Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for energi- og prosessteknikk

Isak August Solberg

Balancing Renewable Energy and Biodiversity

Impact from Habitat Loss and Collisions in Future Norwegian Photovoltaic Solar Parks

Masteroppgave i Industrial Ecology
Veileder: Francesca Verones
Medveileder: Jan Borgelt
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Abstract

The state of biodiversity is critical at the global, regional, and national levels. With a growing world population and many being lifted out of poverty, the global energy demand is increasing. Geopolitical unrest also pushes states to secure increased domestic energy production. Over the past couple of decades, photovoltaic (PV) solar technology has become more efficient and affordable, with a price reduction of over 90%. Large-scale solar parks have thus recently developed into a viable option in Norway, where the first concession was granted in 2022. Due to the great potential for development and the critical state of biodiversity, it is important to map the environmental consequences of PV solar park development in Norway. In this thesis, the impact of the PV solar parks on biodiversity is calculated using species distribution maps and spatial data on planned PV solar parks in Norway. The biggest threat to global biodiversity is habitat loss. Therefore, this thesis examined the impact of solar parks on mammals through habitat loss. Additionally, the impact on birds due to collision risk was investigated. PV solar power was found to require roughly twice the amount of land occupation per GWh produced compared to hydropower reservoirs. The bird species investigated were more severely impacted by PV solar parks than wind turbines regarding collision risk. These results provide increased insight in renewable energy technologies impact on biodiversity and therefore strengthen the basis for decision-makers facing the present growing energy demands. The applicability of modelling habitat loss and collision risk for future PV park installations was demonstrated.

Sammendrag

Tilstanden til biologisk mangfold er kritisk på globalt, regionalt og nasjonalt nivå. Med en økende verdensbefolkning, samtidig som mange løftes ut av fattigdom, vokser verdens energibehov. Geopolitisk uro fører også til at stater ønsker å øke energiproudksjonen innenfor egne landegrenser. I løpet av de siste tiårene har solcelle-teknologi blitt mer effektivt og rimelig, med en prisreduksjon på over 90%. Solcelleparker i storskala har derfor nylig blitt et reelt alternativ i Norge, og første konsesjon for utbygging ble gitt i 2022. Grunnet det store potensialet for utbygging, samt den kritiske statusen for biologisk mangfold, er det viktig å kartlegge de miljømessige konsekvensene av solcellepark-utbygging i Norge. I denne oppgaven beregnes påvirkningen fra solcelleparker ved hjelp av artsfordelingskart og data om planlagte solcelleparker i Norge. Den største trusselen globalt mot biologisk mangfold er tap av habitat. Solcelleparkers påvirkning på pattedyr gjennom tap av habitat blir derfor undersøkt i denne avhandlingen. I tillegg er påvirkngen på fugler grunnet kollisjonsrisiko undersøkt. Det ble estimert at solcelleparker krever omtrent dobbelt areal sammenliknet med vannkraft-reservoar, per GWh produsert. Påvirkningen på fugler grunnet kollisjonsrisiko var større for solcelleparkene enn vindturbinene. Disse resultatene gir økt innsikt tilknyttet påvirkning på biologisk mangfold fra forskjellige typer fornybar energi, og styrker dermed grunnlaget for beslutningstakere i møtet med dagens økende krav til energi. Oppgaven demonsterer den praktiske muligheten for å modellere av tap av habitat og kollisjonsrisiko for fremtidige solcelleprosjekter.

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Contents

1 Introduction

Shifting towards sustainable energy production is a pivotal challenge for mankind, further complicated by a growing population and increasing energy demands (IEA, 2020; Ritchie et al., 2023). While the installed capacity of renewable energy is increasing, this growth must be further accelerated by another 60% to achieve an energy sector with net zero carbon emissions by 2050 (IEA, 2022). Solar power is the fastest growing energy source globally, which has evolved from being a minuscule contributor in the global energy market to a major one over the course of a few decades. The global installed capacity of photovoltaic (PV) solar power was 600 GW in 2020, and is expected to grow by almost 1500 GW between 2022 and 2027 (IEA, 2022; World Bank, 2020). With this projected growth, PV solar power overtakes all fossil and renewable energy sources in installed power capacity, though not in energy production due to the fluctuating nature of PV solar power.

PV solar power is in rapid growth, both on a global scale and in Norway specifically. In Norway, PV usage was typically tied to off-grid locations such as cabins and lighthouses (Hofstad, 2023). However, the installed capacity connected to the national grid grew by more than 300% over the last four years (NVE, 2023). Approximately three quarters of the current installed capacity are tied to private households or other industry, and there are no completed utility-scale PV solar parks in Norway. Several are planned for the near future, with the first concession for a large-scale ground-mounted PV solar power plant granted in 2022 (NVE, 2022b). Scaling up national solar PV production with 5-10 TWh between 2022 and 2030 is considered realistic, with the total national potential estimated at 199.0 TWh/year (Multiconsult, 2022).

While solar power is carbon neutral during the operational phase, it requires large land areas. The construction can also lead to emissions of greenhouse gases through the destruction of carbon sinks. Therefore, solar power parks may directly or indirectly harm wildlife and ecosystems. Biodiversity is under threat on a global scale, thoroughly illustrated by the 68% average population decline across mammals, birds, amphibians, fish, and reptiles between 1970 and 2016 (WWF, 2020). Besides the intrinsic value of healthy biomes and thriving ecosystems, functional biodiversity is vital to human life on Earth. Through intricate and complex pathways, biodiversity enables human survival and well-being by providing provisioning, regulating, supporting, and cultural ecosystem services, e.g., pollination and nutrient cycling (Mace et al., 2012; WWF, 2020). The largest driver of biodiversity loss is the loss of habitat (WWF, 2020), which the construction of solar power parks undoubtedly contributes to. In light of the expected growth of the solar power sector in Norway, it is of high interest to investigate the connection between biodiversity impacts and solar park installations. Furthermore, quantification of these impacts and comparison to other alternatives for renewable energy production is of paramount importance. An improved understanding of the impacts on biodiversity from alternative energy production in Norway further empowers decision-makers to make well-informed choices in the face of growing energy demands.

This thesis investigates the impact on mammals and birds from seven planned PV solar power parks in southeastern Norway. For mammals, the impact due to habitat loss is quantified, whereas for bird the impact pathway investigated is collision. The impacts are measured in potentially disappeared fraction (PDF) per unit of production for each park and species group. The land occupation per unit of production is calculated, and compared to the average land occupation from hydropower reservoirs in Norway. The average impact from PV solar power on birds due to collision is compared with a similar study on wind turbines.

2 Background

2.1 Photovoltaic solar power

Utilization of solar power is done in various ways, but can be generalized into two main categories: using the sun as a source of heat (thermal) or generating electricity (photovoltaic, PV) (Lachner, 2019). Thermal usage, such as housing design with thermal absorption in mind, is the older of the two, but photovoltaic technology is not a novelty either (Jones & Bouamane, 2012). The French scientist Edmond Becquerel discovered that illuminating two electrodes immersed in an electrolyte produced an electromotive force in 1839 (Fink & Adler, 1941).

PV solar power saw limited use after its discovery in the 1800s, and well into the 20th century. The technology was not economically competitive with other energy sources such as oil and coal. However, PV solar power had a noteworthy advantage in being operational with minimal maintenance. Thus, PV solar power became a crucial technology for remote off-grid structures such as lighthouses and satellites (Hofstad, 2023; Roser, 2023).

In recent decades, solar power has grown at an accelerating rate. This is due to several key factors. The most important one is the price reduction of the technology itself, coupled with reductions in related material sectors such as the semiconductor sector (U.S. Bureau of Labor Statistics, 1976, 1984). Consequently, the prices for utility-scale PV solar power decreased by 89% between 2009 and 2019 in the United States (Roser, 2023). Initially reserved mainly for off-grid, this massive price drop made the technology more appealing for installations at large and small scales and in a multitude of applications (Fraas & Partain, 2010). Current state-of-the-art PV cells have an efficiency of 18-20% at optimal conditions, however the overall efficiency of a PV cell in use is often reduced by factors such as dust, overheating, or imperfect cell angle (Chandrasekar et al., 2022; Lachner, 2019; Paul, 2022). The electricity generated by the PV cell must either be stored in a battery, transmitted to the power grid, or be used by a connected load.

The potential for PV solar power production is dependent on the geographic location of the park. Solar irradiance is the singular most important factor, which in turn is determined by secondary factors such as latitude, elevation, cloud formation and atmospheric aerosol concentrations (World Bank, 2020). The second most important factor is air temperature, which often is inversely correlated with solar irradiance (World Bank, 2020). PV power production is negatively impacted by increased module temperature (Alonso-Marroquin & Qadir, 2023; Rahman et al., 2015; Shan et al., 2014). Due to these two factors, irradiance and air temperature, the difference between the countries with the highest expected output per PV surface area (Namibia) and the lowest (Ireland) is roughly a factor of two (World Bank, 2020).

Due to PV solar powers nature of fluctuating power production, energy security has historically been an argument for other energy sources than PV solar power. The development of PV solar energy might be accelerated by geopolitical unrest in fossil fuel producing regions, as was the case during the oil crisis of the 1970s (Aklin & Urpelainen, 2018). The ongoing war between Ukraine and Russia, and the affiliated sanctions of Russia, has presented European nations with challenges in terms of energy security. While the war has affected the energy policy of European countries, the long-term effects on the development of PV solar power is unclear (Osička & Černoch, 2022; Umar et al., 2022; Zakeri et al., 2022).

2.2 Global biodiversity crisis and ecosystem services

The term biodiversity is a rather recent addition to scientific literature, first used by biologist Elliot Norse in the 1980s (Dyke, 2008). To the public, as well as the law, equating the number of species to biodiversity can be quite useful in effectively getting the point across (Dyke, 2008; Mace et al., 2012). However, a more precise term would be ”the structural and functional variety of life forms at genetic, population, community, and ecosystem levels” (Sandlund et al., 1992). This definition captures the importance of the inter-linkages between the species, as opposed to just a cluster of unrelated, individual species, as well as that the concept of biodiversity applies to multiple biological levels. A species population that with a high level of genetic diversity is more resilient to outside pressures such as climate change (Sgrò et al., 2011; Thompson et al., 2009). This in turn strengthens the resilience of the ecosystem as a whole. Furthermore, biodiversity, ecosystem resilience, and ecosystem functioning and production are fundamentally related (Cardinale et al., 2012; Thompson et al., 2009).

Biodiversity is threatened both globally and locally. The Living Planet Index (LPI) tracks the abundance of 20 811 populations of 4392 different species. The LPI shows a global population decline of 68% between 1970 and 2016 (WWF, 2020). While some regions were more severely impacted than others, the same general trend of declining overall populations was found in all regions examined. The single most important driver of these impacts is changes in land and sea use, followed by over-exploitation of species, invasive species and diseases, pollution, and climate change (WWF, 2020). Changes in land and sea use includes loss of habitat or degradation of habitat quality. In Norway specifically, ecosystems are under serious pressure due to human-driven land use changes. On a national scale, 2166 km^2 is planned for development for residential buildings, vacation homes, or commercial use (Simensen et al., 2023). Expanding the scope to include other municipal uses, energy production, and road network, the figure grows to approximately 4000km^2 (Miljødirektoratet, 2024).

While some will argue that biodiversity has an intrinsic value, it is also essential to human life on Earth. This is due to a myriad of ecosystem services, which are sorted into four categories: provisioning, cultural, regulating, and supporting ecosystem services (Millennium Ecosystem Assessment, 2005). Provisioning services are the products obtained directly from the ecosystems, such as freshwater, medicinal plants, firewood or fibres (UNEP, 2009). Regulating services include flood protection, climate regulation and disease control (Millennium Ecosystem Assessment, 2005). Photosynthesis and soil formation are examples of supporting ecosystem services, and recreation, aesthetic and spiritual benefits are categorized as cultural services (Millennium Ecosystem Assessment, 2005; UNEP, 2009). Ecosystem services are therefore essential to human survival, in a multilayered relationship. For example, our food production relies on the primary production of the ecosystems. To uphold this primary production over time, the ecosystem depends on removal of toxins and protection from disease, potentially also assisted pollination by supporting species. It is therefore adequate to say that the quality, quantity, and reliability of the ecosystem services, which are vital for human life, depends on interactions between the biotic and abiotic components of the ecosystem (Mace et al., 2012).

2.3 Biodiversity impacts from PV solar power

While PV solar power is an energy source without greenhouse gas emissions during operation, it is not without environmental impact. There are many pathways that connect PV solar power with biodiversity impacts. Not all of the impacts are negative, thought the majority and the most severe are. PV solar power contributes to land use changes, the dominating driver of biodiversity losses globally, through habitat loss, habitat degradation and fragmentation (Leskova et al., 2022; Tinsley et al., 2023). For bird species, the panels represent a collision risk (Kosciuch et al., 2020). For some polarotactic insects, the reflection of horizontally polarized light is similar to that of water surfaces, which in turn allures the insects to attempt to lay eggs in the PV panels (Black & Robertson, 2020; Horvath et al., 2010). The solar panels thus act as ecological traps. The panels also alter factors such as temperature amplitude, average temperature, soil temperature, moisture and quality, and shade (Armstrong et al., 2016; Barron-Gafford et al., 2016; Lambert et al., 2021; Schindler et al., 2018; Suuronen et al., 2017). All of these factors lead to complicated impacts on flora and fauna, which may vary greatly from region to region and ecosystem to ecosystem. On vascular plants specifically, studies in different regions comes to completely contradictory conclusions. Hampered succession, increased stress and mortality, and decreased abundance was all found in studies conducted in France (Lambert et al., 2021, 2022), while in arid, desert-like conditions in China, positive impacts such as increased species richness and biomass was found (Liu et al., 2019). Extended blooming window was found in a study conducted in Oregon, US (Graham et al., 2021). Given the large variance in results from studies from different regions, the lack of research conducted in Norway on biodiversity impacts from PV solar power represents a major knowledge gap. This knowledge gap is especially problematic as solar power plants are subjects to the requirements for environmental impact assessment by Norwegian law (Forskrift om konsekvensutredninger, 2017). Several strategies can be deployed in order to mitigate the impact, such as combined area usage with agriculture or pastures. Design choices for the PV cells can have a positive impact, such as including white lines to reduce the maladaptiveness for polarotactic insects. The structure of the park can also be tailored to reduce impact on nearby ecosystems of particularly high value.

3 Method

3.1 Data

3.1.1 PV solar power shapefiles

The shapefiles containing the physical extension, peak power output, and expected annual production of seven planned solar parks in Norway was retrieved from Kenawi et al. (in prep.). The parks were named Barkåker, Bronkemoen, Buer, Løvbergsmoen sør, Prestegårdskogen, Sem, and Simonstad. The peak power and expected production values were cross-checked with their individual concession applications at the Norwegian Energy and Water Directorate (NVE). In the case of discrepancies between the values retrieved from Kenawi et al. (in prep.) and NVE, the latter was chosen, which led to one major and three small alterations. For three parks (Bronkemoen, Prestegårdskogen, and Sem) the expected annual energy production was slightly increased. Additionally, the peak power capacity of Sem was marginally decreased. Both peak power and expected annual energy production was approximately halved for Barkåker. The final specifications of each individual solar park can be observed in Table 1. The concessions were also used to document strategies deployed, if any, by the developers to reduce the impact on biodiversity from the PV solar parks. While Barkåker park's application for concession was withdrawn, this was done due to local resistance and not ecological concerns. The park was therefore included for the calculations, as it was still a valid representation of potential PV solar parks from an ecological point-of-view.

Table 1: Peak power output and expected annual energy production for the planned PV solar parks.

Solar park	**Peak power [MW]**	**Expected annual prod. [GWh]**	**Source**
Barkåker	15.85	16.384	(Solgrid AS, 2023)
Bronkemoen	10	10.93	(NØK Fornybar AS, 2023)
Buer	1.1	1.2	(NVE, 2022a)
Løvbergsmoen sør	50	50	(ANEO AS, 2023)
Prestegårdskogen	33	35	(Hafslund Magnora Sol, 2023)
Sem	59	62	(Fred. Olsen Renewables, 2023b)
Simonstad	50	50	(Fred. Olsen Renewables, 2023a)

3.1.2 Species distribution maps

The species distribution maps for mammals and birds originated from two different studies. The data regarding birds was derived from a study on life-cycle impacts of wind turbines on birds in Norway (May et al., 2021), whereas the mammals data originated from a study on habitat fragmentation impacts of electricity transmission and distribution lines (Gilad et al., in prep). Both datasets were composed of a single raster for each individual species. The data was geographically limited to mainland Norway, and each pixel in the rasters had the spatial extent of 1 km^2. The value of the pixel represented the probability of the species being present within the area. The datasets included a total of 251 bird species and 28 mammal species, which were sorted into 13 bird groups based on taxonomy and 4 mammal groups based on taxonomy and species functionality respectively (May et al., 2021)(Gilad et al., in prep.).

3.1.3 Birds - collision risk

Collision risk for birds was estimated from data measured in Kosciuch et al. (2020). The article observed a total of 10 PV solar facilities across 13 cite-years in California and Nevada. Seven of the parks were monitored over one year, and three were monitored over two. Notably, the studies included only data from inside the PV facilities, which excluded impacts due to associated infrastructure such as power lines and fences (Kosciuch et al., 2020).

Kosciuch et al. (2020) provide both the total number of carcass detections as well as a figure for "adjusted composition". A carcass might not be detected due to several cases, such as being removed pre-detection by scavengers or strong winds, or missed by the searcher due to human error. The calculation of adjusted composition is displayed in Equation 1. F represents the adjusted total number of fatalities, c is the number of detections, r is the probability of the carcass being available for detection, p represents the probability of detecting an available carcass, and a is the proportion of the PV field surveyed (Kosciuch et al., 2020). In this thesis, the figure for adjusted composition was preferred over total detections, which was disregarded.

$$F = \frac{c}{r * p * a} \tag{1}$$

3.2 Calculation - Loss of Habitat for Mammals

The PV solar power shapefiles from Kenawi et al. (in prep) and the mammal raster maps from Gilad et al. (in prep) were loaded in ArcGIS Pro. The 28 mammal species rasters were sorted into the predetermined categories (Gilad et al., in prep.). The categories were carnivores, rodents, ungulates and "other mammals", and contained 10, 11, four and three species respectively. Aggregated rasters for the four categories were produced with the "raster calculations" tool in ArcGIS Pro. Furthermore, a grid with the exact same geographical extensions as the rasters was created. This was performed with the tools "raster to polygon", notably with the "simplify polygon box" not ticked, and "grid index features" (with specified polygon width and height of one kilometer). With the "tabulate intersection tool", a table was generated displaying all pixels in the grid partially intersected by the planned solar parks, as well as the extend of the intersection in square meters. This table was exported to Excel and expanded by adding the value from the four aggregated mammals rasters in all relevant pixels. By utilising ArcGIS Pro's inbuilt Python notebook, the value of all pixels summarized was produced individually for the four mammal group rasters. The python code can be found in Appendix A.

The PDF due to habitat loss for each category of mammals was calculated for each impacted pixel in the grid. The entirety of the PV parks were considered to be lost habitat for this calculation. Furthermore, the impact was summarized for each of the seven solar parks, which could then be ranked both based on total impact and impact per expected annual energy production. The PDF value for each pixel was calculated following the equation deveolped by May et al., Equation 2. $S_k \cdot P_{k,i}$ is the total number of species in group k, A_{org} is the habitat before alteration, A_{lost} is the habitat lost due to the PV park, and z is the species-area relationship (SAR) slope coefficient. The lower-half SAR slope coefficient was by Storch et al. (2012) found to be 0.26 for mammals in Eurasia (Storch et al., 2012).

$$PDF(H)_{k,w} = \frac{S_k \cdot P_{k,i} \cdot (1 - (\frac{A_{org} - A_{lost}}{A_{org}})^z)}{\Sigma_i^I S_k \cdot P_{k,i}} \tag{2}$$

The average impact of the seven parks was calculated to compare the number with other alternatives of energy production relevant in the Norwegian context. Additionally, the average of all parks but Buer was calculated. Buer, having roughly 10% of the production capacity of the second smallest park, was arguably too small to be considered a large-scale PV solar plant. Consequently, Buer was also an outlier in expected annual electricity production and spatial extent.

3.3 Calculation - Impact from Collision for Birds

The species distribution data for birds originated from a study investigating life cycle impacts from wind turbines on birds, specifically investigating impact from habitat loss, collision, and disturbance (May et al., 2021). The data was loaded in ArcGIS Pro, and the 251 bird species were grouped in the 11 categories. These were the categories specified by May et al. (2021), with the alternation that the categories "herbivorous songbirds, "insectivorous songbirds", "and "polyphagous songbirds" were combined into a single category for songbirds. The final categories were corvids, gallinaceous birds, gulls, owls, raptors, seabirds, songbirds, waders, waterbirds, waterfoul, and "other species". Similar to the calculation performed in section 3.2, the generated table displaying all pixels partially intersected by the planned solar parks was utilized. This could be reused as the spatial extent and geometry of the species distribution maps for mammals and birds were identical. Additionally, the same python script was utilized to calculate the sum of all pixels within the raster of the individual bird groups.

As May et al. (2021) investigated the impact from wind turbines, the equation for calculating impact on birds due to collision had to be altered to reflect that the impact is due to land coverage, not vertical surface area. The impact was quantified as the PDF for each species group in the dataset, i.e., the fraction of the species groups population that is lost due to the impact. This adjusted equation can be observed in Equation 3. $S_k \cdot P_{k,i}$ is the total number of species in group k in the cell, A_{org} is the cell area, A_{pv} is the area of the cell to be within the PV solar park, R_k is probability of annual per-farm collision within group k, and z is the SAR slope coefficient. The lower half SAR slope coefficient of 0.21 found by Storch et al. (2012) for birds in Eurasia was used (Storch et al., 2012).

$$PDF(C)_{k,w} = \frac{S_k \cdot P_{k,i} \cdot (1 - (\frac{A_{org} - R_k \cdot A_{pv}}{A_{org}})^z)}{\Sigma_i^I S_k \cdot P_{k,i}} \tag{3}$$

The probability coefficient for group k, R_K, was found by converting the per-species average mortality rate of the individual farm, $rate_k$, within a group (May et al., 2020). This conversion is shown in Equation 4. $rate_k$ is the average number of mortalities due to collisions for the species within group k, retrieved from Kosciuch et al.(2020). This figure is given in mortalities per MW per year. R_K represents the probability of at least one collision occurring per year, for each species in the local population. R_k is calculated for each bird group and each individual PV solar park.

$$R_k = 1 - e^{-rate_k} \tag{4}$$

Data from an American study on bird mortalities due to collision with utility-scale solar energy (USSE) PV facilities was used to calculate the R_k for each group (Kosciuch et al., 2020). As the composition of species present in the two regions surveyed (Southwestern US and Norway) were quite dissimilar, as well as structural differences in their method of species grouping, a framework was designed to reclassify all species found in the American study to fit with the categorizing in the research by May et al (2021):

1. If a species was present in both studies, its category in May et al. (2021) remained unchanged.
2. If a species from Kosciuch et al. (2020) was not present in May et al. (2021), but another species from the same taxonomic family was, the species was placed in the same category as its taxonomic relative.
3. If a species was within the suborder Passeri, it was placed in **songbirds**, unless the species was part of the corvidae family, in which case it was classified as **corvids**.
4. Apodidae, Caprimulgidae, Columbidae, Cuculidae, Picidae, and Upupidae species were placed in **Other species** as per described in May et al. (2021). Species in the Trochilidae family is closely related to species in the Apodidae family, and were therefore also placed in the **Other species** category.
5. Species in the Stringidae family were placed in the **Owls** category.
6. Species in the Galliformes order were placed in **Gallinaceous birds.**
7. Species in the Podicipediformes were placed in **Waterbirds**. This was supported by pretext from May et al. (2021), with three species in the podiceps family and one in the tachybaptus family.
8. Species in the Pelecaniformes order were placed in **Seabirds**, due to being within the same clade as suliformes, of which there were two species in May et al. (2021).
9. Species in the anatidae family were placed in the **Waterfoul** category.
10. Tyrannidae species and the domesticated chicken were disregarded as there were no similar species in May et al. (2021).
11. Mortalities of birds where species could not be precisely determined were disregarded.

With this method, all the species documented in Kosciuch et al. (2020) were either confirmed in its category, reclassified, or disregarded. The full list of the species present in Koscuich et al. (2020), their status as reclassified, confirmed, or discarded, as well as the reasoning for the sorting can be observed in Supporting Document (S1).

Kosciuch et al. (2020) provided a figure for the "adjusted composition" value for each species. This figure represented what fraction of the total number of collision-related bird fatalities (2.49 mortalities/MW/year) can be attributed to each specific species. Each category was summarized and averaged to find the average mortality rate per MW per year for each species group, which in turn was used to calculate the R_k. Having now obtained the area impacted and number of species present in each species group for all pixels, as well as the risk coefficient for each species group and PV park combination, the impact form collisions could now be calculated.

4 Results

4.1 Habitat loss for mammals

The impact of habitat loss for carnivores, rodents, ungulates, and ”other mammals” can be observed in Table 2. All mammal groups were impacted by habitat loss from each of the planned PV solar parks. Buer was an outlier in these results, being almost a factor of 10 smaller than the second smallest park, Bronkemoen, at 10.92 GWh expected annual production. Buer park had the highest impact per unit of production for all mammal groups, with its impact on rodents being the single largest impact from any park on any species group. The smallest impact per GWh found was from Sem park on carnivores, which was a factor of 12.1 smaller than Buer parks impact on rodents.

Table 2: The impact on mammals due to habitat loss per unit of production. The parks are Barkåker, Bronkemoen, Buer, Løvbergsmoen sør, Prestegårdskogen, Sem, and Simonstad, and the unit is PDF/GWh. Buer* is accented due to being an outlier in size and production, and therefore potentially not representative for future PV solar parks. Barkåker** is also accented, as local resistance led to the withdrawal of the concession application.

Mammal group	Bark.**	Bronk.	Buer*	L. sør	Prest.	Sem	Simon.
Carnivores	7.62E-09	7.59E-09	1.03E-08	8.13E-09	5.27E-09	4.71E-09	6.93E-09
Rodent	4.40E-08	2.95E-08	5.68E-08	2.94E-08	2.33E-08	2.83E-08	2.70E-08
Ungulates	2.78E-08	2.02E-08	3.80E-08	1.97E-08	1.81E-08	1.74E-08	2.97E-08
”Other mammals”	2.87E-08	1.22E-08	3.28E-08	1.12E-08	1.25E-08	1.97E-08	1.61E-08

In general, habitat loss had the greatest impact on rodents, followed by ungulates, ”other mammals”, and ultimately carnivores. Rodents were the most severely impacted species group for all parks except Simonstad, where ungulates instead was the most impacted group. Figure 1 displays the location of the parks, as well as the species distribution raster for the group rodents.

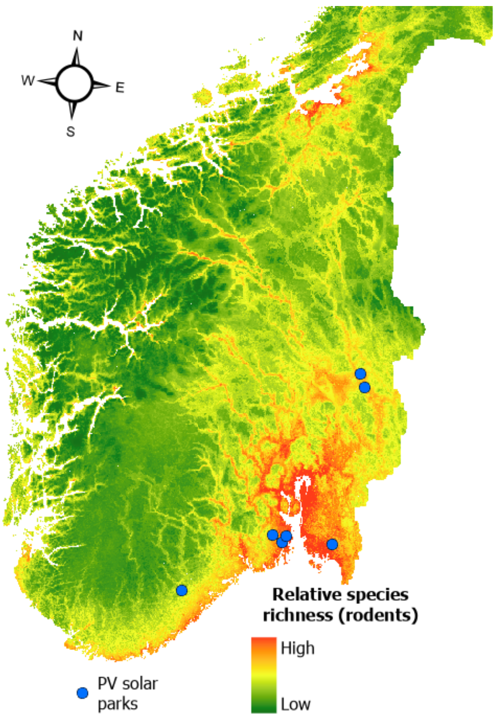


Figure 1: Locations of the seven planned solar parks and the species distribution raster for rodents, which was the mammal group most severely impacted by habitat loss.

Ungulates was the species group with the second highest impact for Løvbergsmoen sør, Bronkemoen, Prestegårdskogen, and Buer. Carnivores was found to be impacted the least by habitat loss for each of the seven parks. The impacts from all parks on all mammal groups are visualized in figure 2.

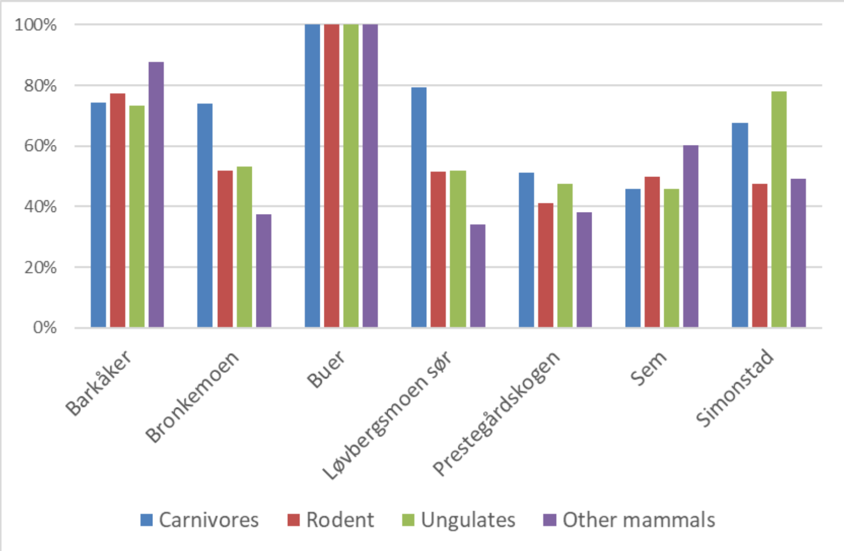


Figure 2: PDF/GWh from habitat loss for each PV park and mammal group. All values are relative to the highest calculated PDF/GWh for that particular group of mammals, e.g., all bars representing impact on carnivores is reflecting the park's value compared to Buer's value for carnivores.

The expected annual production from the planned parks varied from 1.2 GWh (Buer) to 62 GWh (Sem). Table 3 displays the average impact per GWh, as well as the average if Buer were to be excluded due to its difference in characteristics.

Table 3: Average impact from PV solar parks on mammal groups due to habitat loss, per unit of production.

Mammal group	**Average impact [PDF/GWh]**	**Average impact w/o Buer [PDF/GWh]**
Carnivores	7.22E-09	6.71E-09
Rodent	3.41E-08	3.03E-08
Ungulates	2.44E-08	2.22E-08
"Other mammals"	1.90E-08	1.67E-08

The results of Barkåker, Prestegårdskogen and Sem were particularly interesting due to their geographical proximity. The three PV parks were spaced no more than 15 kilometers apart as the crow flies. Nevertheless, the PDF per GWh from habitat loss was substantially greater for Barkåker than the other two, for all four mammal categories. The impact on carnivores for Prestegårdskogen and "other mammals" for Sem were comparable, at 69.2 and 68.5% of Barkåker's values respectively. The PDF per unit of production for "other mammals" due to Prestegårdskogen PV park was as low as 43% of the figure for Barkåker. The location of the parks and the species raster for the "other mammals" group can be observed in Figure 3. Based on the figure, it would be reasonable to assume that Sem park has the highest impact on "other mammals". However, as Sem park had almost four times the expected annual production of Barkåker, the impact per unit of production from Sem was 68.5% of Barkåker's value for the "other mammals" group.

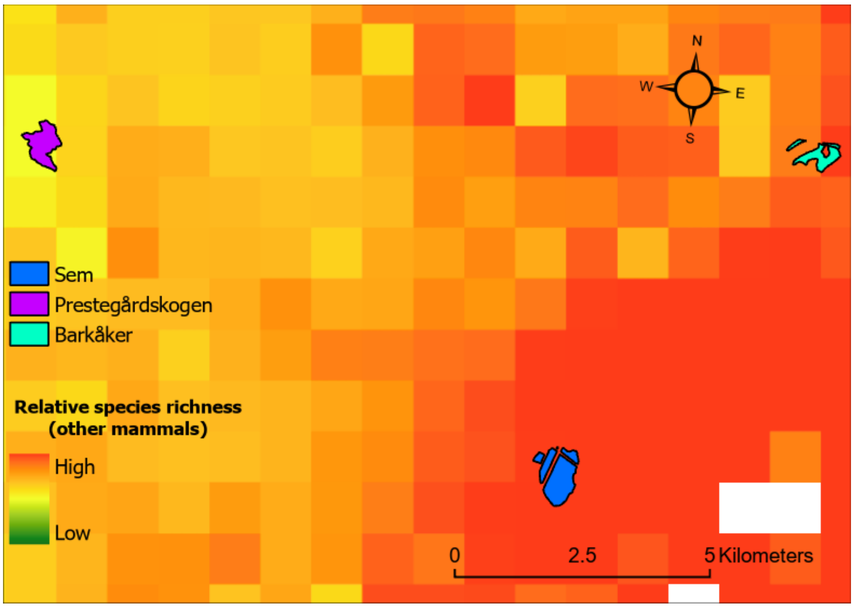


Figure 3: The PV solar parks of Barkåker, Prestegårdskogen, and Sem, as well as the relative species distribution map for the "other mammals" group. Barkåker is located in the north-east, Prestegårdskogen in north-west, and Sem in the south. The white pixels in are cells with NaN-value in the species distribution data.

4.2 Bird group mortality rates and R_k values

As there were no finished PV solar parks in Norway, no figures were available for the collision risk in this region. Therefore, the data had to be retrieved from studies performed in other regions, and then analyzed to identify how the results should be implemented in the Norwegian context. Kosciuch et al. (2020) reported an average figure (adjusted composition, not total detections) of 2.49 bird mortalities per MW per year (Kosciuch et al., 2020). This figure was converted to a group-specific mortality rate, following the species groups defined by May et al. (2021) Table 4 displays the mortality rate for each group of birds, as well as the fraction of the adjusted composition from Kosciuch et al. (2020) attributed to this group. Songbirds were the most impacted group, followed by "other species" and waterbirds. 24.3% of the adjusted composition was disregarded, either due to the species' taxonomy or uncertainty regarding the species of the carcass found.

Table 4: Mortality rates for the bird groups defined by May et al., after reclassifying the species observed by Koscuich et al. (2020). The rates correspond to a fraction of the "adjusted composition" from Koscuich et al. (2020).

Bird group	**Mortalities/MW/year**	**Percentage**
Corvids	4.38E-02	1.8%
Gallinaceous birds	1.32E-02	0.5%
Gulls	9.71E-03	0.4%
Owls	2.37E-02	1.0%
Raptors	2.37E-02	1.0%
Seabirds	1.39E-02	0.6%
Songbirds	1.12E+00	45.1%
Waders	2.24E-03	0.1%
Waterbirds	1.63E-01	6.5%
Waterfoul	2.61E-02	1.1%
"Other species"	4.42E-01	17.8%
Not included	6.06E-01	24.3%

Displayed in table 5R_k, the probability of at least one collision per year for each species within species group k, was calculated for each individual park.

Table 5: R_k, the probability of at least one annual collision for each species in bird group k, for the parks Barkåker, Bronkemoen, Buer, Løvbergsmoen sør, Prestegårdskogen, Sem, and Simonstad. The birds groups are corvids, gallinaceous birds, gulls, owls, raptors, seabirds, songbirds, waders, waterbirds, waterfoul, and "other species". Buer* is accented, as the park is an outlier in terms of size and annual production. Barkåker** is accented as the parks concession application was withdrawn due to local resistance.

Bird group	**Bark.****	**Bronk.**	**Buer***	**L. sør**	**Prest.**	**Sem**	**Simon.**
Corvids	0.293	0.197	0.024	0.666	0.515	0.726	0.666
Galli.	0.099	0.064	0.007	0.281	0.196	0.322	0.281
Gulls	0.143	0.093	0.011	0.385	0.274	0.436	0.385
Owls	0.171	0.112	0.013	0.446	0.323	0.502	0.446
Raptors	0.072	0.046	0.005	0.211	0.145	0.244	0.211
Seabirds	0.054	0.034	0.004	0.160	0.109	0.186	0.160
Songbirds	0.352	0.239	0.030	0.746	0.595	0.801	0.746
Waders	0.035	0.022	0.002	0.106	0.071	0.124	0.106
Waterbirds	0.276	0.184	0.022	0.639	0.489	0.699	0.639
Waterfoul	0.050	0.032	0.004	0.151	0.102	0.175	0.151
"Other sp."	0.583	0.424	0.059	0.937	0.838	0.962	0.937

4.3 Impact on birds due to collision

Collision risk was estimated from data measured in Kosciuch et al. (2020). For most parks, the potentially disappeared fraction due to collision was calculated to be highest for the "other species" group. Sem was the only exception, where the impact on waterbirds was larger. Sem and Simonstad parks had the highest impact on the individual species groups, with the former impacting waterbirds, raptors, gulls, seabirds, waterfoul, and waders the most, whereas the latter had the highest impacts for the groups songbirds, "other species", corvids, owls, and gallinaceous birds. Buer park had the lowest impact per unit of production for all bird groups. Table 6 displays the values for the individual parks and bird group, and a visual comparison is provided in Figure 4.

Table 6: PDF/GWh from each park for the various bird groups due to collision, for the parks Barkåker, Bronkemoen, Buer, Løvbergsmoen sør, Prestegårdskogen, Sem, and Simonstad. Buer* is accented due to being an outlier in regards to capacity (MW), expected annual production (GWh), and size, and averages are produced both including and excluding Buer park. Barkåker** is also accented, as local resistance led to the withdrawal of the concession application. The bird groups are corvids, gallinaceous birds, gulls, owls, raptors, seabirds, songbirds, waders, waterbirds, waterfoul, and "other species".

Bird group	**Bark.****	**Bronk.**	**Buer***	**L. sør**	**Prest.**	**Sem**	**Simon.**
Corvids	9.36E-09	4.53E-09	9.48E-10	1.47E-08	8.74E-09	1.59E-08	1.85E-08
Galli.	1.99E-09	9.66E-10	2.11E-10	4.01E-09	2.35E-09	3.92E-09	5.62E-09
Gulls	5.36E-09	1.92E-09	4.30E-10	7.18E-09	2.78E-09	1.27E-08	6.38E-09
Owls	5.48E-09	2.86E-09	5.60E-10	1.09E-08	5.41E-09	1.09E-08	1.21E-08
Raptors	2.44E-09	9.18E-10	2.24E-10	3.76E-09	2.01E-09	5.44E-09	5.09E-09
Seabirds	1.23E-09	3.23E-10	7.81E-11	1.18E-09	5.66E-10	4.65E-09	1.51E-09
Songbirds	1.15E-08	4.61E-09	1.20E-09	1.39E-08	9.81E-09	1.83E-08	2.16E-08
Waders	1.07E-09	3.52E-10	8.61E-11	1.59E-09	5.98E-10	2.68E-09	1.57E-09
Waterbirds	1.47E-08	4.66E-09	1.38E-09	1.40E-08	6.93E-09	2.80E-08	1.38E-08
Waterfoul	2.32E-09	7.31E-10	1.90E-10	2.86E-09	1.33E-09	5.81E-09	3.37E-09
"Other sp."	2.32E-08	1.01E-08	2.91E-09	2.20E-08	1.87E-08	2.60E-08	3.51E-08

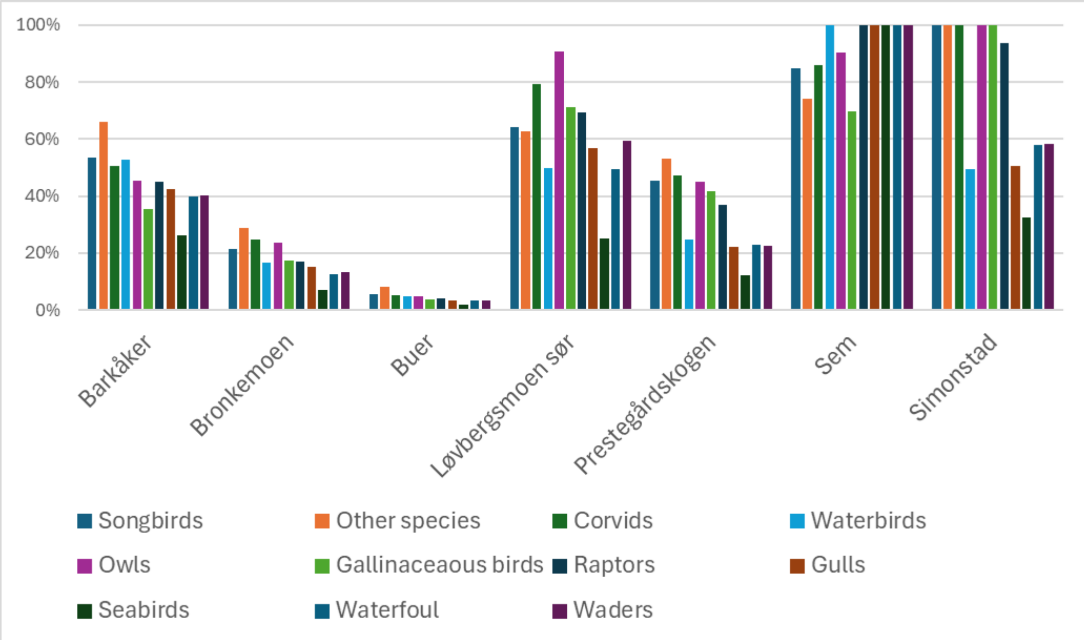


Figure 4: PDF/GWh from collision for each PV park and bird group. All values are relative to the highest calculated PDF/GWh for that particular group of birds, e.g., all bars representing impact on songbirds is reflecting the park's value compared to Simonstad's value for songbirds.

The non-weighted average impact on the various bird species was calculated, and is displayed in Table 7, alongside the average if Buer park would be disregarded. Overall, the "other species" group (including species such as mourning dove and rock pidgeon) was the most impacted, followed by waterbirds and songbirds. The least impacted species groups was waders.

Table 7: Average impact per production unit on birds from PV solar parks due to collision. Averages are provided with and without Buer due to it being an outlier in terms of size and expected annual production.

Bird group	**Average [PDF/GWh]**	**Average w/o Buer [PDF/GWh]**
Corvids	1.04E-08	1.19E-08
Gallinaceous birds	2.72E-09	3.14E-09
Gulls	5.25E-09	6.05E-09
Owls	6.89E-09	7.94E-09
Raptors	2.84E-09	3.28E-09
Seabirds	1.36E-09	1.58E-09
Songbirds	1.15E-08	1.33E-08
Waders	1.14E-09	1.31E-09
Waterbirds	1.19E-08	1.37E-08
Waterfoul	2.37E-09	2.74E-09
"Other species"	1.97E-08	2.25E-08

4.4 Spatial efficiency

As an extension of the solar park data, the production efficiency in terms of area usage was calculated. The least effective park was Simonstad, with an expected annual energy production per area of 43.26 GWh/km^2. Sem was the most efficient, at 107.08 GWh/km^2. Figures for all individual parks, as well as the average with and without Buer park included, can be observed in table 8.

Table 8: Each PV park's spacial extent in km^2, the expected annual energy production and the ratio of production per area usage. Buer* is accented due to being an outlier in terms of size and expected production, and therefore potentially being a worse representation of future PV park installments in Norway. Barkåker** is accented as local resistance led to the withdrawal of the concession application.

Bird group	**Area [km^2]**	**Expected annual prod. [GWh]**	**Spatial efficiency [GWh/km^2]**
Barkåker**	0.252	16.4	64.97
Bronkemoen	0.153	10.9	71.28
Buer*	0.025	1.20	47.90
Løvbergsmoen sør	0.660	50.0	75.78
Prestegårdskogen	0.382	35.0	91.64
Sem	0.579	62.0	107.08
Simonstad	1.156	50.0	43.26
Average	0.458	32.2	71.70
Average w/o Buer	0.530	37.4	75.67

5 Discussion

5.1 Habitat Loss for Mammals

Rodents were the most impacted species group on average, followed by ungulates, "other mammals", and carnivores was the least impacted species group. All of the parks are located in Southern Norway, as well as east of the Scandinavian Mountains. Figure 1 in the results section displays the park locations on a backdrop of the rodents species distribution raster. As is demonstrated by the figure, the park location is of utmost importance regarding the impact of habitat loss for rodents. Obtaining regionalized data with sufficient resolution is therefore key when analyzing the impact from PV parks.

A key assumption in the habitat loss calculations provided in this thesis was that the area of the PV solar parks was rendered entirely uninhabitable for the mammal species. In reality, the picture is more nuanced. Alternative methods exists, such as the countryside SAR which includes the species group's affinity with the impacted area (Martins & Pereira, 2017). Utilising this method might more accurately capture the impact on species that were still able to use the PV solar park as habitat, albeit degraded. However, since most PV solar parks utilize enclosures, the countryside SAR was generally less valid than the traditional SAR method. Of the planned parks in Norway, Barkåker, Bronkemoen, and Prestegårdskogen were planned to be constructed with a fence, which for the former two parks was specified to include a small gap at the bottom or channels to allow the passage of smaller animals (Hafslund Magnora Sol, 2023; NØK Fornybar AS, 2023; Solgrid AS, 2023). Buer, Løvbergsmoen sør, and Sem parks were planned not to have fences, while Simonstad park was undecided (ANEO AS, 2023; Fred. Olsen Renewables, 2023a, 2023b; NVE, 2022a). These decisions were made specifically with the impact on wildlife in mind. Fences were the main reason that the park area would be more habitable for species of smaller stature, but the PV panels also contribute to this through restricting vertical space. The presence of vascular plants can vary from park to park, potentially providing shelter for small mammals.

While outside the scope of this thesis, the loss of habitat will by definition lead to habitat fragmentation. On a global scale, approximately 9% of mammal species loss due to habitat loss and fragmentation is caused by the latter (Kuipers et al., 2021a). The parks also require infrastructure such as power lines and roads. These barriers will have an unequal impact on the various mammals, rendering the area completely inaccessible for some and accessible for others, independent on the species affinity for the PV park area, and further magnify the habitat fragmentation.

Studies on impacts from other energy sources were valuable reference points, especially if performed in recent times and in similar regions. One such study was conducted by Dorber et al. (2018), investigating the land occupation of hydropower reservoirs in Norway. The area inundated by the hydropower reservoirs led to 7 m^2 per MWh (Dorber et al., 2018) land occupation. On average, the direct land occupation from the investigated PV solar parks was 15.3 m^2 per MWh, roughly twice as area-intensive as hydropower. Disregarding Buer, the average land occupation is reduced to 14.3 m^2 per MWh. The study by Dorber et al. (2018) calculated reservoir-specific land occupation, disregarding land occupation from associated infrastructure, and was therefore a particularly applicable point of reference. It is worth noting that the habitat loss from hydropower reservoirs are not final, as the inundated area correlates with the water level. The water level is in turn dependent on factors such as precipitation and energy demand. However, reservoirs are generally steep water bodies, which is unlikely to be suitable as habitat for many species (Dorber et al., 2018). Furthermore, the creation of water reservoirs leads to various impacts in the river course, such as altering water temperature, sediment transportation, species composition, and creates migration barriers. The total impacted area is therefore likely much larger for hydropower.

The results of Barkåker, Prestegårdskogen, and Sem parks highlighted the importance of site selection and spatial efficiency. Species distribution is a product of ecosystems, and a location discrepancy of a few kilometers can result in a substantial divergence in affected species, as well as the magnitude of the impact. Furthermore, the three parks serve as an example of the value of spatial efficiency. As can be observed in Figure 2, Sem park is located in an area with a higher number of species present than Barkåker in the "other mammals" group. However, due to the discrepancy in spatial efficiency, Sem has a lower impact per unit of production for these species. This suggests that selecting sites with a high number of species impacted can be justified, given sufficient improvement in spatial efficiency compared to alternative sites.

In this thesis, the impact of habitat loss was calculated for each individual pixel. The more common approach in ecology is to apply the calculation for the entirety of the connected habitat at the landscape level (Kuipers et al., 2021b; Pereira et al., 2014). The method utilized in this thesis allowed for the calculation to be performed with the species distribution data, but included the simplification that all area within each pixel was of equal value to the species found. In reality, the suitable habitat might cover all of the pixel, or just a slight fraction of it. The parks might interfere with suitable habitat to a varying degree, but this level of detail is not obtained.

For all PV parks, the habitat loss was found to have the least impact per GWh produced on carnivores. The population of larger carnivore species (wolf, wolverine, lynx, and bear) are in Norway specifically managed in predatory game regions (Rovviltnemd, n.d.). The topic of the wolf population is a particularly polarized topic, and a healthy wolf population from an ecological point-of-view is in conflict with the interests of game hunters and farmers (Skogen & Krange, 2020; Ulset & Nordby, 2024). The current population of wolves in Norway is small and suffers from extreme levels of inbreeding (Rovdata, n.d.). As the impact calculation only accounted for current species distribution data, as opposed to suitable habitat, the impact on current population was low, while this population was caused by other human activities.

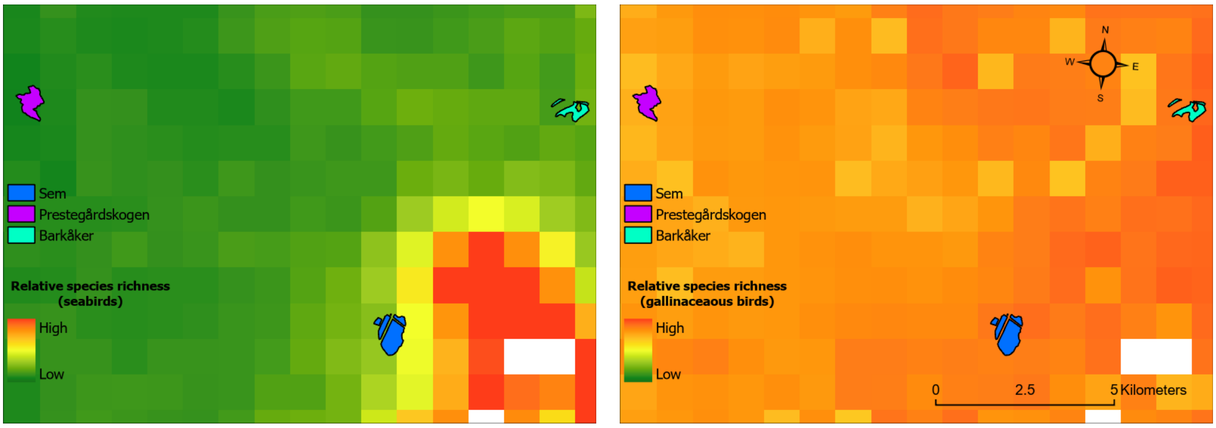
5.2 Impact on Birds due to Collision

Overall, the results highlight a trend where smaller parks had lower impact due to collision per unit of produced electricity. The highest PDF/GWh for each of the 11 bird groups was related to either Sem or Simonstad, who at annual productions of 62 and 50 GWh are the largest by some margin. Similarly, Buer park was by almost a factor of 10 the smallest PV park in terms of peak power and expected annual electricity production, and was the PV park with the least impact from collision per GWh for every group of birds.

Revisiting the three parks in close proximity, Barkåker, Prestegårdskogen, and Sem, the impact of location and regionalized data was highlighted once again. Local discrepancies in species distribution patterns between the bird groups were also present, more so than for mammals. The contrast was the most striking for the bird groups seabirds and "other species", displayed in Figure 5. This stark difference was reflected in the calculated impact per energy production on the two groups. While Sem had the highest PDF/GWh for both bird groups, Prestegårdskogen and Barkåker had an impact per GWh of 60% and 51% respectively for gallinaceous birds. For waders, these relative figures shrunk to 22% and 40%, with Prestegårdskogen then having the lowest impact of the three parks.

A point of particular interest was to compare the results with the findings from May et al. (2021) regarding impact from collision for wind turbines. In this research, it was found that raptors was the species group most severely impacted by collision with the turbines, followed by gulls, and corvids and seabirds (May et al., 2021). The least impacted species group was gallinaceous birds. On the contrary, the species groups "other species", waterbirds and songbirds was found to be most impacted by collision with PV solar parks per unit production. Per unit of production, the impact on each species group was estimated to be more severe from PV solar parks than the values found for wind turbines by May et al (2021). Seabirds had the most comparable results, where the impact per production unit was a factor of 26.2 times larger for PV solar parks. Disregarding Buer, this figure grew to 30.3. The most extreme difference was found for "other species", where the impact was a staggering 533.0 times larger for PV solar power. This figure grew again if Buer is disregarded, to 608.7.

These results indicated that PV solar power installations led to higher impact on birds compared to producing the same amount of energy with wind turbines. However, there were some sources of uncertainty to consider. Firstly, the data regarding collisions per MW per year originated from a different region



(a) (b)

Figure 5: The planned PV parks Bronkemoen, Prestegårdskogen, and Sem, with the rasters seabirds (a) and gallinaceous birds (b) rasters as background. Bronkemoen is located in the northwest, Prestegårdskogen in the northeast, and Sem in the south. Each pixel of the raster is one square kilometer. The white pixels in the southeastern corner are no-data values in the species rasters.

to where it was applied. The relevant biomes of California and Nevada were likely to be different from the impacted ones in southeastern Norway, with a discrepancy in species composition. While the species distribution maps implicitly included most of these factors, the presence of lakes might yield an over- or underestimation of the impacts in the Norwegian context for certain groups. A separate American study of avian mortalities at solar energy facilities theorized that some bird groups misinterpret PV solar facilities as lakes, as groups dependent on lakes were over-represented in the casualities due to collision (Kagan et al., 2014). If PV solar farms are located near important areas for water-dependent birds, this might lead to higher collision rates for these species.

It is also possible that a higher percentage of the actual collisions are detected for the PV solar parks. Wind parks are in Norway significantly larger in size, averaging over 9 km2 per park, and usually located along the coast (NVE, 2022c). Turbine collisions might occur at various elevation levels, and the difficult terrain and proximity to the sea is likely to reduce the fraction of collisions that are detected. The source for collision rates used by May et al. (2021) considers detectability, but the majority of the source's data came from the landscape types forests (36%), agricultural areas (29%), and grassland (14%) (Thaxter et al., 2017). May et al. (2021) might therefore have underestimated the detections lost in the sea due to the turbines coastal locations in Norway.

One could argue that the distance between the locations of the wind turbines examined by May et al. (2021) and the planned PV solar parks presented another issue of regional disparity. The wind turbines were mostly located in the coastal regions of Rogaland, Trøndelag, and Northern Norway, whereas the PV solar parks were all located in southern Norway, east of the Scandinavian Mountains. Both instances were examples of energy production delivering to the same national grid, albeit to differing regional grids, located in the regions with the highest potential energy production for its respective technologies. Future PV solar power and wind turbine installations are likely to be located in the respective areas where they are already present. The comparison was therefore appropriate in terms of investigating the impact from potential future energy sources for the Norwegian electricity grid. The location of the PV parks compared to the wind turbines studied by May et al. (2021) might also party explain the differences in calculated impacts, as southern Norway was richer in species in general (May et al., 2021)(Gilad et al., in prep).

A total of 24.3% of the mortalities due to collision from Koscuich et al. (2020) was disregarded, and therefore not placed in a bird group defined by May et al. (2021). 3.1% was disregarded due to taxonomy, being either *tyrannidae* species or the domesticated chicken, where as the remaining 21.2% was disregarded due to the species not being identified. The full list of species from Koscuich et al. (2020), and the reasoning for the categorization in this thesis, can be found in the supporting document (S1). The identification requirement for inclusion was stringent, necessitating a species-level identification to be included. Therefore, there are examples from Koscuich et al. (2020) such as "unidentified goose" and "unidentified tern" that are disregarded, as well as species with higher levels of taxonomic uncertainty such as "unidentified large bird". The identification requirement was set to be so rigorous to eliminate the risk of re-categorization errors. Including the mortalities of birds which were identified at family or genus level might more accurately reflect reality, however this comes with a risk of wrongfully categorizing the casualities. On the other hand, the rigorous identification requirement might have led to some species not being detected as impacted, as well as an overall underestimation of PV solar power park's impact on birds.

The calculation for the risk coefficient R_k was dependent on data from Kosciuch et al (2020), which yielded a figure of annual mortalities per MW for each species group. It was not the power generated by the PV solar panels that represent a collision risk, but rather the surface area of said panels and other structures such as transformers, power lines, and fences. While only the surface area of the park itself was within the scope of this thesis, basing the impact calculation of annual mortalities per MW instead of annual mortalities per area was likely to be a source of inaccuracy. As displayed in Section 4.4, the GWh/km^2 for the PV parks in this study varied quite a lot, with Sem park generating almost 150% more energy per surface area than Simonstad. Therefore, the impact due to collision calculated in Section 4.3 were likely overestimating the impact generated from the more spatially efficient parks (Sem and Prestegårdskogen), and potentially underestimating the impact from the less spatially efficient ones (Simonstad and Buer). Furthermore, technological advancements in recent years are likely to further reduce the impact per GWh compared to the figures given in Section 4.3. The PV solar parks investigated in California and Nevada were monitored between January 1st 2013 and September 1st 2018, with no park being monitored for more than two years (Kosciuch et al., 2020). PV solar projects commissioned in present times are likely to incorporate more efficient PV panels, due to technological advancements and price reductions both.

The calculation for impact due to collision assumes that species abundance is "relative to the use of area" (May et al., 2020). The adapted equation from May et al., $PDF(C)_{k,w} = \frac{S_k \cdot P_{k,i} \cdot (1-(\frac{A_{org}-R_k \cdot A_{pv}}{A_{org}})^z)}{\Sigma_i^I S_k \cdot P_{k,i}}$, is dependent on R_k, the probability of at least one annual collision for the species within species group k. If the value of R_k approaches 1, as well as the area of the PV solar park A_{PV} completely encompasses one pixel of the species distribution raster, the equation yields a total loss of species abundance within that cell for group k. In other terms, if the probability of at least one annual collision equals one, the area of the solar park leads to a complete loss of species in group k for its area. This is a poor reflection of reality. Depending on the distance between the rows of PV panels, there will be areas within the park's parameter that does not represent a collision risk for the bird species in the area. Furthermore, birds might take advantage of the PV park for foraging, due to PV panels' trait of attracting insects. The threshold of applicable R_k values is unclear. Three parks obtained R_k values above 0.9 for the species group "other species", namely Løvbergsmoen sør, Sem, and Simonstad. Values over 0.7 were obtained for in several instances, namely the group corvids for Sem park, and the songbirds group for the parks Løvbergsmoen sør, Sem, and Simonstad.

The non-trivial number and magnitude of potential errors had consequences for the level of confidence for the results regarding impact on birds due to collision. As the method was consistent across the 11 groups of bird species, the confidence level was high regarding inter-species comparisons, e.g., that the groups "other species" and songbirds were impacted more severely than waders. The level of confidence was lower for comparing different technologies, such as comparing PV solar power with wind turbines.

5.3 Trade-offs between habitat loss for mammals and collision rates for birds

For mammals, higher expected annual production and park size were both negatively correlated with impact due to habitat loss per GWh. The correlation was the most impactful for rodents, and almost negligible for carnivores. For the impact on birds due to collision, the trend is reversed, with all 11 species groups observing higher PDF per GWh produced with increasing annual energy production or park size. Visualizations of these trends are shown in Supporting Documents (S1, S2). These conflicting trends represent a dilemma for decision-makers, as favouring reduced impacts on one group of species leads to increased impacts on the other. The trend was more potent for birds, suggesting that smaller PV solar parks might be preferable overall. However, dividing solar projects in smaller and more numerous parks will lead to increased conflict of interest with other area intensive commercial activities. Fragmentation of PV parks will also lead to an increase in habitat fragmentation and amplify edge effects on the remaining habitat in the area. Scattered PV parks is also likely to have increased infrastructure demands.

5.4 Mitigation Strategies and the Future of PV Solar in Norway

The planned parks have employed some strategies for mitigating impact on biodiversity. Some are changes to the park structure, such as not including fences, reducing the gap between the rows of PV cells to occupy less area, or tailoring the park layout to not impact valuable types of nature (NØK Fornybar AS, 2023; NVE, 2022a; Solgrid AS, 2023). The most ambitious mitigation strategy was to be employed at Sem park, where the developers planned to experiment with peatland resurrection in combination with the PV solar park (Fred. Olsen Renewables, 2023b).

These observations demonstrated that technical modifications to the PV parks to reduce the impact on wildlife was practically feasible, especially when the cost was low and had no meaningful impact on the production capacity of the park. Only the developers of Prestegårdskogen park had not taken wildlife habitat preservation into consideration when designing the borders of the park. However, the developers in general estimated the impact to be ”little to almost negligible” in ecosystems in close proximity to the park. In the case of Bronkemoen, a beech forest engulfed in the park would be spared as it was a particularly valuable nature type. The actual habitat quality of this forest would likely be degraded, due to effects such as habitat fragmentation, edge effects, and disturbance (Fontúrbel et al., 2015; Magrach et al., 2014). Excluding Sem park's experiment with peatland restoration, the developers had uninspiring plans for end-of-life restoration, ranging from reforestation to the very vague statement of ”restoring the area to as close to their original condition as possible” (ANEO AS, 2023; NØK Fornybar AS, 2023; NVE, 2022a; Solgrid AS, 2023). The former often results in the plantation of mono-cultures, while the latter is essentially not promising any active effort to restore the habitat.

The concept of combined area usage, and especially agrivoltaics, should have been explored by multiple of the planned PV solar parks. Buer and Løvbergsmoen sør were both located in the immediate vicinity of agricultural activities (ANEO AS, 2023; NVE, 2022a). Similarly, Barkåker and Prestegårdskogen were located in areas dominated by forests and agricultural land (Hafslund Magnora Sol, 2023; Solgrid AS, 2023). Given the proximity of agricultural practice for these parks, it is likely that some form of agricultural practice would be applicable within the parameter of the PV solar parks. This could materialize as crop production for human consumption or pastures for livestock. PV panels' impact on vascular plants are complicated and conflicting, ranging from improved species richness and biomass to increased plant stress and mortality (Lambert et al., 2022; Liu et al., 2019). Increased soil heterogeneity and altered soil moisture and temperature have also been documented (Armstrong et al., 2016; Graham et al., 2021; Liu et al., 2019; Schindler et al., 2018). Specifically in combination with edible crops for humans, PV solar power was found to negatively impact the early growth of lettuce, durum wheat, and cucumber growth, but not after the plants' juvenile stage (Marrou et al., 2013). Alternatively, the area of the park could be utilized specifically as habitat for pollinators. Insect populations in dramatic decline, and 87 major food crops globally depend on animal pollination (Hallmann et al., 2017; van der Sluijs & Vaage, 2016). The current trend will, if unchecked, have massive consequences for food security on a global level. Urban habitat can be utilized by native pollinators. (Baldock et al., 2015). Furthermore, PV panels can extend bloom timing (Graham et al., 2021), providing resources in times with limited sources of nutrition. Given all of these factors, PV solar parks have the potential to provide valuable habitat for native pollinators.

Incorporating crops or livestock in the PV park area might lead to increased impact from the park on certain species. If seen as a food source, the crops might attract birds, which in turn might experience an increased risk of collision. Protecting the crops from being consumed by animals might require fences without gaps, rendering the park completely inaccessible for small game. The park will then be a complete loss of habitat also for the species that previously could utilise the park area.

PV solar power is rapidly growing in Norway, with a total of 53 applications for concession as of late May 2024 (NVE, n.d.). Moreover, the European Union ruled in April 2024 that solar energy installations must be installed, if technically suitable and economically and functionally feasible, on all new residential buildings by 2030 and all existing public and non-residential buildings larger than 750 m^2 (Directive 2024/1275, 2024). It is therefore very likely that PV solar power will be developed at an accelerating pace in Norway, both integrated in buildings and as PV solar parks.

5.5 Further work

Habitat loss and collision risk are two significant impact pathways, but as previously discussed, there are many more. Extending the scope to incorporate more impact pathways is a natural continuation of the investigation of PV solar parks' impact on biodiversity. Similarly, the impact due to habitat loss and habitat degradation for other groups of species such as insects and amphibians should be examined. A focus shifted towards impact on endangered species would also yield valuable information for decision-makers. Additionally, recalculating the impact on birds due to collision based on mortalities per surface area instead of mortalities per MW might improve the accuracy of the results. This could be done by using the PV parks' average figure for MW per km^2 to convert the annual mortalities per MW to annual mortalities per km^2.

The scope should in the future be expanded beyond the PV park itself. Necessary infrastructure such as transformers, power lines, and road networks also produce an impact, particularly in the form of habitat loss and fragmentation. Similarly, expanding the scope to include impacts from the production of components of the PV park would improve our understanding of the life-cycle impacts from the park. This would preferably also be performed for alternative energy sources in the Norwegian context, such as wind turbines and hydropower. Elaborating further on the topic of PV solar power could also be done by including floating parks. The concept of floating PV solar power is currently in a premature stage, but is being experimented on in the European context (Statkraft, 2023). Concession was given for a pilot project in Norway, but the application was later withdrawn, as the construction was not completed within the deadline (NVE, 2024). Additionally, the impact of incorporating the mitigation strategies described in Section 5.4 should be investigated. The strategies utilised by the parks were not considered in the calculations of this thesis, and the quantification of the impact from other mitigation alternatives would be valuable for future PV park installations.

6 Conclusion

The global population is growing, and with it comes an increased demand for energy. In Europe, the Russian invasion of Ukraine has dramatically changed the policies of European countries, with a greater focus on domestic energy production to achieve energy security and energy sovereignty. Due to recent technological advancements and dramatic price reductions, PV solar power is likely to grow at an accelerating pace globally, in Europe, and in Norway specifically. Given our reliance on ecosystem services provided by biodiversity, it is urgent to investigate the impact on biodiversity from PV solar power. Acquiring this knowledge empowers policymakers in identifying suitable locations for future installments, reducing the impact from already planned projects, and utilising other methods of energy production where this is more favorable.

Two main impact pathways are investigated: habitat loss for mammals, and collision risk for birds. Rodents are the most impacted mammal group by habitat loss, followed by ungulates, "other mammals", and carnivores. The park area is assumed to be inhabitable for all species investigated, but in reality, the park might prove useful habitat for some species, especially for parks without enclosing fences. Building PV solar parks is more area-intensive than reservoirs for hydropower, yielding approximately half the energy output per m^2 of land occupation. However, the creation of reservoirs are more likely to impact surrounding areas and the river downstream. While only the PV parks themselves have been considered for the habitat loss calculations, the impact from habitat loss will inevitably be magnified due to habitat fragmentation, edge effects, and park-related infrastructure.

Regarding bird collisions, the most impacted groups were "other species", waterbirds, and songbirds. Waders were the least impacted group. Compared to a study of impact from wind-turbines in Norway, all bird groups were more severely impacted by PV solar power, ranging from 26.2 to 533.0 times higher PDF per GWh produced. The confidence level is high for the comparison of impact from PV solar parks on the various groups species. However, due to several sources of uncertainty, the comparison with wind turbines should be interpreted with caution.

The importance of accurate, regionalized data was highlighted by discrepancies in impact from neighboring PV solar parks. Additionally, a trade-off between migitating impact on mammals and birds was discovered. Larger parks generally lead to less habitat loss per unit of production for mammals. This was reversed for bird collisions, where the highest impact per GWh was found for the two largest PV parks, and the smallest park had the least impact per GWh by a substantial margin for all bird groups.

A growing PV solar power sector in Norway seems all but inevitable, given the willingness to invest and the external pressure from the European Union. Modelling the impact on biodiversity from PV solar parks is vital to to avoid impacts already in the planning stage. The goal should not be to maximise PV energy production, nor to have the most efficient PV parks possible. The focus should rather be to utilise PV solar parks in the most suitable locations based on production and impacts both, in tandem with other means of energy production. Incorporating ambitious mitigation strategies such as agrovoltaics and habitat restoration might prove critical for PV solar power to compete with alternative energy production.

References

Aklin, M., & Urpelainen, J. (2018). *Renewables : The Politics of a Global Energy Transition*. The MIT Press. https://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=1735466&site=ehost-live&scope=site

Alonso-Marroquin, F., & Qadir, G. (2023). Synergy between Photovoltaic Panels and Green Roofs [Number: 13 Publisher: Multidisciplinary Digital Publishing Institute]. *Energies*, *16*(13), 5184. https://doi.org/10.3390/en16135184

ANEO AS. (2023). Løvbergsmoen sør solkraftverk: Forhåndsmelding og utkast til utredningsprogram. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/7507be20-c337-4922-b200-c5eae1db489a/202311151/3434746

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling [Publisher: IOP Publishing]. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Baldock, K. C. R., Goddard, M. A., Hicks, D. M., Kunin, W. E., Mitschunas, N., Osgathorpe, L. M., Potts, S. G., Robertson, K. M., Scott, A. V., Stone, G. N., Vaughan, I. P., & Memmott, J. (2015). Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects [Publisher: Royal Society]. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1803), 20142849. https://doi.org/10.1098/rspb.2014.2849

Barron-Gafford, G. A., Minor, R. L., Allen, N. A., Cronin, A. D., Brooks, A. E., & Pavao-Zuckerman, M. A. (2016). The photovoltaic heat island effect: Larger solar power plants increase local temperatures. *Scientific Reports*, *6*, 35070. https://doi.org/10.1038/srep35070

Black, T. V., & Robertson, B. A. (2020). How to disguise evolutionary traps created by solar panels. *Journal of Insect Conservation*, *24*(2), 241–247. https://doi.org/10.1007/s10841-019-00191-5

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity [Publisher: Nature Publishing Group]. *Nature*, *486*(7401), 59–67. https://doi.org/10.1038/nature11148

Chandrasekar, M., Senthilkumar, T., & Gopal, P. (2022). Cooling Approaches for Solar PV Panels. In A. Al-Ahmed, Inamuddin, F. A. Al-Sulaiman, & F. Khan (Eds.), *The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions* (pp. 213–234). Springer International Publishing. https://doi.org/10.1007/978-3-030-84635-0_8

Directive 2024/1275. (2024). DIRECTIVE (EU) 2024/1275 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 April 2024 on the energy performance of buildings (recast). https://eur-lex.europa.eu/eli/dir/2024/1275/oj

Dorber, M., May, R., & Verones, F. (2018). Modeling net land occupation of hydropower reservoirs in norway for use in life cycle assessment. *Environmental Science & Technology*, *52*(4), 2375–2384. https://doi.org/10.1021/acs.est.7b05125

Dyke, F. (2008). Biodiversity: Concept, Measurement, and Challenge. In *Conservation Biology: Foundations, Concepts, Applications* (pp. 83–119). Springer Netherlands. https://doi.org/10.1007/978-1-4020-6891-1_4

Fink, C. G., & Adler, E. (1941). THE PHOTOVOLTAIC EFFECT. *Trans. Electrochem. Soc.*, *79*, 367.

Fontúrbel, F. E., Candia, A. B., Malebrán, J., Salazar, D. A., González-Browne, C., & Medel, R. (2015). Meta-analysis of anthropogenic habitat disturbance effects on animal-mediated seed dispersal. *Global Change Biology*, *21*(11), 3951–3960. https://doi.org/10.1111/gcb.13025

Forskrift om konsekvensutredninger. (2017). *Forskrift om konsekvensutredninger* (FOR-2017-06-21-854). Lovdata. https://lovdata.no/dokument/SF/forskrift/2017-06-21-854/%C2%A71#%C2%A71

Fraas, L., & Partain, L. (2010). Solar cells: A brief history and introduction. In *Solar cells and their applications* (pp. 1–15). John Wiley Sons, Ltd. https://doi.org/https://doi.org/10.1002/9780470636886.ch1

Fred. Olsen Renewables. (2023a). Forhåndsmelding simonstad solkraftverk: Åmli kommune, agder. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/fb395645-8b26-4414-8068-76a2caac6897/202303735/3433984

Fred. Olsen Renewables. (2023b). Melding for sem solkraftverk. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/6b5d950a-a774-444a-acbf-12c203b95a2c/202301637/3430959

Graham, M., Ates, S., Melathopoulos, A., Moldenke, A., DeBano, S., Best, L., & Higgins, C. (2021). Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Scientific Reports*, *11*, 7452. https://doi.org/10.1038/s41598-021-86756-4

Hafslund Magnora Sol. (2023). Melding for prestegårdskogen solkraftverk. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/c0cc5ca6-4412-48a6-ab2f-a441f5bfdbe4/202308381/3434748

Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D., & Kroon, H. d. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas [Publisher: Public Library of Science]. *PLOS ONE*, *12*(10), e0185809. https://doi.org/10.1371/journal.pone.0185809

Hofstad, K. (2023, December). Solenergi. Retrieved April 16, 2024, from https://snl.no/solenergi

Horvath, G., Blahó, M., Egri, A., Kriska, G., Seres, I., & Robertson, B. (2010). Reducing the maladaptive attractiveness of solar panels to polarotactic insects. *Conservation biology : the journal of the Society for Conservation Biology*, *24*, 1644–53. https://doi.org/10.1111/j.1523-1739.2010.01518.x

IEA. (2020, June). *Global Energy Review 2019: The latest trends in energy and emissions in 2019*. OECD. https://doi.org/10.1787/90c8c125-en

IEA. (2022). *Renewables 2022* [License: CC BY 4.0]. IEA. https://www.iea.org/reports/renewables-2022

Jones, G., & Bouamane, L. (2012). "Power from Sunshine": A Business History of Solar Energy.

Kagan, R. A., Viner, T. C., Trail, P. W., & Espinoza, E. O. (2014). Avian mortality at solar energy facilities in southern california: A preliminary analysis. *National Fish and Wildlife Forensic Laboratory*, *28*.

Kosciuch, K., Riser-Espinoza, D., Gerringer, M., & Erickson, W. (2020). A summary of bird mortality at photovoltaic utility scale solar facilities in the southwestern u.s. [Publisher: Public Library of Science]. *PLOS ONE*, *15*(4), e0232034. https://doi.org/10.1371/journal.pone.0232034

Kuipers, K. J. J., Hilbers, J. P., Garcia-Ulloa, J., Graae, B. J., May, R., Verones, F., Huijbregts, M. A. J., & Schipper, A. M. (2021a). Habitat fragmentation amplifies threats from habitat loss to mammal diversity across the world's terrestrial ecoregions. *One Earth*, *4*(10), 1505–1513. https://doi.org/10.1016/j.oneear.2021.09.005

Kuipers, K. J. J., May, R., & Verones, F. (2021b). Considering habitat conversion and fragmentation in characterisation factors for land-use impacts on vertebrate species richness. *Science of The Total Environment*, *801*, 149737. https://doi.org/10.1016/j.scitotenv.2021.149737

Lachner, E. (2019). *Solar Power*. Britannica Educational Publishing. Retrieved March 8, 2024, from https://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=1927339&site=ehost-live&scope=site

Lambert, Q., Bischoff, A., Cueff, S., Cluchier, A., & Gros, R. (2021). Effects of solar park construction and solar panels on soil quality, microclimate, CO2 effluxes, and vegetation under a mediterranean climate [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ldr.4101]. *Land Degradation & Development*, *32*(18), 5190–5202. https://doi.org/10.1002/ldr.4101

Lambert, Q., Gros, R., & Bischoff, A. (2022). Ecological restoration of solar park plant communities and the effect of solar panels. *Ecological Engineering*, *182*, 106722. https://doi.org/10.1016/j.ecoleng.2022.106722

Leskova, O. V., Frakes, R. A., & Markwith, S. H. (2022). Impacting habitat connectivity of the endangered florida panther for the transition to utility-scale solar energy. *Journal of Applied Ecology*, *59*(3), 822–834. https://doi.org/https://doi.org/10.1111/1365-2664.14098

Liu, Y., Zhang, R.-Q., Huang, Z., Cheng, Z., López-Vicente, M., Ma, X.-R., & Wu, G.-L. (2019). Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ldr.3408]. *Land Degradation & Development*, *30*(18), 2177–2186. https://doi.org/10.1002/ldr.3408

Mace, G. M., Norris, K., & Fitter, A. H. (2012). Biodiversity and ecosystem services: A multilayered relationship. *Trends in Ecology & Evolution*, *27*(1), 19–26. https://doi.org/10.1016/j.tree.2011.08.006

Magrach, A., Laurance, W. F., Larrinaga, A. R., & Santamaria, L. (2014). Meta-Analysis of the Effects of Forest Fragmentation on Interspecific Interactions. *Conservation Biology*, *28*(5), 1342–1348. https://doi.org/10.1111/cobi.12304

Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., & Wery, J. (2013). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology*, *177*, 117–132. https://doi.org/10.1016/j.agrformet.2013.04.012

Martins, I. S., & Pereira, H. M. (2017). Improving extinction projections across scales and habitats using the countryside species-area relationship [Publisher: Nature Publishing Group]. *Scientific Reports*, *7*(1), 12899. https://doi.org/10.1038/s41598-017-13059-y

May, R., Jackson, C. R., Middel, H., Stokke, B. G., & Verones, F. (2021). Life-cycle impacts of wind energy development on bird diversity in Norway. *Environmental Impact Assessment Review*, *90*, 106635. https://doi.org/10.1016/j.eiar.2021.106635

May, R., Middel, H., Stokke, B. G., Jackson, C., & Verones, F. (2020). Global life-cycle impacts of onshore wind-power plants on bird richness. *Environmental and Sustainability Indicators*, *8*, 100080. https://doi.org/10.1016/j.indic.2020.100080

Miljødirektoratet. (2024). Planlegger utbygging av 4000 km² - Miljødirektoratet. Retrieved May 7, 2024, from https://www.miljodirektoratet.no/aktuelt/nyheter/2024/mai-2024/planlegger-utbygging-av-4000-km/

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. World Resources Institute.

Multiconsult. (2022). *Norsk solkraft 2022 – innenlands og eksport* (Market report). Solenergiklyngen. Retrieved April 29, 2024, from https://www.multiconsult.no/assets/220815-markedsrapport-solenergiklyngen-final-.pdf

NØK Fornybar AS. (2023). Konsesjonssøknad bronkemoen solpark. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/c502130a-361b-4478-87ae-3cd23f0271f9/202305183/3432972

NVE. (n.d.). Konsesjonssaker. Retrieved May 29, 2024, from https://www.nve.no/konsesjon/konsesjonssaker/%22

NVE. (2022a). Bakgrunn for vedtak buer solkraftverk: Sarpsborg kommune i viken fylke. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/681b963b-4ef6-4e5d-b390-ce84f5618239/202119271/3428192

NVE. (2022b, May 5). NVE tildeler den første konsesjonen til et solkraftverk i Norge - NVE. Retrieved December 12, 2023, from https://www.nve.no/nytt-fra-nve/nyheter-konsesjon/nve-tildeler-den-foerste-konsesjonen-til-et-solkraftverk-i-norge/

NVE. (2022c, August 18). *Direkte påvirket areal*. Retrieved June 6, 2024, from https://www.nve.no/energi/energisystem/vindkraft/arealbruk-for-vindkraftverk/direkte-paavirket-areal/

NVE. (2023, August 2). *Oversikt over solkraft i Norge - NVE*. Retrieved November 27, 2023, from https://www.nve.no/energi/energisystem/solkraft/oversikt-over-solkraft-i-norge/

NVE. (2024). Solflyt1 - bortfall av konsesjon. Retrieved May 29, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/94d99ecc-de30-418e-a523-fc7a66384df5/202100867/3438313

Osička, J., & Černoch, F. (2022). European energy politics after Ukraine: The road ahead. *Energy Research & Social Science*, *91*. https://doi.org/10.1016/j.erss.2022.102757

Paul, D. I. (2022). Dust Deposition on Photovoltaic Modules: Its Effects on Performance. In A. Al-Ahmed, Inamuddin, F. A. Al-Sulaiman, & F. Khan (Eds.), *The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions* (pp. 3–46). Springer International Publishing. https://doi.org/10.1007/978-3-030-84635-0_1

Pereira, H. M., Ziv, G., & Miranda, M. (2014). Countryside Species–Area Relationship as a Valid Alternative to the Matrix-Calibrated Species–Area Model. *Conservation Biology*, *28*(3), 874–876. https://doi.org/10.1111/cobi.12289

Rahman, M. M., Hasanuzzaman, M., & Rahim, N. A. (2015). Effects of various parameters on PV-module power and efficiency. *Energy Conversion and Management*, *103*, 348–358. https://doi.org/10.1016/j.enconman.2015.06.067

Ritchie, H., Rodés-Guirao, L., Mathieu, E., Gerber, M., Ortiz-Ospina, E., Hasell, J., & Roser, M. (2023). Population Growth. *Our World in Data*. Retrieved December 7, 2023, from https://ourworldindata.org/population-growth

Roser, M. (2023). Why did renewables become so cheap so fast? *Our World in Data*. Retrieved April 16, 2024, from https://ourworldindata.org/cheap-renewables-growth

Rovdata. (n.d.). Bestandstatus - ulv. Retrieved June 5, 2024, from https://rovdata.no/ulv/bestandsstatus.aspx

Rovviltnemd. (n.d.). Regionale rovviltnemder. Retrieved June 5, 2024, from https://www.rovviltnemnd.no/

Sandlund, O. T., Hindar, K., & Brown, A. H. D. (1992). Conservation of biodiversity for sustainable development. *Norbok*. Retrieved May 6, 2024, from https://urn.nb.no/URN:NBN:no-nb_digibok_2018103007151

Schindler, B. Y., Blaustein, L., Lotan, R., Shalom, H., Kadas, G. J., & Seifan, M. (2018). Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production. *Journal of Environmental Management*, *225*, 288–299. https://doi.org/10.1016/j.jenvman.2018.08.017

Sgrò, C. M., Lowe, A. J., & Hoffmann, A. A. (2011). Building evolutionary resilience for conserving biodiversity under climate change [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1752-4571.2010.00157.x]. *Evolutionary Applications*, *4*(2), 326–337. https://doi.org/10.1111/j.1752-4571.2010.00157.x

Shan, F., Tang, F., Cao, L., & Fang, G. (2014). Comparative simulation analyses on dynamic performances of photovoltaic–thermal solar collectors with different configurations. *Energy Conversion and Management*, *87*, 778–786. https://doi.org/10.1016/j.enconman.2014.07.077

Simensen, T., A'Campo, W., Atakan, A., Heggdal, J. E., Aune-Lundberg, L., Vagnildhaug, A., Kristensen, Ø., & Lindaas, G. O. (2023). *Planlagt utbyggingsareal i Norge. Identifisering av mulig framtidig utbyggingsareal i kommunale arealplaner etter plan- og bygningsloven*. Norsk institutt for naturforskning (NINA). Retrieved May 7, 2024, from https://brage.nina.no/nina-xmlui/handle/11250/3085779

Skogen, K., & Krange, O. (2020). The Political Dimensions of Illegal Wolf Hunting: Anti-Elitism, Lack of Trust in Institutions and Acceptance of Illegal Wolf Killing among Norwegian Hunters. *Sociologia Ruralis*, *60*(3), 551–573. https://doi.org/10.1111/soru.12309

Solgrid AS. (2023). Pv solkraftanlegg - barkåker: Søknad om anleggskonsesjon rev02. Retrieved May 9, 2024, from https://webfileservice.nve.no/API/PublishedFiles/Download/0428318e-24bd-4624-8059-ce8dbbd7f4b8/202306176/3434454

Statkraft. (2023, March 9). Flytende solcelleanlegg i kommersiell drift ved Statkraft-verk i Albania. Retrieved May 29, 2024, from https://www.statkraft.no/Presserom/nyheter-og-pressemeldinger/2023/flytende-solcelleanlegg-i-kommersiell-drift-ved-statkraft-verk-i-albania/

Storch, D., Keil, P., & Jetz, W. (2012). Universal species–area and endemics–area relationships at continental scales [Publisher: Nature Publishing Group]. *Nature*, *488*(7409), 78–81. https://doi.org/10.1038/nature11226

Suuronen, A., Muñoz-Escobar, C., Lensu, A., Kuitunen, M., Guajardo Celis, N., Espinoza Astudillo, P., Ferrú, M., Taucare-Ríos, A., Miranda, M., & Kukkonen, J. V. K. (2017). The influence of solar power plants on microclimatic conditions and the biotic community in chilean desert environments. *Environmental Management*, *60*(4), 630–642. https://doi.org/10.1007/s00267-017-0906-4

Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., Tobias, J. A., Foden, W. B., O'Brien, S., & Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1862), 20170829. https://doi.org/10.1098/rspb.2017.0829

Thompson, I., Mackey, B., McNulty, S., & Mosseler, A. (2009). *Forest resilience, biodiversity, and climate change: A synthesis of the biodiversity/resiliende/stability relationship in forest ecosystems*. Secretariat of the Convention on Biological Diversity.

Tinsley, E., Froidevaux, J. S. P., Zsebők, S., Szabadi, K. L., & Jones, G. (2023). Renewable energies and biodiversity: Impact of ground-mounted solar photovoltaic sites on bat activity [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/1365-2664.14474]. *Journal of Applied Ecology*, *60*(9), 1752–1762. https://doi.org/10.1111/1365-2664.14474

Ulset, J. O., & Nordby, A. (2024). Ga fellingstillatelse på ulv etter funn av død sau på øverbygdskjølen i gausdal. *NRK Innlandet*. Retrieved June 6, 2024, from https://www.nrk.no/innlandet/ga-fellingstillatelse-pa-ulv-etter-funn-av-dod-sau-pa-overbygdskjolen-i-gausdal-1.16903748

Umar, M., Riaz, Y., & Yousaf, I. (2022). Impact of Russian-Ukraine war on clean energy, conventional energy, and metal markets: Evidence from event study approach. *Resources Policy*, *79*. https://doi.org/10.1016/j.resourpol.2022.102966

UNEP. (2009). *Ecosystem management programme* (tech. rep.). United Nations Enironment Programme.

U.S. Bureau of Labor Statistics. (1976, June 1). *Producer price index by industry: Semiconductors and related device manufacturing: Other semiconductor devices, including parts such as chips, wafers, and heat sinks* [FRED, federal reserve bank of st. louis] [Publisher: FRED, Federal Reserve Bank of St. Louis]. Retrieved November 14, 2023, from https://fred.stlouisfed.org/series/PCU334413334413A

U.S. Bureau of Labor Statistics. (1984, December 1). *Producer price index by industry: Semiconductor and other electronic component manufacturing* [FRED, federal reserve bank of st. louis] [Publisher: FRED, Federal Reserve Bank of St. Louis]. Retrieved November 14, 2023, from https://fred.stlouisfed.org/series/PCU3344133441

van der Sluijs, J. P., & Vaage, N. S. (2016). Pollinators and Global Food Security: The Need for Holistic Global Stewardship. *Food Ethics*, *1*(1), 75–91. https://doi.org/10.1007/s41055-016-0003-z

World Bank. (2020). *Global photovoltaic power potential by country*. https://doi.org/10.1596/34102

WWF. (2020). *Living Planet Report 2020 - Bending the curve of biodiversity loss* (Almond, R.E.A, Grooten, M., & Petersen, T., Eds.). https://www.wwf.org.uk/sites/default/files/2020-09/LPR20_Full_report.pdf

Zakeri, B., Paulavets, K., Barreto-Gomez, L., Echeverri, L. G., Pachauri, S., Boza-Kiss, B., Zimm, C., Rogelj, J., Creutzig, F., Ürge-Vorsatz, D., Victor, D. G., Bazilian, M. D., Fritz, S., Gielen, D., McCollum, D. L., Srivastava, L., Hunt, J. D., & Pouya, S. (2022). Pandemic, War, and Global Energy Transitions. *Energies*, *15*(17). https://doi.org/10.3390/en15176114

A Appendix

Python code, summarizing raster pixel values

```
#Import the arcpy site package
import arcpy, numpy

#Your input floating point raster
raster_mammals_other = r"C:\Users\isaka\Documents\2023\Thesis\ArcGis\
    Species_map\Species_map.gdb\mammals_other_categorical_approach"


#Convert the raster to a numpy array
array_mammals_other = arcpy.RasterToNumPyArray(raster_mammals_other,
    nodata_to_value = 0)


#Summarize the array and print the result
print('Sum, mammals_other:', array_mammals_other.sum())
```

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