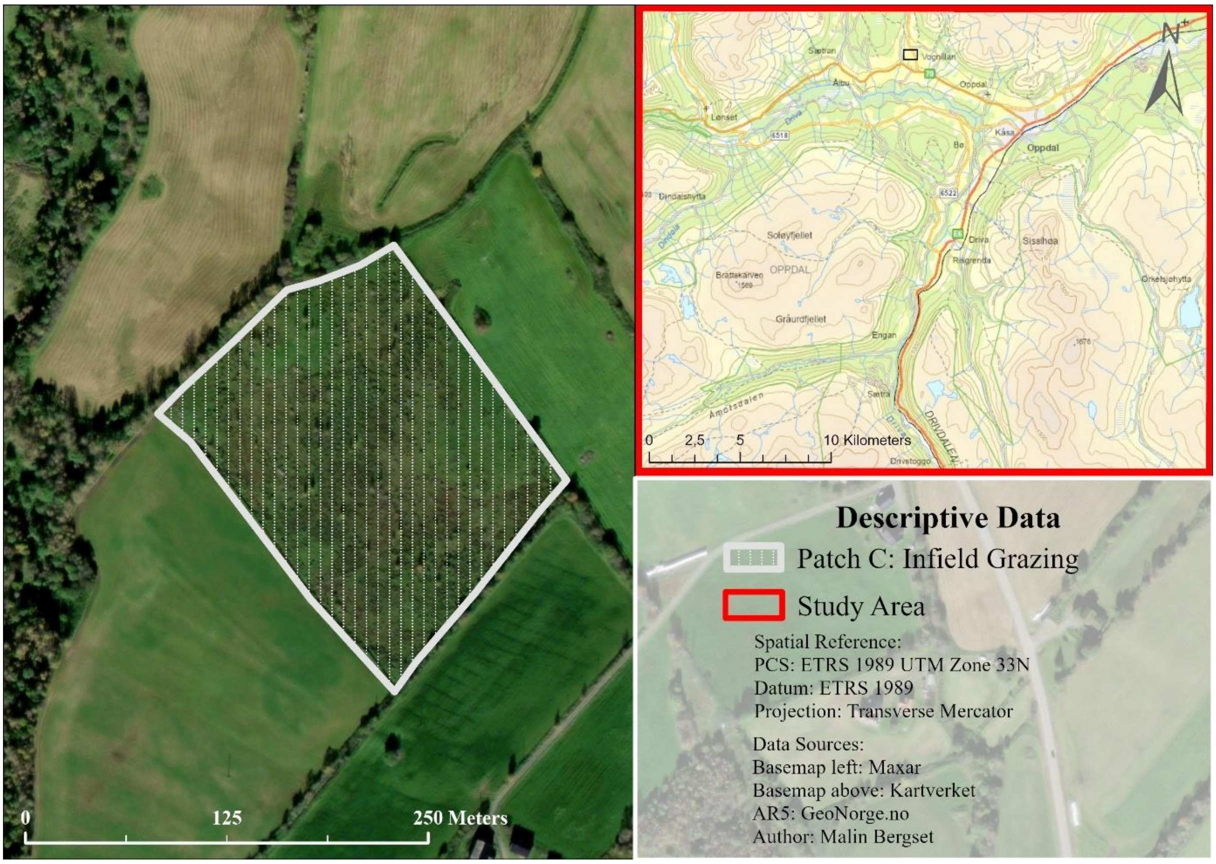

Figure 14: Patch C

Utilizing agricultural areas this way could contribute with electricity for heating, powering electrical machines and devices for agricultural purposes, in addition to contributing with electricity for household appliances such as charging electrical cars, running heat pumps. In summer, when production potential is the largest with high amounts of insolation, excess electricity could be distributed to neighborhoods through a micro grid or supplied to the main transmission grid. This creates a larger degree of self-sufficiency, and could in turn potentially reduce costs when production is lower and the need for electricity from external sources are larger, through agreements with power companies.

Using only 33% of the land area for PV modules, opens for still using the patch as area for infield grazing for livestock, such as sheep or cattle. The modules could provide shadowing when warm days where animals, plants and other organisms could safely find areas with lower temperatures, at the same time as it produces electricity without making noise or emitting any dangerous gases. Tractors and other machines could still pass between the modules if needed. Figure 15 provides an example on how such modules could look in the landscape.

Figure 15: Ground-Mounted PV Modules Could Provide Popular Shadow for Livestock. Source: Enel Green Power (2022).

If the modules are installed on land with soil of higher quality, foods could be grown in-between modules, or in the shadows behind – depending on what type of climate they prefer. Utilizing patches in several ways increases productivity and creates a synergy between agriculture and energy production, instead of occupying it for one specific purpose or degrading large amounts of vulnerable topsoil that future food production or livestock relies on.

5.2 Challenges for Implementation

Even though electricity production potential is large, there are several factors that could be challenging to overcome when transitioning to RES and implementing land-based PV modules. This section discusses some of them.

5.2.1 New Geographies of Energy Production

Implementing RES implies more than just replacing the energy source and its related technology. The green transition in the energy sector is a socio-technical transition, meaning that energy and society is co-constituted. Large scale implementing of RES will affect more than just energy use, but will require new ways of producing, living and working with new energies. It is not sufficient to restructure energy infrastructures to ensure a green transition, but important assessments and choices related to location, landscape, territory, scale and spatial differentiation and development has to be made (Bridge et al., 2018, p.78-79).

5.2.2 Conflict of Interests

Installing land-based PV modules on agricultural land will alter existing structures and landscapes, and can cause controversies. Landscapes are more than just natural properties distributed across space, but also refers to cultural evaluations and emotional attachment that people have to the material forms (Bridge, Bouzarovski, Bradshaw & Eyre, 2013, p.335). A common controversy is the *Not in My Backyard*-responses (NIMBY) to instalment of new energy infrastructure. Utilizing landscapes in new ways will require new acceptance of the form and functions of them, which requires time.

In addition to being a foreign and disturbing element in the landscape, installing ground-mounted PV modules on private ground could also directly conflict with local strategies and policies. Oppdal municipality emphasizes the importance of the cultural landscape and beautiful nature that is basis for agriculture and tourism. Installing large PV modules in the natural landscape could break with the vision the policymakers have for future development and preservation strategies and make it more challenging to convert to RES (Oppdal Kommune, 2019, p.4).

5.2.3 Variability in Production

Variability in production throughout the year could cause scepticism and prevent investments in solar energy. For instance, heating requires large amounts of electricity but is most needed in winter when temperatures are low and animals are inside on stalls. According to the analysis, the potential to generate energy is at its lowest during winter. As for now, batteries and other options for storage of discontinuous solar energy exists – but are limited and needs to grow significantly (IEA, 2022). To replace fossil fuels in agriculture, it will be essential for renewable energy grids to develop storage solutions for excess power when the sun is absent, to ensure flexibility and predictability (IEA, 2022).

5.2.4 The Economic Factor

Lastly, a major factor that could prevent implementation of solar energy in combination with agriculture, is capital. Investing in solar energy in larger scale is a large and long-term investment. Even though production costs have dropped and efficiency has increased for the technology over the past years, Norwegian agriculture is not a particularly profitable occupation and income can be a limiting factor (SSB, 2023). Collective ownership and shared grid could be organized through a local community, but without strong incentives and financial support schemes for farmers looking into making such investments, it is likely that only the largest and most resourceful farms will have capital to serve their loans. This creates a great divide between farmers who operate on a small-scale versus on a larger scale with higher efficiency and economic pay-off.

5.3 Limitations and Assumptions

There are several elements that can affect the results of the analysis. This section reflects on and discusses some of them, and how a similar analysis could be done better for later research.

5.3.1 Reflected Radiation and the Snow's Albedo Effect

As previously mentioned, the model does not take reflected radiation from the ground or other surfaces into account (Rød, 2015, p.234). This is especially relevant for the northern latitudes where sun is low during winter and sun hours are limited, but surfaces such as snow has high albedo-effect and reflects radiation (Brennan, Abramse, Andrews & Pearce, 2014, p.1). Calculated global radiation in months where snow is present is therefore likely underestimated. By optimizing the selection of PV materials for specific environments and microclimates, electricity production potential is also likely higher than the calculations estimate (Brennan et al., p.6).

5.3.2 Calculating the Electricity Production Potential

Considering that different types of PV technologies work optimally under different conditions, it is difficult to make accurate estimations of how much energy they can convert into electricity. Three different technologies are taken into account in the calculations above, but these are still a rough estimate. Several factors could affect the actual productivity of the PV modules, such as how they are mounted, angle of potential tilt, if they track the sun or are bifacial to mention some. In addition, when the PV panels share land with agricultural activities, dust from grazing animals or machines could gather on top of the modules and reduce productivity.

One major challenge regarding the calculations, is if the PV panels are mounted horizontally and snow accumulates on top of the modules and fully block insolation in winter time. These factors are not taken into account in the calculations, and is an important source of error. The issues could be taken account for by cleaning the modules or looking at solutions where solar panels can melt the snow before it accumulates (Innos, n.d.). Considering these factors, the calculations should only be regarded as a rough estimate.

Creating Key Performance Indicators (KPIs) for the different patches would make the calculations more tangible, but considering that energy demand depends heavily on what type of farm, size and production one has – which is hard to estimate or generalize. In addition, finding energy consumption statistics were challenging, but such investigations could be part of further research.

5.3.3 Software, Data and Parameters

The solar radiation analysis is time-consuming and requires significant processing capacity. Therefore, the study area does not cover the whole municipality. The study area was decided on because large amounts of the municipality's agricultural land is situated within the area shown in figure 5.

The GIS analysis takes many parameters, and changing one of them can alter output results. This problem could be minimized by calibrating the values to data from PV systems in the area, and then try using different input parameters to find the ones that that best match the real-life data before running a large-scale analysis. Otherwise, the results could be compared with observed insolation from meteorological agencies, and furthermore the parameters could be adjusted to better match the modelled insolation with observed insolation. Running the analysis with a higher resolution DSM and larger sky size could also have made the results more reliable – but processing capacity and time was a limiting factor[1].

Including other criteria for deciding on areas that electricity production potential was calculated for would make the analysis more reliable. This could for example include distance to settlements, distance to transmission grid, aspect or slope. Also, by using a buffer around the areas that are not suited because of their utilization or function, only realistic areas for implementation would be subject for further discussion and analysis.

Lastly, the dataset includes several subcategories for each classification number. Category 21 includes both fully cultivated land and bog, while category 23 includes fifteen different subcategories of topsoil and area types (Geovekst, 2022). This makes the analysis less precise,

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[1] I tried running the tool with a 1-meter DSM, but the computer crashed after 16 days. Therefore, a 10-meter DSM was used instead.

as they cannot be separated in the dataset. Some areas in the categories could therefore be unsuitable, even though they fulfil requirements used for this analysis.

Executing solar radiation analyses is a fitting first step to assess insolation and identify areas which receive sufficient radiation, but should be followed by further and more in-depth assessments of top soil quality, biodiversity and ecosystems at. More precise calculations are also needed, to give more accurate information on how reflected radiation, tilt angle and other factors alter electricity production potential.

6. Conclusion

Reducing GHG-emissions to achieve climate goals will require significant shifts in how landscapes are utilized. According to this analysis, ground-mounted PV modules could be a measure with great potential to reduce carbon footprint from energy use in high latitudes. Agricultural land could be utilized to produce considerate amounts of green energy from ground-mounted PV panels without occupying the areas for energy production purposes only, but create synergies with other agricultural activities. Considering Norway has small amounts of high-quality topsoil for food production, land with lower quality should be prioritized for installing such infrastructure.

Solar energy is though not sufficient to power agricultural applications or households on its own, as there are considerate temporal variations in insolation and potential production over the course of a year and limited options for storing electricity as for now. Furthermore, implementation of green energy entails more than installing new energy infrastructure. Involvement of local interests and public actors should be a central measure to collectively identify locations and solutions for implementation of the RES, to create engagement and inspiration rather than controversies due to conflicting use of land regarding the green energy transition.

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