Establishing Photovoltaics in Sweden

A Critical Analysis of Land Use and Win-Win Scenarios

Master’s thesis in Industrial Ecology

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Cover: Regional power lines over agricultural land, close to Steninge, Halland. ©Author
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Abstract

Access to agricultural land and proximity to the electric grid are two governing factors for establishing Ground-Mounted Photovoltaic (GMPV) parks in Sweden. GMPV can offer locally produced renewable electricity, but can also have negative impacts like mechanical soil compaction, decreased soil organic content, increased erosion and surface runoff, as well as reduced biomass production due to shading. These factors adversely affect soil conditions below GMPV systems. Further, changing agricultural land to GMPV has negatively impacts on food security by reducing food production. To limit these negative impacts, two strategies for multifunctional land use were identified: Agrivoltaics (AV) combining food and electricity generation, and Wetland Photovoltaics (WLPV) combining greenhouse gas mitigation and electricity generation.

This study focuses on Skåne and Halland in southern Sweden, analysing the challenges and opportunities of GMPV establishment. For large-scale GMPV installations (>1 MW installed capacity) the average distance to a regional power line currently is 800 meters, while the average distance to an electrical substation is 1800 meters - highlighting the importance of grid proximity. An economic analysis reveals that GMPV developers are willing to pay much higher land rent than current land rents in agriculture to gain access to arable land close to power lines, and that this surplus land cost could cover the increasing cost for extending power lines to less valuable and cheaper land.

Building on these results, the thesis uses Geographic Information System (GIS) studies to assess land cover within three distance classes from the regional grid: 1.2 km, 2.5 km, and 5 km. Findings show arable land and forestry dominate within all distance classes, but possible constraints significantly limit available arable land, forests, and wetlands. Although limited, the identified areas allow an important solar power expansion, suitable for AV and WLPV, without resorting to highly productive arable land. These areas, ideally identified through farmer-led initiatives with high local acceptance, may enable socially, technically, and economically successful GMPV projects.

Keywords: Photovoltaics, PV, GMPV, organic agricultural soils, GIS, land use, agriculture, food production

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Oskar Belzons Berthelemot, May 2024

Table of content

1. Introduction

1.1 Background

The phasing out of fossil fuel in the energy and industrial sector is a top priority in Sweden (Wallén, 2021). Solar power, i.e., photovoltaics (PV) is seen as one interesting technology for a rapid energy transition (Cherp et al, 2021). In southern Sweden there is a strong interest for establishing large-scale Ground-Mounted Photovoltaics (GMPV) installations on agricultural land, which leads to a conflict of interests as continued food production and food security are of vital societal concern (Björnsson et al., 2022; Schindele et al. 2020). Therefore, agricultural land in Sweden and particularly in the southern parts, face a pressure from a new actor, adding to an existing demand from an expanding urban area (Ljungström and Svensson, 2021). Declining numbers of both active farmers and productive land areal, not unrelated to profitability issues, combined with the previous factors further illuminates the importance of addressing this competition on land.

In a survey of GMPV developers in Sweden 2021, two governing factors of design and localisation were identified: proximity to electrical grid and cost/rent of land (Björnsson et al., 2022). Firstly, any new solar park needs to be connected to and transfer electricity to end users by the regional power lines, so distance-to-grid of a plot is decisive for minimising development costs. While the carrying capacity of power lines is seen as a potential bottle-neck of GMPV development, building more power lines to increase it is a key part of the transition towards a renewable energy system in southern Sweden. Because of this, a lot of investments is allocated for increasing it (E.ON, personal comm., mars 2024). Secondly, cost/rent of land is currently a question of the price that developers are willing to pay for the land. However, arable land in Sweden is protected by the environmental law. The protection consists of a legal status as of *National Interest* and can only be claimed in the interest of *Essential Societal Functions*, functions which cannot be achieved on any other land (SOU 2024:8, 2024). Up until now, the legal status has proven to hinder construction permits of solar parks, but recent development show it is likely that some arable land will be needed to fulfil other essential societal interests (County Administrative Board of Halland, 2024a). An land efficient way of proceeding consists of focusing on multi-functional uses of land, which could help minimise competing interests. But, any suggestions of specific plots outside the governing factors of Björnsson et al. (2022) need to be based on an understanding of the economic implications of this change in design and location.

In an example of multi-functional use of land, Agrivoltaics (AV) shows potential to help the agricultural sector adapt to climate change. By integrating food and energy production on the same plot, that is a delimited area of land characterised by constant (legal) owner conditions, competition on land can be limited (Schindele et al., 2020). Further arguing for the case of AV is the limited available land, on which different societal interests are forced to compete (Trommsdorff et al., 2022). The land designated for AV deployment imposes different set of challenges and possibilities, both from an economic and environmental perspective.

Agricultural organic soils, that is carbon-rich soils drained during the famines of the 19th century, represent a major source of GHG emissions in Sweden. The soils are rich in organic carbon, which built up as dead biomass accumulated in the waterlogged soil before drainage. The subsequent ditching increased available oxygen and thus the decomposition of carbon, today representing a third of the total emissions from agriculture. Despite representing a minor part of Sweden´s arable land (140 000 ha out of 2.5 Mha), the organic arable soils are estimated to emit 3.2 Mton CO2e/yr. Based on current understanding the most effective method to significantly reduce greenhouse gas emissions from agricultural organic soils is to restore them to wetlands (Swedish Board of Agriculture, 2018). Current estimates from the Swedish Board of Agriculture (SBA) on nutrient-rich organic arable land in south Sweden, are that yearly emissions can be reduced by 21 tons of CO_2e/ha when this land is re-wetted. However, re-wetting of agricultural land is associated with decreased profitability, as re-wetted land cannot be used for production (Swedish Environmental Protection Agency, 2023b). An interesting multi-functional scenario consists of establishing PVs on the re-wetted agricultural land, which would allow simultaneously harvesting solar power and reducing the agricultural sectors GHG emission, while conserving other high-yielding land for food production.

1.2 Aim and research questions

This thesis project aims to investigate land use impacts, technical implications, and economic consequences of establishing GMPV on various land covers, and to analyse and identify potential win-win scenarios that leads to multifunctional land use. To do so this thesis tries to answer the following research questions:

- Where are built, large-scale GMPV (>1 MW) located in relation to the regional grid and what technological features characterises them?
- Which land cover and uses exist within relevant distances to regional grid?
- What consequences does various land cover and distances have on GMPV electricity costs?
- What challenges and possibilities are associated with GMPV on various land covers and usages?

1.3 Limitations

The study focuses on an area limited to the region of Skåne and Halland in southern Sweden. While GMPV have been established in most Swedish regions, the region of Skåne and Halland are highly relevant for two reasons: first, they correlate roughly with electricity market area SE4 which have had very fluctuating electricity prices in the last years, attracting a large interest from GMPV developers to establish specifically in the region. Secondly, the solar irradiation decreases in intensity with the distance to the equator, so the most southern parts of Sweden are of high interest for GMPV establishment. Further arguing can be made by the large amount of applications for the establishment of new GMPV in the region (County Administrative Board of Halland, 2024).

Impacts of land use on biodiversity was not considered in the study due to time restraints. It rests however an important aspect given the interest of establishing GMPV on agricultural land, and its potential implications for nature conservation and restoration targets.

The only forest considered suitable for establishment of GMPV was assumed to be readily available forest. This was considered to be final felled forest in the last three years, or to be notified for clear-felling in the coming three years. As an interest in establishing GMPV on forest cleared specifically for such establishment have been identified, an analysis of such a case would be highly relevant for the case of Swedish solar power. However, it was not included in this study due to time constraints, and neither was costs associated with establishment on felled forest land. A penultimate stage of this study is intended to cover the aspect more in detail.

2. Background

2.1 Techno-economics of Solar Power Development

Technology and economics have large implications for the historical and future development of solar power in Sweden. Generally, the term regional power line is used when referencing to effects related to a specific power line, and regional grid when referencing to more system wide effects.

2.1.1 History and future direction of solar power

Photovoltaics PVs in Sweden consisted of up until early 2000s of off-the-shelf, small scale power solutions for stand-alone systems, used for example as power supply in boats or holiday houses (Lindahl & Stoltz, 2017). Starting from 2007, off-grid capacity was surpassed by grid-connected, including the emergence of ground mounted photovoltaic GMPV parks, which has growing in both installed capacity and absolute numbers since (Lindahl & Stoltz, 2017; Björnsson et al., 2022). In southern Sweden, growth of GMPV have been exponential (Roos, C., 2024). This is especially true in Halland and Skåne, where permit applications have sky-rocketed (CAB, 2024a). In the early phase of Swedish PV industry, domestic research failed to materialise onto the market and the subsequent market that did develop, is based on imported goods (Andersson et al., 2021). The authors notes that "strategic policy interventions" have been absent during the development, which could be one explanation to the current situation of dependence on imported goods.

Future growth of the sector is expected and based on different scenarios of energy consumption in Sweden, within their long-term market analysis Svenska Kraftnät (SVK) (SVK 2021) have developed four scenarios with different compositions of energy sources to meet the demand. In line with the Swedish government's ambitions of revamping nuclear power, the scenarios were revised in 2024 (SvK, 2024). The scenarios include electricity demand spanning Business-As-Usual to a sharp increase, and high to low levels of investments in and on expansion of PV. The scenario pathways are visualised in figure 2.1, and can serve as a basis for relating potential electricity generation originating from GMPV throughout this thesis. An average pathway of all scenarios has been added and included in the chart.

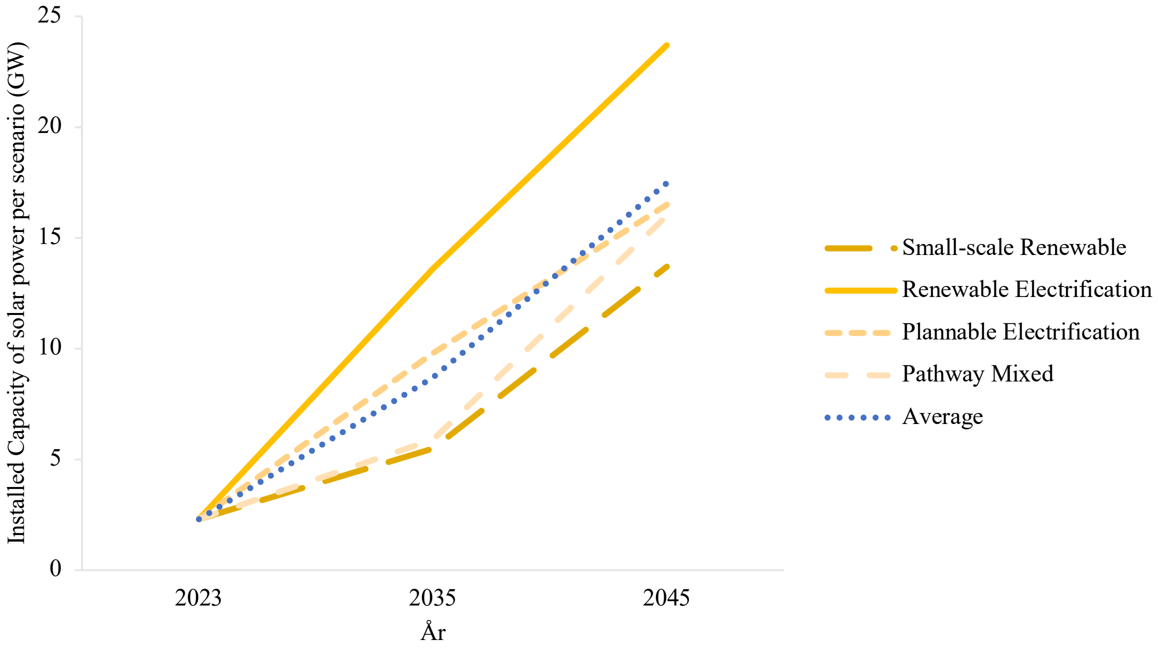


Figure 2.1
Pathways of installed solar capacity (MW) for four scenarios, based on long-term market analysis (data from SvK, 2021, figure, author's own).

As can be seen in Figure 2.1, a first target of roughly five GW of installed capacity is envisioned in all scenarios, a point from which the scenarios develop different. In the final year of the scenarios, 2045 solar power ranges from 12-23 GW of installed capacity. Skåne Capacity Commission, a coalition of energy actors within the region, initiated by Skåne region, has established a thorough energy pathway analysis in which two GW of solar power is expected as of 2030 in Skåne alone, combining roof-top PV and GMPV (Skåne Capacity Commission, 2023). Above 2 GW installed capacity, which roughly correlates with peak demand in the region during summer, solar electricity generation is believed to cross a threshold were PV profitability is voided due to negative or zero electricity prices during summer.

Energy density vary amongst GMPV systems. Bolinger and Bolinger (2022) used satellite data and GIS modelling to determine power and energy density of utility-scale GMPV built in the United States since 2019, The authors were able to propose updated figures and show a relationship between power potential and latitude, both for fixed-tilt and tracking panels. By extrapolating the results to latitudes corresponding to Sweden, an expected power density of 1.9 ha / MW for fixed tilt and 1.8 ha / MW for tracking panels can be calculated. These estimations are well in line with the current Swedish large-scale (>1 MW) fleet, which's average is 1,84 ha / MW (County Administrative Boards, 2023). Figure 2.5 shows land requirements for PV development according to SVK's scenarios, assuming an average power density as today and that all solar power demand is met with similar PV based technology.

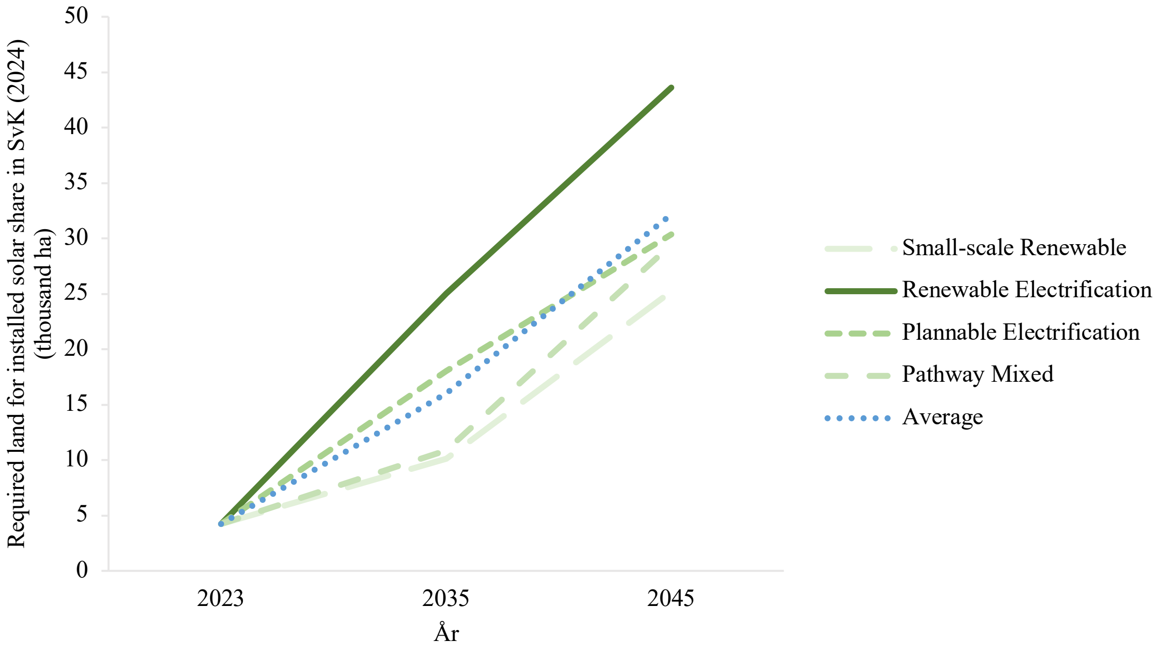


Figure 2.5
Associated land requirement with yearly development of installed solar capacity (ha) between four scenarios (data from SvK, 2021, County Administrative Boards, 2023, figure, author's own).

2.1.2 Regional grid carrying capacity - bottleneck and key criteria

A governing factor of GMPV design and establishment is the proximity to grid (Björnsson et al., 2022), but the grid have different characteristics depending on technical and geographic conditions. The regional power grid is one of three components of the Swedish electricity grid, tasked with connecting the transmissional grid (producers) with the local grid (end consumers). The Swedish electricity grid can be divided into two levels, the Transmissional (400,220kV) and distributional grid, the latter divided into Regional (50 or 130 kV), and local grid (>40kV). The transmissional grid is owned and operated by the transmission system operator (TSO), SVK (state owned) in the case of Sweden. The regional is divided between three distribution system operators (DSOs): Vattenfall, Ellevio and E.ON, while the local net is owned and operated by many local DSOs. Large power plants, such as nuclear or large hydro plants are commonly connected directly to the transmissional grid. Renewables, such as wind and GMPV however, are mostly connected to the regional grid. In Halland and Skåne, the regional grid operates at both 130 and 50 kV depending on location, the local grid is a mix of 10 and 20 kV (Erkander, 2018). Existing substations connected to the local and regional grid are assumed either rated at a capacity of 40 or 63 MVA, which is crucial for what size of PV park that in theory can be connected to the substation (1 MW = 1 MVA). However, in reality transformers are often of lower capacity than 40 MVA, especially in less urban areas and are dependent on local grid characteristics. All these elements combined makes generalities very hard to make. (Pettersson, T, E.ON, personal communication, mars 2024).

An electrical grid is made up of an assembly of power lines, each with a specific carrying capacity, i.e., the maximum amount of current the specific cable can transport. Growth of end user demand and installed renewable capacity have put the regional grid under pressure, with many regional power lines being close to maximum carrying capacity. However, from the DSO's perspective this is not black and white. While building new power lines is the ultimate solution, other alternatives are available during build-out time, such as electricity demand management and other flexibility solutions (Roos, 2024).

Specific carrying capacity for each line within the regional grid is not publicly available information. Instead, to know whether a connection is possible or not, and what power could be supplied, a producer must contact the operator for the concerned power line and make a formal inquiry. GMPV developers use a large scope inquiry method (OX2, 2023; LC energi, 2023; Ilmatar Solar 2023), consisting of localising what the company internally decides are potential plots, and then systematically making inquiries to concerned DSO of closest power line. Work to meet future demand is ongoing at high pace, and in some areas the possibility to meet growing demands and new installed capacity are good, while in other they are dependent on reinforcements (of capacity) from the TSO (Pettersson, T, E.ON, personal communication, mars 2024, Roos, 2024). Further, in Halland a major investigation is currently underway, were TSO and DSO are evaluating the current grid and future needs. Any reinforcements would "take height" to be in line with future projection. One major challenge that the company face is that applications for new connections have sky-rocketed, leading to a high number of applications on hold with a limited workforce.

PV modules cannot be connected directly to the power line. The connection instead occurs at a substation, where a collection of electric infrastructure undertakes diverse action, such as transforming mid voltage to low (and vice-versa) to connect the regional to the local grid. For GMPV developers, space at the busbar ("slot" for connecting) is of high relevance as it is where the in-current to the grid is fed. If no space is available, the busbar must be built out to incorporate the connection, which can be a relatively simple operation (installing a bigger busbar) or impossible (busbar is neighbouring a rock), with corresponding financial implications. In the case of the construction of a new sub substation, it is unclear how this cost would be split between grid operators and GMPV developers. It is clear however that any new substation is a major financial investment and no examples of established GMPV with a dedicated new substation have been found within the context of this thesis.

2.1.3 Current GMPV characteristics

Currently, GMPV is the only used solar technology in Sweden considering large-scale, electricity generation plants. The characteristics of all Swedish GMPVs combined, as of 2021, have been summarised in table 2.1 (Björnsson et al., 2022). The report uses a survey for GMPV developers with GIS data and concludes that arable land is most frequently used for establishment. One potential explanation noted is the large continuous plots (i.e. field size) with high solar irradiation (i.e., no shadows), considering that such continuous plots of similar size except on arable land are rare in Sweden. Due to the large continuous plots, acquisition of arable land for GMPV is of low complexity, as often only one landowner is involved. Panel inclination, row width and distance between rows adapted for maximum electrical efficiency (low distance between rows, around 30° inclination and large rows), and proximity to power line (grid) are key criteria for half of the assessed GMPV. While mentioning that measures on biodiversity have been undertaken, the report does not study what measures are undertaken, leaving a knowledge gap. Some of this gap is filled by Ljungström and Hörnelius (2023) who report that most common practices for biodiversity in Sweden are *"avoiding areas with high biodiversity"* and *"minimizing measures such as leaving vegetation and sensitive micro habitats within the park"*. The reports indicates that the Swedish GMPV fleet have been designed with energy optimisation in mind, striving for a maximum of fully exposed panels per unit of land, with low or no consideration of biodiversity or agricultural activity, as close as possible to existing power lines. Proximity to a power line of the regional grid is an ultimate criterion for many developers when identifying potential land, but initially a range of 1-5 km is typically used in project planning by developers, when asked by regional authorities to assess alternative locations, before claiming agricultural land (OX2, 2023; LC Energi, 2023; Ilmatar Solar 2023).

Table 2.1
Technological characteristics of Swedish GMPV >1MW installed capacity based on survey by Björnsson et al. (2022). The percentage (%) indicates the proportion of respondents who answered "yes" to the consideration of specific characteristics.

Consideration	Governing factors of design and localisation	Additional features	Panel inclination	Row width	Distance between rows
High (> 50%)	Cost of land (55%) Proximity to grid (50%)	Measures for biodiversity (50%)			
Average (50-30%)	Locals' acceptance (30%)	Livestock (25%)	30° (35%) > 30° (30%)	3-4m (45%) < 3m (35%)	> 4m (30%) 3-4m (30%)
Low (< 30%)	Regard to valuable arable land (20%) Regard to nature values (20%) Increased profit for landowner (10%)	No additional features (25%) Cultivation (10%)	20° (20%) 25° (7.5%) 15° (7.5%)	> 4m (20%)	< 3m (25%) n.d. (15%)

To complement statistical data presented above, assessed planning reports from a selection of actors shows a technology trend of ground-mounted, fixed axle PV modules, supported by a metallic structure which have been anchored in the ground with beams, descending 1-3 m into the soil (OX2, 2023; LC energi, 2023, Ilmatar Solar 2023). A schematic representation of a typical fixed axle GMPV module can be seen in figure 2.2. Mentioned future potential technological developments includes solar-tracking PVs that can rotate around one or two dimensions, to improve electrical efficiency (LC Energi, 2023).

A general view on the construction phase, with the metallic support structure visible, as well as a pilling rig in action can be seen in figure 2.3.

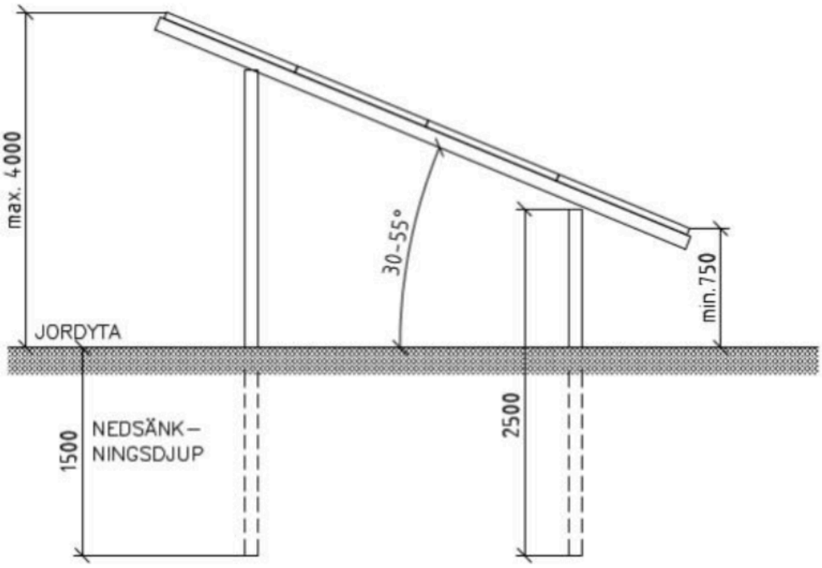


Figure 2.2
Schematic representation of typical ground mounted PV module (Ilmatar Solar, 2023). Variations include support structures with one pile, and "portrait" positioning of two modules instead of "landscape" of four as in figure.

Depending on the installed capacity of the GMPV, plot characteristics, and specification of local electricity infrastructure, different components of electrical infrastructure is needed, ranging from electrical substations(s) (LC Energi, 2023) to complete switchgear for high voltage grid connection (OX2, 2023).

Figure 2.3
Imagery illustrating installation of a typical GMPV in Sjöbo, southern Sweden (OX2, 2023).

On plot level, the GMPV layout can vary. Three categories of GMPV based on layout and design was identified in the grey literature (i.e. not formally published literature) mainly corresponding to planning reports and work permit applications (Swedish: "samrådsunderlag", "planeringsunderlag"), provided by GMPV developers. The three categories are referred to in this thesis project as: "close to existing electrical infrastructure", "new electrical infrastructure" and "high-capacity new infrastructure" and general technical characteristics are found in table 2, and a visualisation in figure 2.4. The three different categories differ as they can include or not a new substation, can be at a varying distance to power lines. Any new substation can be either operating at low or high voltage and is of high or low capacity (over/under 63 MVA). In theory connections at any voltage level is possible, with the use of a corresponding transformer, shown by dashed line from alternative transformer in figure 2.4. This study however is limited to the first category, close to existing electrical infrastructure.

Table 2.2
Three categories of GMPV in relation to electrical infrastructure

Category	Distance GMPV-regional grid	Substation (local/regional grid)	Capacity of substation	Voltage of new power line
Close to existing electrical infrastructure	Short/long	Existing	<63 MVA	Low
New electrical infrastructure	Short/long	New	<63 MVA	Low
High-capacity new electrical infrastructure	Short/long	New, high capacity	>63 MVA	Low/mid

Suggestions for real world examples, based on estimations from remote observations (i.e., satellite imagery) can be seen in appendix I, but should not be taken for concrete examples as construction sequences and ownership have not been confirmed with either developers or DSO.

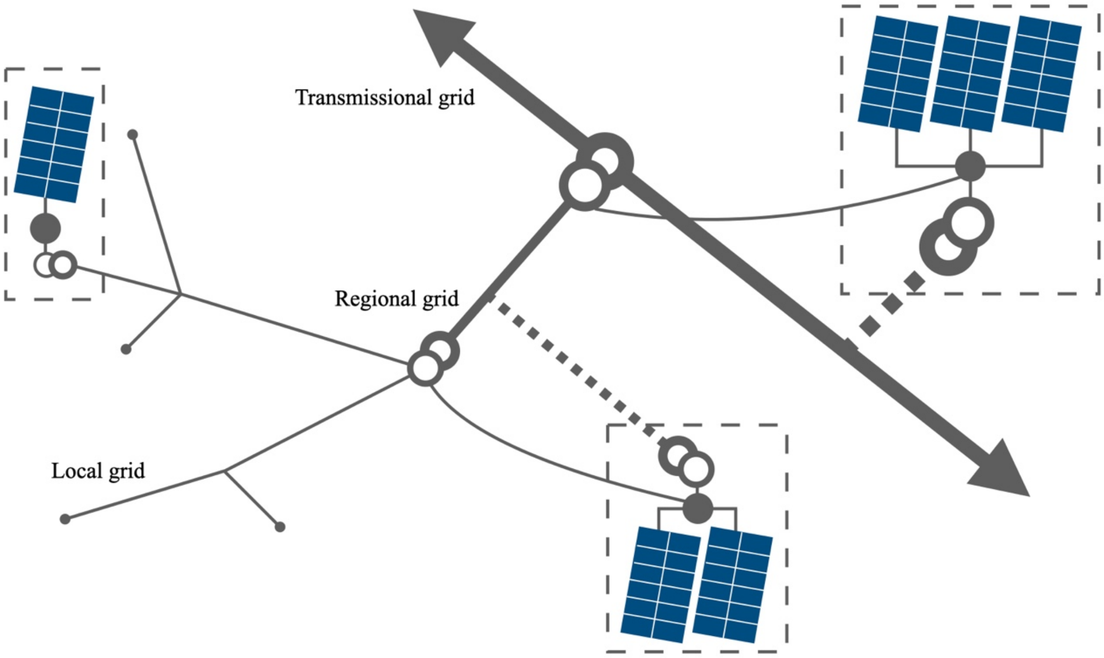


Figure 2.4
Three categories of GMPV depending on grid characteristics. Lines represent power lines at different voltages (transmissional high, regional mid and local low voltage). GMPV differs as transformer (two overlapping circles) for grid connection can be either new within the plot (dashed rectangle) or existing, with connection by a low voltage power line (dashed line). The distance relevant in this thesis is labelled "assessed distance". Note that cases of transformer within plot is not part of the scope of the thesis.

All three GMPV categories shares the basic electric components: arrays with groups of PV modules mounted on structure, cables, collector(s) and inverter(s) that collects DC electricity from the individual PV arrays and transform it to AC, and a transformer on the plot that brings voltage up to that of the connection point. In a final step, the GMPV is connected to the grid with a new power cable, either 12 or 24 kV depending on local grid characteristics, at an existing substation where the voltage is increased to mid voltage and distributed to the grid.

2.1.4 Economic preconditions

The Levelized cost of Electricity (LCOE) is a common way to calculate the cost of a specific energy producer measured in cost per provided energy (such as SEK / kWh or € / MWh). It is done by dividing the present value of discounted revenue with the present value of discounted costs, or put in another way, what price is needed to precisely cover costs associated with a power plant (Lindhal, 2021). By relating present value of discounted revenues and costs, the method provides a way to compare energy costs from plants of varying size, lifetime, energy source and financing. Key criteria of LCOE consists of investment costs (Capital expenditure CAPEX), yearly depreciation, lifetime, costs for operations and management (Operational Expenditure OPEX), reinvestments at a specific year and costs on capital. In the case of six new GMPV in Sweden, high initial investment costs compared to low later operational costs means that the financing model of the GMPV is of high importance for the final cost per energy (Nilsson, 2021). Other key parameters are cost for land and capacity(CAPEX), while net tariffs were a driver of OPEX. Further, the same author shows that the LCOE of large scale GMPV in Sweden, with an installed capacity in the range of 3 to 20 MW, is on an average 43 öre per kWh (roughly 43 € per MWh) with a low estimate of 29 and a high of 52 öre per kWh. The yearly electricity price in southern Sweden was during the period 2020 – 2024 on average 100 öre per kWh, with 1% difference between the summer and winter months (Vattenfall, 2024).

Lindhal (2021) proposes a range of 3-25 thousand kr per MW for typical rent of land (in Swedish “arrende”), paid by the GMPV owner to the landowner, with an average of 7240 kr per MW. However, different owner structures can motivate different financial models, and thus influence the price of yearly land payments. For example, if the same company owns both the land and the GMPV a low yearly payment could increase profit at park level, while a high yearly land payment would increase landowner profitability. The effect of high rent paid by developers to secure access to land is also reflected in the literature. Land rents of arable land for GMPV up to 5-10 times higher than that of equal land rent for agricultural practice have been mentioned (Dupraz, 2023a). To complete the data given by the authors, table 3.2, shows the economic conditions for landowner before the introduction of GMPV on arable land. It should be noted that the category forest does not include a rent but a purchasing price, as renting forestry currently is not in practice.

Table 2.3
Yearly land payments in kronor per hectare (SEK / ha). Production area 1 roughly corresponds to arable land in Halland and Skåne country. Arable land, high rent corresponds to the price paid by some GMPV developers (Lindahl, 2021, Dupraz, 2023a) to secure access to specific land. Area 1 corresponds to region of Halland, Skåne and Blekinge.

Land type	**Use**	**Purchase price (SEK / ha)**	**Rent (SEK / ha)**	**Year**	**Geographical limit of average**	**Source**
Arable land	Agricultural practices	n/a	4006	2022	Production area 1	SBA (2023a)
Arable land	GMPV	n/a	25 000	2024	-	Lindhal (2021), Dupraz (2023a)
Pasture	Agricultural practices	n/a	669	2022	Sweden	SBA (2023b)
Forest	Forestry	150 000	n/a	2023	Area 1	Ludvig & co (2024)

2.2 Challenges When Using Arable Land for GMPV

Agricultural land is a finite resource. Any actions on arable land taken without adequate protective measures might leave permanent damages on and in the soil, leaving coming generations with less productive land.

2.2.1 Soil quality impacts

The main disturbance of soil during the GMPV life cycle occurs in the construction phase, which can negatively affect agricultural land quality, and can take years to or never fully recover (Welsh Government, 2023). A recent UK report reports possible consequences of GMPV, and a focus is on the beams, driven down to 1-1.5 meters depth in the soil at a regular interval. The beams are used at a frequency of roughly 450 beams per ha, and compacts the soil both under the beam, around the beam and under the machinery that drives down the beams. Examples from Sweden (*Solinarum* in the Gothenburg area) shows a slightly lower figure, around 400 (Göteborgs Energi, 2024). The UK report notes that depending on preconditions of the soil as well as weather during installation phase, the impacts are low to high and compaction of soil to depths up to 45 cm have been observed. Thus, careful planning with respect to site-specific conditions is essential for achieving reversibility as the change would have negative implications for future use as arable land. Further, disturbances caused by the panels, combined with the lower density of plants below the panels is reported as a potential driver of erosion. Such disturbances include so-called “rivulets”, a trace created by water dripping down from the gaps between PV modules, which over time may create a “channel” formed below the array. This effect may both increase erosion by waterflow in the “channel”, as well as increasing overall runoff from the land due to the stratified rivulets of the land. An example of rivulets can be seen in figure 2.6.

Figure 2.6
Example of rivulets created after 12 operational months under an array of PV modules (Welsh Government, 2023).

An increased of soil organic carbon (SOC) in the topsoil can be expected with the conversion of arable land to grassland, but, these changes in SOC are only permanent if the conversion of land is permanent. Any increase of SOC is quickly lost in the case of grassland converted back to arable land (Welsh Government, 2023). However, when considering shading and the micro-climatic effects of a GMPV system, the increase of organic matter associated with land use change to grassland is significantly limited under the PV modules (Moscatelli et al., 2022). This thus limits the effect of increased soil carbon contents to the area between the arrays. The topsoil is highly sensitive to mechanical compaction (e.g., use of heavy machinery) and especially exposed is heavy soils rich in clay, during periods of high rainfall such as autumn and winter. On example is visible can be seen in figure 2.7 where bad topsoil management have visible implication of topsoil structure, for difference the example shown in figure 2.3 shows the less impact, even though the central alleys in the Swedish example show signs of significant disruption of vegetation. (Welsh Government, 2023)

The exact procedure of the decommissioning of GMPV is unknown (Welsh Government, 2023, Harplinge samråd 2024) as practical experience is limited, which is natural considering that not a lifetime has passed since early commercial GMPV was built. However, it is thought to involve machinery heavier than during installation work, which will require uprating access roads to cope with the increased load and increase topsoil stress. Suggested typical machinery to be used for removal of piles are 13-ton excavators with vibrating pile driver attachments. Soil effects during removal include mixing of soils and collapse if the hole left by the pile is neither filled naturally or by the machine operators and overall, the decommissioning phase is considered a "grey" area, with "few conclusions" to be made (Welsh Government, 2023). It should be noted that agriculture today is not without the intervention of heavy machinery. Land drainage trenchers and excavators are used when installing piping for drainage and combine harvesters have grown with the increasing size of individual arable land, not without consequences for yields and soil conditions (Parvey et al, 2022). The difference is present in the way such machines are used, as movement is limited to "tramlines" for harvesters and trenchers to trenches, as compared to PV installation/decommissioning, which is spread out evenly over the field, with intensive use of access roads and GMPV array alleys.

Figure 2.7
Visual degradation of topsoil during construction phase of GMPV in UK. Assumed "worst case" scenario of topsoil management and assumed permanent compaction with negative consequences for any future reconversion back to arable land. Source: Welsh Government (2023).

A study at array level assessed microclimate and soil thermal regimes in the Gobi Desert, and concludes, that the PVs significantly impacted the local climate and ecosystem in a poorly understood way, mainly by changing dramatically wind speed and solar irradiation (Zheng et al., 2023). One consequence of these changes was that the areas under the array worked as heat sink during spring and summer, and source during autumn and winter. On a similar note, but closer to south-west Sweden, a 7-year study of an GMPV system in central Italy draw similar conclusions when stating that soil properties during PV deployment is poorly investigated (Moscatelli et al., 2023). The study compared the soil directly beneath the PV module to soil between the arrays, as well as to a reference plot unaffected by the plant. It shows that the studied soil showed a significant reduction in its ability to hold water, of temperature as well as soil organic matter. While considered reversible, Moscatelli et al. also notes the stratification of the land, which impacts the soil characteristics.

In a US court ruling, the establishment of GMPV and the preceding clearing of 400 ha of timber, farm and other land was done without proper measures for erosion and sediment control, eventually ruled the cause for catastrophic consequences for the plot and its neighbour's soil (Schoeck, 2023). The event took place in Georgia with a humid subtropical climate, much different from the geographical area of this thesis project, but still offers insight in potential land use change effects if such are left unmanaged. A study ordered by the Dutch government concludes that GMPV in the Dutch fleet with modules arranged in arrays east-west suffers vegetation cover loss, which will lead so soil deterioration over the assumed plant lifetime of 25 years (van Aken et al, 2021). The identified pathway for the decreased soil quality is the removal of supply of organic matter and other nutrients from plants, that have stopped growing due to the appearance of a continuous shadow from the densely packed PV arrays

2.2.2 Nutrients, erosion and changing precipitation patterns

One potential effect resulting from the bare land under PV arrays, as identified in the case of US and Netherlands (Schoeck, 2023, van Aken et al, 2021) is nutrient leakage. Any land without or with low vegetation on top cover of soil is susceptible of leakage as no vegetation is present to take up nutrients in the soil, so that nutrients available are lost by downwards transportation. Moreover, there is no mechanical resistance from vegetation that captures runoff water, which causes excessive transportation of nutrients away from the land. In a run-off and erosion modelling assessment, large-scale PV was shown to "considerably" impact both categories (Liu et al., 2023). Nutrient leakage has been shown to increase in a changing climate. Increased periods of hot and dry weather increases losses of nutrient to soil, decreases plant uptake and, increased runoff as precipitation comes rarer but more intensely (Bowles et al., 2018). The focus adapted by plants on above-ground biomass could also imply increased losses of nutrients. According to the authors, one main mitigation strategy for adapting to nutrient losses due to changing precipitation patterns (increased drought and intensification of rainfall) induced by climate change is to *"breed for belowground traits"*, essentially to develop larger more complex root-system of crops, allowing it to cope with change. However, the AV system offers some physical protection towards intensified rainfall (albeit the fact that the precipitation has to go somewhere, see the phenomena of Rivulets described above) and increased temperature due to its covering and a trade-off, that needs more research to be addressed, between advantages from physical protection or root development can be imagined.

One nutrient of particular interest in the region is Phosphorous, which has a particularly high pressure on eutrophication on the Swedish southwest coast. The Agency of water information systems in Sweden, VISS, have established an action map for regions were action to mitigate phosphorous leachate are of varying importance, measured in a physical amount of removal needed (Erlandsson Lampa et al., 2021). The combination of dried out land and intensified rainfall results in land less capable of absorbing large quantities of water, which further increases the loss of nutrients. These effects are also described in soil erosion assessment models, where rainfall erosivity is seen a major driver for soil and nutrient loss world-wide, and climate change is the major driver of change in these effects (Panagos et al, 2022). Understanding areas prone to eutrophication by Phosphorous in the region, and implications of land use change when establishing GMPV thus become important. This is especially true considering changing precipitation patterns in the future, which could impose a cascading effect where leakage of nutrients are increased for multiple reasons.

To understand erosion by water, based on factors such as precipitation, soil type, topography, land use and land managements, the Universal Soil Loss Equation USLE developed by Wischmeier, and Smith (1978) can be used. The equation, later Revised into RUSLE, includes effects from long term rill and sheet erosion (Renard et al, 1997). RUSLE2015 is a further development by Panagos et al (2015), which improves the equations by adding high quality input data from sources such as LUCAS, Corine, Eurostat, and metrological services a transparent way. ESDAC, part EU Joint Research Centre JRC have developed datasets based on RUSLE2015, covering the globe in two datapoints, 2010 and 2016 (Panagos et al, 2015). GMPV are deployed on land where, in a context of changing precipitation patters (part of the rainfall or R-factor in the RUSLE tool), erosion by water is likely to change over time. The change is due to precipitation intensity and quantity, both of relevance for water erosion level. Panagos et al. (2022) provides a dataset that models the R-factor on a global level, based on a wide scope of models and three IPCC climate pathways (2.6, 4.5 and 8.6).

2.2.3 Lost food production and volatile yields

The region of Skåne produces 30 percent of all consumed food, have the most productive soils in, and counts 85 percent of all orchards in Sweden. Adding to that, 20 percent of the workers active in the Swedish food industry work in Skåne, and food is the main export of the region (LRF, 2024). The factors together shows the sector's importance in the studied region. According to the County Administrative Board (CAB) of Halland, the food industry counts for seven percent of employments, the second most in the country (CAB of Halland, 2024b), arable land takes up 27 percent of the total area and even though it is the eight smallest of the Swedish regions its landscape is the fifth most productive of Sweden (Karlsson, 2024).

Anthropogenic activity dominates the land use in the region, be it forestry, urban area, or industrial sites, so any type of land lost is hardly replaced by converting another type of land. Considering the limited resource that is arable land, any areas taken out of production for energy generation represents lost food production. To illustrate the effect, assuming a yield of a field of winter wheat of 7 tons per hectare, and an average consumption per capita of 60 kg wheat per year, a GMPV power plant of 50 hectares would reduce the yearly capacity to supply wheat to 5 800 persons. For comparison, a GMPV plant of 50 ha roughly equals 30 MW installed capacity, or roughly 30 GWh of electricity generation per year, corresponding to the consumption of 6000 houses (assuming an average consumption of 5000 kWh per year). Further, the Swedish government is developing new strategies for food security. In a report, measures to increase protection and care of arable land is mentioned as highly important to account for a time in change, with a highly uncertain world market (SOU 2024:8, 2024).

2.3 Alternative land use

The legal status of arable land in Sweden is enshrined into law in the Swedish Environmental Code. According to the law, chapter 3 4§ second paragraph, arable land can only be claimed to fulfil a vital societal interest, and this interest has to be shown not possible to fulfil, by any other means on any other land. GMPV have been agued an essential societal interest. It has also been shown to permanently claim arable land, and thus a trial of essential societal interests against one and another must be made by the county administrative boards (CABs) before accepting an application for GMPV establishment (CAB, 2024). Recently, renewable electricity generation specifically by GMPV have been ruled not a vital societal interest at the highest possible instant, the Environmental and Land Court of Appeal (M 13461-22). Thus, to in theory allow for GMPV to claim arable land, the developer will have to prove that no other source of renewable electricity can satisfy the demand, and that no other land is available to use within a reasonable area. This investigation is called the “principle of localisation” and currently no specific method is have been developed to carry one out (Swedish: *“lokaliseringsutredning”*). In the court of appeal ruling (M 13461-22), such an area to be investigated is loosely defined as the electric market area of the project, in the case of Halland and Skåne SE3 and SE4.

To lift focus from productive arable land, three potential land usages are seen as high potential: establishing GMPV on re-wetted organic arable land (i.e., wetlands), combined agriculture with PV electricity generation, and a combination of both, PVs on re-wetted organic arable land.

2.3.1 Agrivoltaics

Agrivoltaics is a combination of agriculture and electricity generation from photovoltaic panels. The concept initially emerged in Germany (Goetzberger & Zastrow, 1981). For the initial concept, the authors conclude that for a system 2 meters over ground, *“one nearly achieves uniform radiation, (integrated over the day)”*, with a third of the incoming radiation to ground “lost” to the modules. It was however not until 2011, that the first academic use of the term “Agrivoltaic” occurred (Dupraz et al., 2011). The article focuses on the high total production capacity of AV, since both electricity generation and cultivation of food or fuel crops can be done on the same plot. Thus, less land over all is needed, compared to two separate systems with individual production. Further the article highlighted the need for further studies on effect of shading on crops, microclimate beneath panels, impact of agricultural practices on panels and potential technological developments. The concept could have large implication for the agricultural sector, for example in the personal vehicle fuel efficiency gain proposed by switching from low efficiency (solar energy-photosynthesis-harvesting-refining-thermal combustion-mechanical energy) to high efficiency systems (solar energy-PV cell-grid-battery-electrical engine-mechanical energy) which could drastically reduce the environmental impact of both sectors (Dupraz, 2011; Chatzipanagi et al., 2023). The respective share of agriculture and PV within the system are widely debated. France, Germany, Italy, Japan, and South Korea have been forerunners in AV developments (Dupraz, 2023a) and have all developed different legal definitions of AV. While some countries, in particular France, Germany, and Japan, have adopted definitions based on relative yields, i.e., the amount of harvest that is lost due to the installation of the PV system, Italy for example choses to focus on maximum lost areas.

Willockx et al. (2020) provides a categorisation of AV and proposes indicators that can be used within the different categories. The categorisation is based on application (crops or livestock), system (open or closed), farming type (field or orchard crops), structure (stilted or increased space) and flexibility (Dynamic or static), which used together provides a complete overview of the AV schemes main attributes. Coupled with the categories are key indicators such as *Ground Cover Ratio* (GCR), dictating the relation of solar energy between PV and ground by relating the maximum area covered by modules to the total area. A second key indicator is *Land Equivalent Ratio* (LER), a measure of spatial efficiency due to integration of PV and agriculture, as proposed by Dupraz et al. 2011, comparing the land needed to produce a specific amount of food and energy of different system. A third key indicator consists of the Price-Performance-Ratio (PPR), which measures annual extra cost for implementation of AV compared to ground-mounted PVs, to revenue of maintaining arable land, electricity and quality aspects.

An AV-focused study assessing the impact of different amounts of shading for different plants (Laub et al, 2022) was able to link varying shading and associated crop output to an AV scheme with corresponding shading level. While all crop yields are reduced by increased shading, different crops responds differently to shading. Some crops initially increase yield with shading (Berries, fruits, and fruity vegetables), some initially react well (leafy vegetables, forages, and roots/tubers), whereas some crops are highly sensible to shading (grain cereals and maize). The authors thus notes that for an efficient AV scheme, it is important to integrate the shade tolerance and design technical parameters around these constraints. In the region of Skåne, a typical rotation, i.e., a cultivation-order of crops designed to maximise yields and minimise diseases and negative impacts on soil quality, consists of growing three crops without fallow: Spring barley, winter wheat, winter wheat, winter rape seed, winter wheat and lastly sugar beets (Tidåker et al., 2016). A detailed table can be found in appendix II. A large share of the crops cultivated in the region are thus associated with crops shown to have high shade sensibility, such as cereals, rapeseed, and turnip as well as maize (Laub et al, 2022). The result obtained in Laub et al. (2022) can be used to compute the associated GCR, used as a limit for what GCR is tolerable within AV. Typical values for being in line with current AV definitions includes a GCR of less than 25%, which corresponds to a statistical certainty of achieving 80% of yield compared to pre-AV implementation. However, some differences occur. French legislators for example, have initially proven a preference for GCR, establishing a guideline value of no more than 50%, but have in turn high demands on maintained yield, accepting initially no losses in relative yield (Dupraz, 2023a), before settling for 90% yield maintained (Décret n° 2024-318, French Government).

Considering soil quality, Weselek et al. (2021) investigate AV impact on yield and microclimate, and notes that increased shading led to plants redirecting energy to grow above-ground biomass ("shade adapting") without necessarily producing more biomass in dry weight, and that soil temperature decreased under the AV system during the study period. Further the authors conclude that in temperate conditions *"...yield reductions under AV are likely, but under hot and dry weather conditions, growing conditions can become favorable"*, which in Sweden is likely to become more and more common in the context of a changing climate (Bowles et al., 2018).

On the technical side, Toledo and Scognamiglio (2021) have made an exhaustive compilation of current AV technologies on open fields to propose a classification from a performance point of view. In the classification, the AV scheme is divided between Spatial, Energy, and Engineering features, and of three-Dimensional pattern features such as crop and energy features. The study provides a very relevant resumé on available technology and developments of, mainly European, AV technology. According to the study, typical AV system deploys two main components, PVs, and crops. As mentioned, the AV concept was initially imagined in Germany in 1981 as panels mounted on a fence-like structure. A second generation emerged in Japan around 2004 with a pergola style structure. Both technologies use modules mounted in arrays, a concept which is mostly kept today, with or without gaps of panels for increased solar irradiation to the ground. A third concept, developing the fence-like structure but omitting the top-mounted panels and instead incorporating them into the fence itself, have also been deployed, either with integrating lay grass or potatoes. Development on PV technology have also found its way into AV, notably the use of semi-transparent modules increasing the amount of solar irradiation on the ground, and solar tracking panels, that exposes the panel to the sun in optimal angle, rotating on one or two axes, to increase electrical efficiency. Se figure 2.9 for a visual overview.

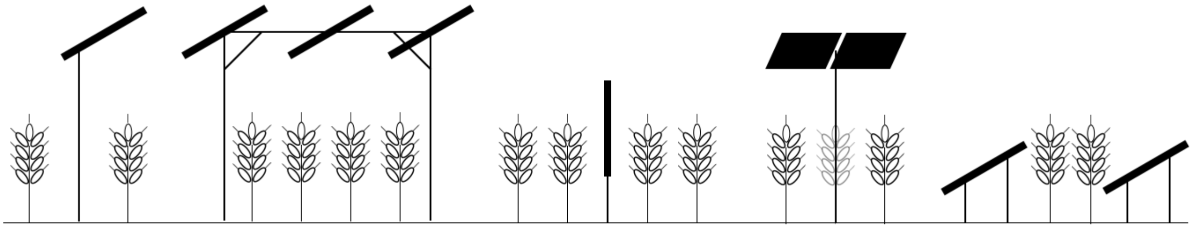


Figure 2.9
Visual representation of current AV technologies showing potential integrations PV-crop. Second from the left typically referred to as "overhead", third "vertical" and fifth "alley-cropping". Adapted from Toledo and Scognamiglio (2021).

Considering costs, one GIS-modelling approach showed that an AV-scheme in the Northern parts of Europe would probably use a substantial amount of distance between rows to let sunlight in, whereas in the southern part a more compact system allowing for crop protection (shading) would be suitable (Willockx et al., 2022). The authors also note that this leads to a higher LCOE of the AV system, as a lower power density means lower electricity generation (row distance), thus the CAPEX, OPEX and revenues are "spread" on less generated electricity. Willockx et al. (2022) notes that the effect is concentrated to the most northern parts of Europe, and drops in intensity rather quickly, and for southern Sweden, an LCOE equivalent to Germany or France can be achieved. Compared to GMPV, AV are associated with a higher CAPEX as more material in super-structures (Schindele et al, 2020), and a LCOE based on a pilot project in Germany, where organic Demeter-certified potatoes where cultivated combined with PV, was estimated to €0.0828 per kWh that is roughly 82 SEK per kWh, below the average electricity price in Halland and Skåne. The increase in price over a conventional GMPV was in the study estimated at roughly 25 SEK per kWh, resulting in a LCOE of GMPV like that of previously in this thesis project assessed technology.

Some practical validation of the AV concept can be obtained in Willockx et al. (2022), which trial wheat and sugar beet cultivation in an AV system. The study notes that sugar beets show less impact from shadowing than wheat, albeit both are exposed to "significant yield losses" during two monitored seasons. In another study, crop quality was shown maintained (Reher et al, 2024). Schindele et al. (2020) showed profitability when combining cultivation of organic potatoes and elevated PV modules in an AV system, and an interesting follow up on this result would inclunde implications when focusing on non-organic potatoes. On the impact of AV induced shade on yields in the temperate region, Weselek et al (2021) noted the following pattern on the examined plot in Germany: "*In 2017 and 2018, yield ranges of the crops cultivated under AV compared to the reference site were −19 to +3% for winter wheat, −20 to +11% for potato and −8 to −5% for grass-clover. In the hot, dry summer 2018, crop yields of winter wheat and potato were increased by AV by 2.7% and 11%, respectively"*. The authors concluded that yield losses are likely, but the effect is limited or reversed in hot and dry conditions.

The literature on AV in Sweden is dominated by a first pilot project, where AV is seen as a possible de-block for PV on agricultural land (Campana, 2023). At the farm, vertically mounted PVs have been built in a pasture, and energy and biomass (grass) is co-produced at an experimental stage since 2021. Areas suitable for AV implementation, with a limiting focus on pasture, where found in most of southern Sweden (Elkadeem et al., 2024). Going beyond pastures, other examples of AV in Sweden include a park of GMPV with a power density of roughly 2.5 ha / MW to be built integrating wheat, rapeseed, beans, forage, and other crops (Oskar Bjärken, Ekoväx, personal communication, Feb. 2024). No further studies were found specifically dealing with AV policy development in Sweden, or any synthesises of current practices in Sweden.

However, while AV systems might be seen as a tool to enable the growth of PV by unrestricting the claim of agricultural land, findings from a participatory workshop including local population close to a proposed AV "plant" in Germany shows that substantial barriers still exist in the form of local resistance (Ketzer et al., 2019). The workshop findings include arguments such as a complete buildout of industrial sites and roofs should be prioritised (as mirrored in Swedish projects, Harplinge samråd), regulation to avoid "pseudo-agriculture" once the PVs are up and running, integration into scenery to avoid negative impacts on recreation and tourism, identification of intrinsically subjective "not beautiful" sites and the inclusion of local actors and governments (e.g. participatory ownership, also mentioned during Harplinge samråd). The authors also conclude on the difference between acceptance towards a pilot and commercial scale project, which is important to keep in mind as its likely that a commercial scale project would meet even more resistance due to its size. Similarly, results from a study of AV scheme in Netherlands show concern about negative wildlife impact and decline in landscape attractiveness amongst residents (Biró-Varga, 2024). One way to minimise visual intrusion of the AV system is to incorporate it to already existing vertical structures (Sirnik et al, 2024). The authors also propose policy to promote sites close to features such as existing vertical vegetation, agricultural support structures and farmhouses, rather than remote pastures where an appearance of industrial features would be more visible.

In an article from EU's Joint Research Centre JRC, Chatzipanagi et al. (2023) concludes that the varying shading effects on different crops in theory means that developers of AV need to cherry-pick suitable crop types to grow in a specifically designed AV scheme. Typical power density of an AV system is quoted at 0.6 MW per hectare or 1.7 hectare per MW, with a range investigated of 0.2 to 0.9 MW per ha (1.1 – 5 ha / MW). To estimate a potential installed capacity of AV in EU, the study uses fictional AV-Shares of total used agricultural area UAA , 10, 5 and 1 percent. The resulting installed capacity ranges from a couple of megawatts to a couple of terawatts per land area sub-category (according to CORINE data) and used share of UAA, but no further detailing on challenges and possibilities with each land area is made.

Chatzipanagi et al. (2023) provide a great resume of the status of policies relevant for AV. Agricultural subsidies in the EU are based on the framework Common Agricultural Policy (CAP). Member states can design part of CAP payments according to specific needs, a potential opportunity to integrate subsidies for AV. AV can either be included as a climate mitigation or adaptation measure. Funding in the region of EUR 10 million are to be invested in AV projects, currently financing three projects. Three countries lead developments (also reflected in the literature review of this thesis): France, Germany, and Italy. France have adopted an initially more, at least legally, concern for protecting and focusing on continued agricultural activity, as PV might not significantly influence quantity or quality of agricultural production. France do however mention some allowable lost yield in the AV scheme compared to the reference case, as the AV system obliges to maintain 90% of reference yield (Décret n° 2024-318, Art. R. 314-114.-I., 2024). On the other hand, both Germany and Italy specifically mention PV electricity generation (Italy no less than 60% of standard PV system, Germany 2nd use of land) and allowable losses of land (Germany 10-15%, Italy crop cover of at least 70% within surface). Price effects on land is also brought up, as some evidence of price increases on AV eligible land have been observed in France, which has led to critique from new actors seeking to establish agricultural practices being denied access for financial reasons. While the potential impact physical obstacles could have on a rational agriculture was not addressed, other challenges mentioned for AV include:

- Lack of an EU-wide general AV definition and legislation which would imply a simplified development process
- Public acceptance
- Technical design, i.e., shading conditions, and
- Biodiversity impact
- Non-sufficient CAP integration as well as
- Grid connectivity.

Focusing on Swedish policy related to CAP and AV, no specific AV measures were found, but an overall focus on renewables, and that of biogas was identified as well as a focus on demand side measures. (Chatzipanagi et al., 2023)

2.3.3 Forests

One alternative to deploying PV parks on arable land is to use cleared forests, and in theory any forest could be cleared and used for PV development. A plot announced for felling results in a grant that is eligible for five years (Swedish Forest Agency, 2024a). All plots of forest that the owner has decided to cut down and applied to do so has to be done by the owner within three years (Swedish Forest agency, 2023b). It should however be noted that forests are protected by the same legal status as arable land in environmental law (SFS1998:808). Forests in Sweden are protected by the same paragraph of the Swedish Environmental Code as arable land, chapter 3 4§, that stipulates that forests “important” for the industry shall be “protected” as far as possible against “actions” that can potentially “render difficult rational forestry”.

One function of forests are to store carbon biomass, absorbed from atmospheric carbon dioxide (CO2), and in the process regulate the atmospheric concentration of CO2. The establishment of GMPV on forest would replace its function of CO2 absorption. Thus, if forest is felled in Sweden for GMPV establishment, it will cause a reduction of the Swedish forest’s carbon sink. As a result, GMPV electricity produced by such a system will cause higher CO2 emissions per energy produced, compared to other land covers (Turney & Fthenakis, 2011). Further effects GMPV systems unique to forests are lower efficiency due to increased cloud formations over forests and reduced solar radiation, even in the case of using de-forested land (Zhang et al., 2024).

2.3.3 Wetlands

An emerging interest in establishing PV on re-wetted land has been identified. Projects of establishing GMPV either floating or on re-wetted land (Ilmatar Solar, 2023), have been initiated at least twice, and one actor is *“currently working on a concept to build PV parks on wetland”* (Ilmatar solar, Pers. Comm.) and a second actor, specialised in floating solar parks, also acknowledge involvement in projects with floating PVs, deployed on wetland (SolarSurf, Pers. Comm.). Both actors mention the “win-win” scenario of establishing solar power on re-wetted land, that is electricity generation and environmental mitigation on the same plot of land. In the project descriptions no particular challenges of building on drained wetlands are mentioned, and the proposed design consists of beams stretching 1.5 meters deep into the organic soil. While the building sequence is not specified, the project plan states that following the GMPV construction phase, ditches present in the land will be plugged, raising the water level to create a wetland. The company states two main reasons for creating the wetland. First, increased profitability since wetlands is believed to imply low plant production, reducing operational costs since less human intervention is needed. Secondly, environmental benefits of establishing the land in the form of “increased biodiversity” and “reduced greenhouse gas emissions” are expected. Once the technical lifetime of the park is passed, the wetland will be left as it is. (Ilmatar Solar, 2023)

From a technical perspective, re-wetting of land is a relatively simple process that consist of plugging ditches with the help of timber and a large excavator (Paulsson, K., 2015). However, the report, based on a program that resulted in the restoration of 35 Natura 2000 wetlands, illustrates how is both site-specific and complex, integrating GIS modelling and water flow analysis to get a precise vision of what wetland will be the result of restauration. An example of such site-specific characteristics considers decision on how to achieve the desired water level. Either the water table can be increased to cover all vegetation by plugging the ditch accordingly, or if some vegetation currently existing is to keep, the water table can be brought up, and any dry peat above can be carried away by the excavator. Material for the plugging of the ditch can either be collected in small “pools” with regular intervals, or all along the way from both rivers of the ditch. Example of both practices can be visualised in figure 2.8.

Figure 2.8
Visualisation of plugging with "pools" to the left, or both rivers to the right (Paulsson, K., 2015). Note that the areas are classified Nature 2000, i.e., acknowledged having high natural values, which is not necessarily true for organic agricultural soils.

Land that is relevant for re-wetting is organic arable land, that is carbon rich soils, such as peatland, drained during the famines of the 19th century to increase the total arable land in Sweden. Such land is associated with high greenhouse gas GHG emissions when carbon decomposes in oxygen rich conditions into carbon dioxide. The total areal of organic soils in Sweden is over six million hectares, corresponding to almost 15% of Sweden's total area. In Sweden, there is around 2.5 Million hectares of arable land, of which 140 000 ha are on organic soils (Markensten et al., 2018). Between the year 2015 and 2021, pasture on organic soils increased whereas arable land on organic soils decreased. The overall result was that during the six year period, organic agricultural land increased with almost four precents (Lindhal & Lundblad, 2021)

The most effective measures for reducing the GHG emissions associated with organic soils is to stop the decomposition of peat. Research have shown that with current understanding, the most effective measure from a climate perspective is to restore the drained land to wetland. This is done by increasing the water table, either up to ground level or slightly above to create a small lake or dam, depending on local preconditions. To promote increased carbon content in the wetland, a water level in line with soil is seen as positive as it promotes plants to grow, reinitiating the formation of peat. Re-wetting organic arable land can be a cost-competitive and efficient, in the region of 21-ton carbon dioxide equivalents per hectare and year, climate mitigation measure but depends on site specific needs.

When selecting a land to re-wet, it is important to assess local conditions, since the geographical data is of varying age and have been collected using different measuring methods. Any selection needs to incorporate carbon content in the soil, which will have changed depending on time passed since drying out, as well as oxygen and water availability in the surrounding land. Water previously available to fill the wetland might have been directed elsewhere due to anthropogenic changes in water flows, and any re-wetting is not possible without a water source it brings up the water table. While Markensten et al. (2018) focuses on active arable land, it is reasoned that some arable lands have been abandoned due to bad conditions imposed by the often very wet organic soils.

From a policy perspective, three important aspects emerge. First, re-wetting organic land is seen as an efficient way of decreasing carbon emissions from agriculture, and secondly, current Swedish policy measures are deemed sufficient for establishing a total of 10 000 hectares re-wetted land (Swedish Environmental Protection Agency, 2023). A third is the need for compensation for the landowner re-wetting land. Losses are induced both as a lost revenue, if agriculture was practiced on the land up until re-wetting, and loss of value for the land itself, as it no longer is associated with production. While the Swedish Environmental Protection Agency (SEPA) notes that the current policy scheme can support large scale implementation, it notes that farmers might be reluctant due to lost revenue and insecurities in relation to compensation measures. Markensten et al. (2018), notes that farmers are dependent on such an economic compensation to be able to re-wet the land. Both reports notes that no specific climate mitigation target associated with organic soils exists today, but organic soils are seen in both cases as a cost-efficient option compared to other policy measures.

A concept which can be linked to PVs on wetland is floating PVs. Floating PV have been studied both as a concept per se (Gorjian et al, 2020) and combined with aquatic production (Pringle et al., 2017). In Sweden floating PVs have a high potential installed capacity, the biggest in Europe, achieved by deploying PVs on waterbodies of anthropogenic origin, such as those created by hydropower dams (Kakoulaki et al., 2024). Floating PVs can be way of increasing use of water as a multi-function asset (energy-biomass production), and benefits are increased electric efficiency due to cooling effects on panels from water, reduction of water evaporation rates and biodiversity effects that can be integrated in the system (Pringle et al., 2017). In a changing climate, Sweden is likely to be affected by more episodes and prolonged periods of high heat and drought (SEPA, n.d.), conditions during which previously mentioned benefits could increase wetland resilience. Other benefits include algae production control by limiting solar irradiance and thus light availability. Humidity could over time prove to have negative impact on PV electric efficiency, and the technology is associated with higher investment costs than land-based alternatives, which can impact competitiveness (Gorijan et al., 2020).

3. Method

For the thesis project, a geographical limitation to the region of Halland and Skåne was used, and the overall method followed the principle of a two staged rocket. First a quantitative stage, focused on plot-level, allows an understanding of preconditions and the context of GMPV development, land cover, and how the economic conditions might change when varying a set of key criteria. A second qualitative stage with a system-level focus, based on a literature review conducted in parallel, enabled a larger discussion and improved the content of the first stage and contributed to frame the thesis in a scientific context. An overview of the methodology can be seen in figure 3.1.

Figure 3.1
Methodological overview of the two stages. The green and yellow represent the focus of the parallel literature review, going from a plot(green) level to system (yellow) level focus.

Another limitation relates to the economy of solar parks. The focus of the thesis project is not investigations on profit maximisation of by benchmarking PV systems against one and another on the different land covers, neither any assessment of maximum deployment. Rather focus is on showing the technological possibilities, the available land cover, and the economical characteristics of using different land, as well as to identify any multi-functional examples of land use.

3.1 Literature review

A systematic literature review was carried out to identify and collect relevant information. The findings were used for identifying possibilities for multifunctional land-use, which could be used both quantitively as a basis for GIS modelling and economic analysis methodology, and for the qualitative part of the project. To identify relevant literature, articles were identified by using key words in academic search engines (Scopus, Google Scholar) during spring 2024, and relevant studies were selected based on abstract.

Once identified, the selected the articles where read, focusing on methodology, discussion, and conclusions, compiled into a spreadsheet complete with comments and quotes, from which a synthesis could be made, and conclusions drawn. Examples of keywords that were used in search engines is: *photovoltaic*, *agriculture*, *land cover*, *land use*, *Agrivoltaics*, *wetland*, and *organic soils*. An overall focus on Sweden was used initially, completing with examples from Europe and areas with similar solar irradiation conditions.

If a finding from the literature review was an example of where land was used not only for one activity but multiple, i.e., land was not only used for electricity generation, the trend was classified as multifunctional land use. Using initial results on land cover from the quantitative part of the thesis, going back into the literature review, allowed to improve the relevance of the qualitative analysis by systematically assessing the available land.

While not explicitly linked to the literature review, field trips were carried out. Field trips were used as a way of improving overall understanding of the main thesis subjects, GMPV parks and AV systems, and to look for signs of in literature identified effects on Swedish cases. No specific methodology was deployed for visits, but the trips were limited to the western part of southern Sweden.

3.2 GIS modelling of land use possibilities

Initial findings of the literature review confirmed the overall tendency of developers to focus on land close to power lines when locating a plot for developing a GMPV park. Thus, the aim of the GIS modelling is to extract data on land cover and soil type in proximity to powerlines of the regional grid. QGIS 3.34 *Prizren* was the software used, which is a Geographical Information System GIS, available to the public free of charge (QGIS.org, 2024). As an overview of methodology and data used, a resume of this chapter is available in table 3.1 and figure 3.1.

To establish and classify land types in proximity to power lines of the regional grid, geographical data of such power lines are available from the Land Survey (Swedish: *"Lantmäteriet"*) in the dataset Property Map (Swedish: *"fastighetskartan"*). In the data, power lines of the transmission, regional, distribution grid, as well as a category of other components of the grid are shown as different classes.

By importing data on current GMPV parks over one MW of installed capacity (the Land Survey, 2023), and using the QGIS function for vector analysis *"shortest line between two objects"*, the shortest distance between each GMPV park and the grid could be established for both the specific distance GMPV park-grid, as well as an overall average for the Swedish system.

Once the average distance extracted, it is then used to create a buffer zone around the power lines of the regional grid. This is done using the vector geometry tool "buffer", specifying the width to be the average distance value. The resulting buffer zone thus represents an area, with as width a specific distance along each side of a power line. In the case of adjacent power lines, eventual overlaps are integrated to form one so that no area is doubled by checking the "dissolve result" box. The buffer zone can then be used to extract relevant data, by cutting out (using the vector layer tool "cut") or by selection (using the vector selection tools "select by position" or "select within distance") any relevant data from a secondary layer within the zone. To assess how different data sets changes with an increasing distance from a power line, two buffer zones on top of the average are made, using 5 km and 2.5 km as distances in line with findings on average distances in the background.

A comprehensive classification of land cover in Sweden have been made by the SEPA, the National Land Cover Data 2018 (NLCD) (Swedish: *"Nationella Marktäckedata 2018"*). The classification is available as a raster of TIF-format, like a pixelized image, where each individual pixel, measuring 10x10 meters, corresponds to a specific land cover. There are 25 classes of land cover, divided into nine categories: Forests (16 sub-classes), open wetlands, Arable land, non-vegetated other open land, vegetated other open land, artificial surfaces (building, road/railway and not road/railway) and water (marine and inland). Of the classes, only marine water is not included in the analysis. To be processable, the raster is vectorised, i.e., is transformed into multiple polygons, where each polygon corresponds to an area of continuous land cover saved to a vector file. By selecting ("select by position") the polygons that overlap with the different buffer zones, a classification of land type within the buffer zone can be made. Selecting the polygons, instead of cutting them along the border of the buffer zone, allowed to account for complete fields, and not only the land cover within distance.

Table 3.1
GIS data used and sources

Domain	Data	Comment	Data Source	Source
Techno- and socio-economic factors	GSD-Property map, vector	Power line geodata	The Land Survey	The Land Survey (2024)
	Built photovoltaic parks over 0.5 MW	Only over 1 MW of relevance	CABs	CABs (2023)
	Population density 2023	Population density geodata	Statistics Sweden	Statistics Sweden (2024)
Land Cover and use	NLCD 2018	Land cover classification: • Open Wetland • Arable land • Non-vegetated other open land • Vegetated other open land • Artificial surfaces, Buildings • AS, not building or road/railway • AS, road/railway • Inland water • Marine water • Forests (16 sub-classes)	Swedish Environmental Protection Agency	SEPA (2018)
	Agricultural land	Agri-practices based on CAP payments: • Wetland • Arable land • Pasture • Arable land – permanent crop • Arable land – permanent grassland • Other land • Unknown	Agricultural blocks 2023	SBA (2024b)
	Notification of Clear felling	Coming three years	Swedish Forest Agency	SFA (2024c), SFA (2024d)
	Final fellings	Forest felled in last three years		
Impact assessment	Soil type data 1:25 000-1:100 000	At 0.5 m from surface and substantial depth	Geological Survey of Sweden	Geological Survey of Sweden (2018)
	Phosphorous mitigation need	Needed removal of P, in Kg per ha for specific water area	Water Agencies	VISS (2024)
	RUSLE2015	Rainwater erosion	ESDAC-JRC	Panagos et al. (2015)
	GLoREDa	R-factor change		Panagos et al. (2022)

Arable land is available as a land cover class in the NLCD, however, to improve detailing of land use, data from the SBA containing all agricultural fields (Swedish: "jordbruksblock") with applications to the EU CAP is used, illustrating the land use in agriculture for the year 2023 (SBA, 2024b). The dataset classes agricultural activities into seven classes: wetland (Swedish: *“våtmark”*), arable land (Swedish: *”åker”*), pasture (Swedish: “bete”), arable land – permanent crop (Swedish: *“åkermark – permanenta grödor”)*, arable land – permanent grassland (Swedish: *“åkermark – permanenta gräsmark”)*, and two generic classes: other land and unknown (Swedish: *”Övrig mark”* and *“okänt”*). A similar approach of selecting polygons overlapping with the buffer zone is used to identify arable land within the geographical constraints of the project.

The Swedish Forest Agency publish two datasets for identifying forest areas relevant for this study, “notification of clear-felling” (Swedish: *“Avverkningsanmäld”*) and “final fellings”(Swedish: *“Avverkad”*). Both datasets contain specific areas of forests as polygons, with matching temporal information. The most likely forests to be used initially is forests that are “naturally” available, i.e., that recently has been or is to be cleared as the timber was/is ready for felling. The plots seen as relevant for the thesis project are either final fellings in the last three years, or notified for clear-felling, which in both cases results in clear land where a GMPV park could be established. Unwanted plots (more than three years old) are removed, using the sorting function within the “attribute table” of respective data set, and then plots are selected and classified using the buffer zones. As a forest owner have a duty to replant trees on productive forest land within three years, three years is chosen as a time constraint for selecting felled patches of forests. These are thus most likely to be used for PV park deployment, as trees are most likely not planted or recently planted on the slot.

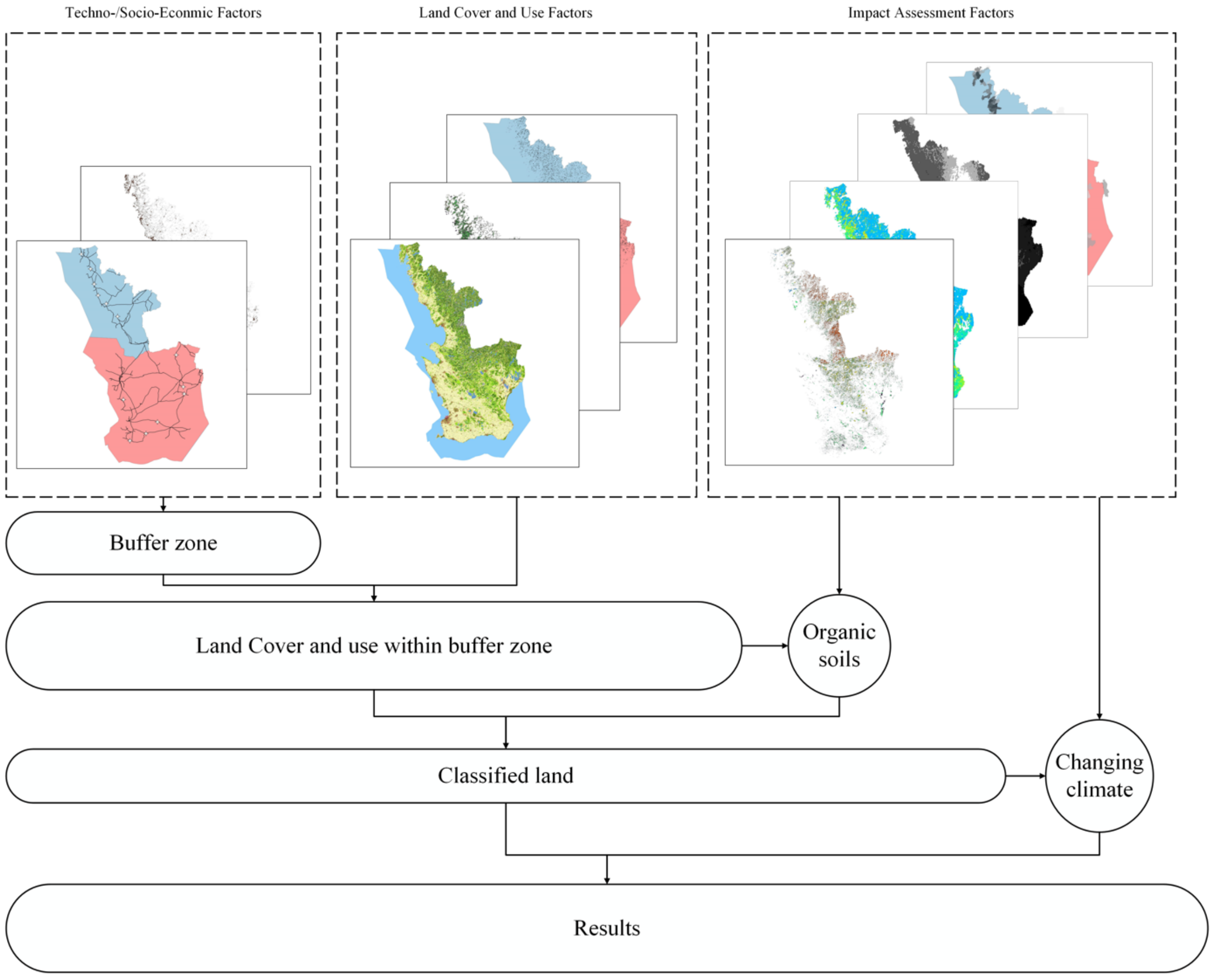


Figure 3.2
GIS modelling methodological overview. Flowchart shows vector analysis and statistical tools used to obtain results from the superposed datasets used. Dataset classed according to three factors, Techno-/socio-economic, Land cover and use and impact assessment.

The Geological Survey of Sweden, SGU, have established a map of the topsoil of Sweden (Geological Survey of Sweden, 2018), called Soil Types 1:25000-1:100000 (Swedish: *"Jordarter 1:25000-1:100000"*). This map contains five categories defined as organic soils: "Kärrmoss", "torvmoss", "gyttjelera/lergyttja", "gyttja" and "torv" respectively (Berglund et al., 2009). To assess how large share of the previously assessed arable land and forestry is situated on organic soils, and thus have a potential to store carbon if re-wetted, the five categories are merged into a single layer and any overlaps with a polygon of either arable land or forestry are identified using the "selection by position" and indicates an area of organic arable land / forestry. The overlapping area is then cut using the tool "cut", to create a polygon only containing the organic arable land / forest.

To assess the relationship between identified plots and the population, an indicator on population density is to be computed by assessing the population within the 1.2, 2.5 and 5 km buffer zone and dividing it by the respective buffer zone area. To improve understanding of where the population lives in relation to the different land covers, geographical data from the statistical agency of Sweden on population density was mapped onto the datasets (Statistics Sweden, 2024). Further, to say something about how large a share of specific land cover is relevant for GMPV development, 5 criteria were developed: plot within 5 km of a power line, 100/500 m distance to closest population, 1 km minimum distance to nature reserve, and outside a biotope protection area. The land covers selected as relevant were Arable land, final fellings of forest and, wetland, in line with the identified potential alternatives for GMPV development on arable land, AV, felled forests and PVs on re-wetted land. Using these three possible socio-cultural constraints allows to evaluate how much land is available for GMPV development, as they are selected to reduce conflict of interest between food and energy, increasing the feasibility of a corresponding GMPV project.

From Panagos et al. (2015) and Panagos et al. (2022), model data on erosion by water and percentual R-factor change was obtained in raster form for the European Soil Data Centre division of the Joint Research Centre ESDAC-JRC. The regional data needed was extracted using the GDAL vector geotransform tool "clip raster by extent". To visualise the percentual change, the raster was shown with a discrete interval. By superposing the initial erosion characterisation factor map with percentual changes of the R-factor in a changing future climate, a map of potential future erosion can be made for the qualitative analysis. In the VISS data set, Phosphorous removal need is shown, and the polygons are mapped on top of the erosion by water map to illustrate potential risk areas, adding a dimension for the qualitative analysis. For illustrative reasons the dominating land use was also mapped on top of the baseline erosion map.

3.3 Economic analysis

For the economic analysis of this thesis project, the length of the electrical line is of primary interest. Other costs associated with electrical infrastructure are assumed equal between land covers and plots, and specific plots do not imply any change in GMPV design as described in chapter 2.1.3. PV park developers are likely initially interested in land close to existing substations (with carrying capacity available), before switching to land further from existing substations necessity the construction of a new substation. The primary focus was to determine the size of cost components for GMPV on an average in Sweden, how it relates to the cost of a power line of varying distance as well as to a varying cost depending on land cover. This as reflected in the aim of the thesis project, to understand how the costs differ depending on land use and distance to the regional grid.

3.3.1 Cost of new power lines at varying distance to regional grid

To allow an economic analysis in the very varying conditions imposed by local electrical infrastructure, a constant archetype of GMPV park, illustrated in figure 2.4 by the first case with existing substation, serves as the basis. To evaluate the sensitivity of the LCOE of such a GMPV park when increasements in initial investment are made (i.e., higher cost of power line), eight cases were made up to evaluate potential GMPV parks.

Each case with a specific installed capacity at different distances from the regional grid, and new power lines where assumed operating at different "mid-voltages", either 12 or 24 kV. Typical installed capacity of GMPV parks used for the eight cases were: 5 MW (small PV park but still industrial site), 25 MW (roughly the biggest parks today), 40 MW and 63 MW (based on standard of transformer capacity in the studied grid). The distance in turn is determined from results of the initial part of the thesis work, such as current average and maximum distances or other distances argued for in the assessed literature.

Initial investments for the average new Swedish PV park are given by Elmkvist (2021) and Lindahl (2021) and focusing on them allows to assess LCOE, as all other parameters are equal, a higher initial investment theoretically results in a higher LCOE. Comparing the costs of the new power line in relation to other initial investments (see chapter 2.1.4) for building a GMPV park, such as grid connection which equals the actual average cost for connection to the grid, allows to determine its importance for overall system costs. The variable initial investment for each case thus depends on two key variables: length of new power line and type of cable used. Each case will need a specific cable where the dimension (cross section area) will be decided by the current I transmitted during peak load through the cable, which in turn is calculated using equation [1] that depends on peak power P_p (in this case equals to installed capacity) and voltage U (12 or 24 kV depending on the system). The result was eight currents that could be used for dimensioning the needed cables.

$$I = \frac{P_p}{\sqrt{3} \cdot U} \quad [1]$$

Once I is established for each case, the minimum cross section needed can be taken from table 18 in the Power Line Manual (Swedish: "Kraftkabelhandboken", NKT Cables, 2015). A cable with a conducting material of Aluminium and maximum temperature authorised of 90°C is assumed to be used. If I is too large for the biggest available cable, several smaller cables are to be used instead. If using multiple cables, the same cable size is assumed to be used according to industry practice.

Once the cable dimensioned, including number of cables needed, the installation cost, expressed in kr / km, can be obtained from the EBR-catalogue for local grid (Swedenergy, 2023a). If the cable selected is unavailable in the catalogue, it is assumed that it is not used in practice and the dimension above available is used instead. When multiple cables are used, machinery, workforce and other is already in place for the first, and consequently the following cables are cheaper and can be laid in the same duct. Only the material cost is roughly constant. As the costs for multiple power lines in same trench is not available for local grid, an average based on cost reduction for the regional grid was used (Swedenergy, 2023b). It was assumed that no more than four cables would be laid in the same duct before resorting to a secondary duct. When the cost of power line for the different cases was established, it was multiplied with the distances used. To allow for comparison, the cost was divided by installed capacity to express the cost in kr per MW, which allowed to compare with average costs for new GMPV expressed in Lindahl (2021).

3.3.2 Cost of using different land covers

A Land Rent is typically paid on a yearly basis. Thus it cannot be directly compared to the total average initial investments. To enable a comparison, land rent (expressed in SEK per MW) is summarised in discounted form, over plant lifetime, assumed here to be 30 years (Lindhal, 2021. Using a discount rate of either 1 and 2 % and adjusting yearly land payments for inflation, 2% in the case of Sweden, allows to calculate the present value according to equation [2]. In the equation, i is the year starting from initial investment, *present value* is the sum of all discounted yearly land payments, *future value* is the yearly land payment adjusted for inflation in the year i and r is the discount rate.

$$Present\ value = \sum_{i=1}^{30} \frac{Future\ value_i}{(1+r)^i} \qquad [2]$$

While applicable for agricultural land, yearly payments for land are rare in forestry today, with some pilot projects underway investigating the possibility (Nilsson, 2020). Thus, the case of PV park on forest assumes a cost for purchasing land, based on a 3-year average for production area one (Ludvig & CO, 2023). Forest prices are either given in kr / m3sk or kr / ha. Using a conversion factor of 1.84 ha / MW, the average land / electrical effect of Swedish PV parks over 1 MW (RISE, 2023), the prices can be expressed in kr / MW. The total discounted (except for forestry) payment for land can then be compared to the costs of power lines and total initial investment costs

The different land cover assessed, arable land, pasture and felled forest likely include some variation in cost for groundwork and preparing the land for GMPV establishment. These cost represent a minor share of the total initial investment, included in Lindahl (2021) in "*pre-assembly and preparation of land"*, but no specific cost of preparation of land is mentioned. Due to limitations in time and data availability, the cost is assumed equal between the three land covers and not is not given any importance for the economic analysis in this study.

4. Results

In the following chapters, the results of the thesis are presented. The structure follows the sequence of the research questions: relation GMPV – regional grid, land cover, economic consequences and, lastly, challenges and possibilities.

4.1 Characteristics of GMPV

The GIS modelling shows that on average, in the southern part of Sweden, GMPV have been established at a distance of 1.2 km from a power line of the regional grid. Compared to the average of southern Sweden, the equivalent average distance for Skåne and Halland is of 800 m, while the distance to the closest substation connected to the regional grid is on average 1800 m. From these results confirms distances disclosed in the background, and three relevant distances from a PV park to the regional grid can be established: 1.2 km motivated by its "Current industry average distance" in the region, 2.5 km which is half the largest distance identified as potentially interesting and relates to average distance to substation, and finally 5 km, the longest distance identified as potentially interesting (OX2, 2023). The land cover within an exact distance is not the main interest of the study, but rather the change in composition moving further from regional power lines.

Table 4.1
Buffer zone area and population density along the regional grid. The population corresponds to the population of the studied area, that is the total of the region of Skåne and Halland combined (Statistics Sweden, 2024).

	1.2 km	2.5 km	5 km
Population (Number)	461 924	1 090 920	1 598 690
Share of total (percentage)	26	62	91
Area buffer zone (ha)	432 965	821 299	1 400 480
Population per ha in buffer zone	1,07	1,33	1,14

Of the 1.765 million inhabitants in the region of Skåne and Halland (Statistics Sweden, 2024), table 4.1 shows how the population density changes between to the different distance classes. As shown, over 90 percent of the population of the region lives within a considerable distance to the regional grid and are thus potentially neighbours to a PV park. This number might initially seem large but considering that the objective of the regional grid is to bring electricity from producers to consumers (i.e., households), it is naturally the case. A visualisation is available in appendix III.

4.2 Current land cover

In table 4.2, the current land cover in the region, classed by region and total for the three identified relevant distance classes can be identified. Overall, including all land within 5 km, arable land is the largest category, followed by forest outside wetland. Third is vegetated other open land (VOOL), followed by forest on wetland and inland waters. Open wetland and artificial surfaces, buildings are the last two significant categories, followed by three smaller categories: artificial surfaces, not building or road/railway; non-vegetated other open land; and artificial surfaces, road/railway.

Table 4.2
Initial land use in the region of Halland and Skåne, classed by distance to power line of the regional grid. Data from NLCD (Swedish Environmental Protection Agency, 2018)

	Total area of land cover (ha)								
	Halland			Skåne			Total		
Type of land	**1.2 km**	**2.5 km**	**5km**	**1.2 km**	**2.5 km**	**5 km**	**1.2 km**	**2.5 km**	**5 km**
Open Wetland	3 946	6 744	10 405	4 799	9 006	16 216	8 745	15 750	26 621
Arable land	35 332	50 447	62 224	132 452	234 211	369 779	167 784	284 658	432 003
Non-VOOL*	242	499	1 410	355	709	1 275	597	1 208	2 685
VOOL*	12 919	22 096	31 730	36 751	69 189	111 961	49 670	91 285	143 691
AS**, building	543	941	1 100	3 838	7 639	10 755	4 381	8 580	11 855
AS**, not building or road/railway	851	1 346	1 595	2 757	5 329	7 428	3 608	6 675	9 023
AS**, road/railway	347	545	759	570	923	1 464	917	1 468	2 223
Inland water	7 562	13 013	16 914	3 791	9 400	28 446	11 353	22 413	45 360
All forest outside wetland	57 764	99 451	154 628	68 502	139 689	252 320	126 266	239 140	406 948
All forest on wetland	8 496	15 326	24 826	5 803	12 202	24 009	14 299	27 528	48 835

*Vegetated Other Open Land, **Artificial Surfaces

Figure 4.1 shows a pie-chart of total land use, using the 2.5 km distance-to-grid class as example to visualise dominating land covers within the buffer zone. As the total size of the buffer zone in Skåne is larger than in the one in Halland, in total agricultural land is the largest land cover accounting for 44% of total. Total forestry (wetland on and off) in turn accounts for 37% of total land cover. A detailed table of the figure is shown in appendix IV.

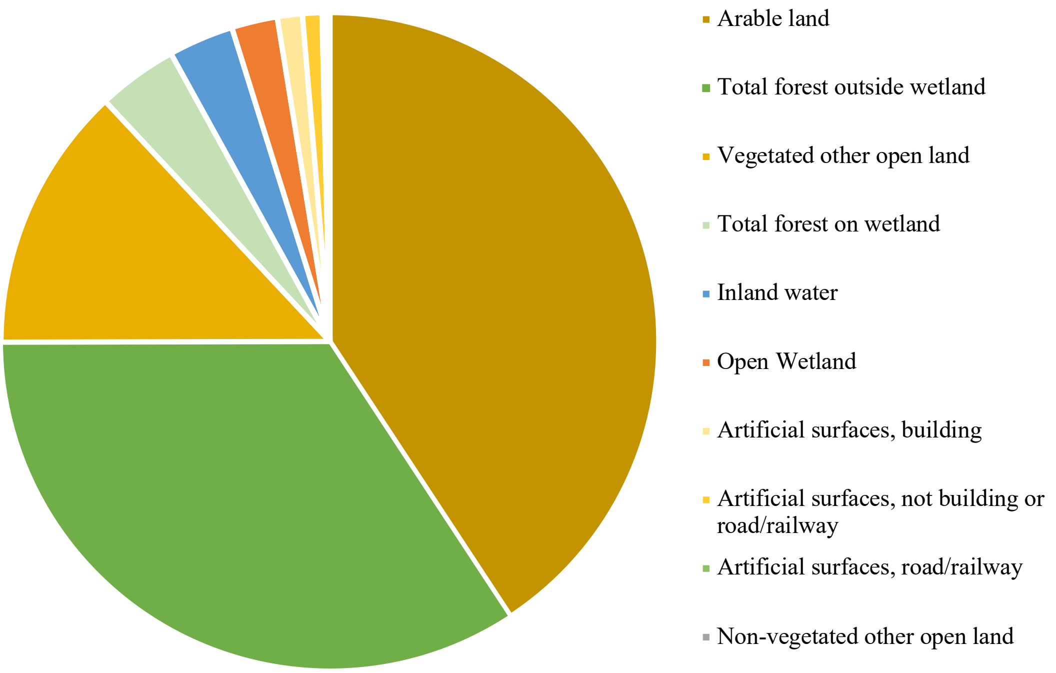


Figure 4.1
Distribution of land covers in Skåne and Halland in 2.5 km distance-to-grid class. Data from National Land Cover Data (SEPA, 2018). Note descending order by size.

In Halland, forest is dominating and accounts for almost half land in the buffer zone, and in Skåne Agricultural land is dominating, also accounting for almost half of all land. Figure 4.2 shows the individual shares of each land cover per region, and in both regions it can be observed that arable land decreases and total forest increases when increasing the distance to the power lines.

Figure 4.2
Regional shares of respective land use within all distance-to-grid classes, based on National Land Cover Data (Swedish Environmental Protection Agency, 2018). Halland inner circle, form inside 1.2, 2.5 and 5 km. Skåne outer circle, from inside 1.2, 2.5 and 5 km.

4.3 Possible constraints for land availability

Table 4.3 show how land availability is influenced of possible socio-cultural constraints. For land cover within 5 km of the regional power lines, arable land is overall closer to the population than forests and wetland. Harder constraints, outside a 1 km distance from natural reserve, followed by outside biosphere protection area, and lastly a 500 m distance to closest population, confirms the order of wetland-forest-arable when assessing land availability. The result is important as even if total area of arable land is bigger by an order of magnitude than the two other categories, shares for both forest and wetland are larger considering the most restrictive constraints.

Table 4.3
land availability and share of total land cover within possible socio-cultural constraints. Includes land within a 5 km buffer to the regional grid (ha (%)). Felled forest only includes final fellings.

Constraint	**Arable land Halland**	**Arable land Skåne**	**Felled Forest, Halland**	**Felled Forest, Skåne**	**Wetland, Halland**	**Wetland, Skåne**
Plot within 5 km	87 111 (100)	342 330 (100)	7 067 (100)	9 901 (100)	10 406 (100)	16 216(100)
Plot within 5 km, >100 m from population	11 905 (14)	38 942 (11)	5 378 (76)	6 734 (68)	8 584 (82)	11 425 (70)
Plot within 5 km, >100 m from population, >1 km from nature reserve	9 661 (11)	29 412 (9)	4 343 (61)	5 547 (56)	7 124 (68)	7 925 (49)
Plot within 5 km, >100 m from population, >1 km from nature reserve, outside area of biosphere protection	9 661 (11)	25 505 (8)	4 343 (61)	4 947 (50)	7 124 (68)	7 655 (47)
Plot within 5 km, > 500 m from population, >1 km from nature reserve, outside area of biosphere protection	527 (0,6)	1 270 (0,4)	1 361 (19)	885 (9)	3 129 (30)	1 565 (10)

4.4 Plot size distribution of available arable land and final fellings of forest

A specific installed capacity of GMPV requires a specific amount of land, on average for GMPV in Sweden 1.84 ha per MW. The distribution of plot (field) size in the region is thus of interest, as reducing the needed plots is believed to facilitate the acquisition of land (less land owners to deal with) and reduce land cost/rent for the same reason. To this adds the lower total costs since need for less interconnecting cables, all three related to governing factors of GMPV establishment (Björnsson et al., 2022). Figure 4.3 below shows the plot size distribution of available arable land, as well as final fellings of forest between 2021 and 2024, considering the possible, socio-cultural constraints. It is thus not reflecting all arable land nor felled forest, but only a selection likely to be used outside 100 meters to closest population, 1 km to a natural reserve and outside a biotope protection area.

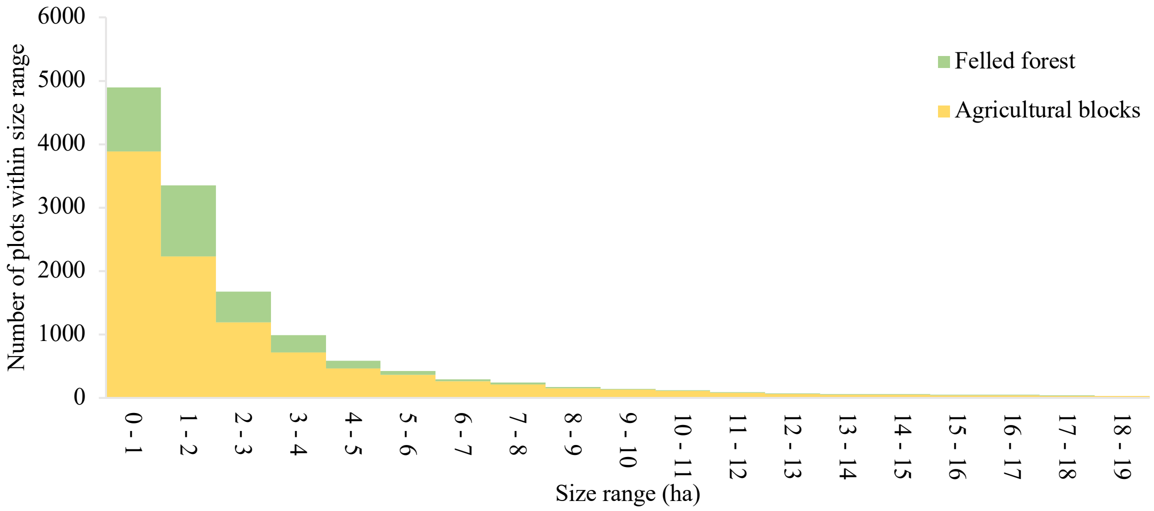


Figure 4.3
Distribution of plot size (ha) for arable land (absolute numbers, yellow) and final fellings of forest since 2021 (absolute numbers, green) within the 5 km buffer zone. All plots within 100m distance to population, with 1 km to natural reserve and/or a biotope protection area have been excluded. A total of 262 plots of arable land larger than 19 ha not shown, maximum size 125 ha.

Comparing arable land to felled forest, as illustrated in figure 4.3, more plots of arable land than final fellings of forest are located within the 5 km buffer zone. This is true both for absolute numbers and total area. While 750 plots of arable land are larger than 10 hectares, only 22 plots in the same range exists in forestry. In the range ten to three hectares, arable land contains 2297 plots, while felled forestry counts 558. For plots smaller than four hectares, arable land counts 7303 and forestry 2341.

In figure 4.4 the distribution of plot (i.e. field) size as a share of total areas is shown. For felled forests about a quarter of all plots are 1-2 hectares in size, declining rapidly with increased plot size. The agricultural blocks (the term in dataset for field) however are decreasing slowly until maximal plot size at 179 ha, illustrating a more even distribution. As relatively large plots of felled forest is rare, it is likely that GMPV establishment will require unconventional felling practices.

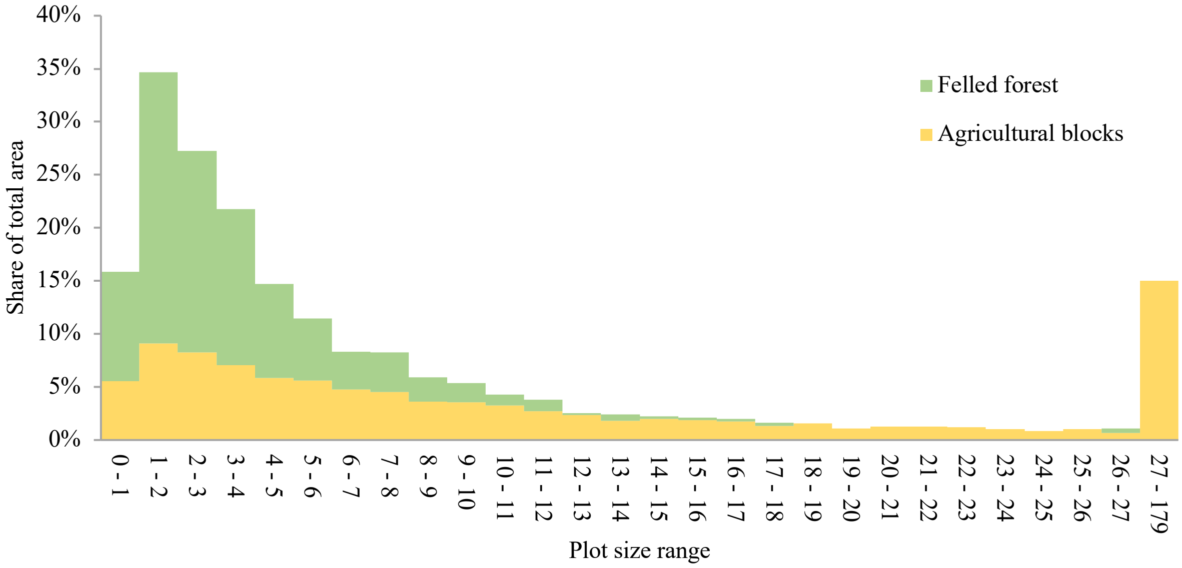


Figure 4.4
Share of total area of plot size range, compared to total specific area of each cover class. Agricultural blocks (yellow) and final fellings of forest since 2021 (green) within the 5 km buffer zone. All plots are within 100m distance to population, with 1 km to natural reserve and/or a biotope protection area have been excluded. 27 ha corresponds to biggest selected forest plot.

4.5 Vegetated other open land

The third overall biggest land use category from table 4.1 is VOOL. According to the NLCD product description it consists of: *"surfaces of anthropogenic origin such as grassland and semi-natural pastures as well as natural surfaces such as heaths, meadows and scrubland"*(SEPA, 2023a) . However, GIS analysis shows that while most areas correlate to pasture, permanent grassland or wetland in agricultural fields (SBA, 2024a), a large share of VOOL within the studied area is either roadside vegetation, lawns, golf courses or scrubland below power lines ("*ledningsgata*" in Swedish, defined here as other open land within 20 meters of grid). This type of land is categorised as unclassified, anthropogenic land, and corresponds to VOOL that did not fall in to another of the four categories during the GIS analysis. Considering the distance to power lines, Halland have more VOOL closer to the regional power lines when compared to Skån

Table 4.4
Sub-categorisation of vegetated other open land within 5 km to the regional grid (The Land Authority). Based on data from: Agricultural blocks (SBA, 2024a), and NLCD (Swedish Environmental Protection Agency, 2018). Unclassified, anthropogenic land corresponds loosely to roadsides, lawns and golf courses.

Vegetated Other Open Land (VOOL)	**Halland (ha)**	**Share 5 km**	**Skåne (ha)**	**Share 5 km**
Within*, 5 km	46 562	100%	111 961	100%
2,5 km	29 934	64%	64 146	57%
1,2 km	18 959	41%	31 617	28%
Scrubland below power lines*	3 205	7%	6 771	6%
Pasture**	15 578	33%	43 744	39%
Permanent grassland**	9 334	20%	18 579	17%
Wetland**	1 183	3%	1 913	2%
Unclassified, anthropogenic land*,**	17 262	37%	40 955	37%

*Source:**SEPA, **SBA*

4.6 Organic soils in agriculture and forestry

Land classified as organic soils are organic agricultural land, forestry and wetlands. The forest notified for clear-felling that finally is felled is unknown. Instead an indicator of final fellings of forest in the last three years on organic soil, over total final fellings has been used. This indicator is used to estimate the final felled forest on wetland, currently notified for clear-felling. Then, both categories ware summarised. The size of the organic land within different distance-to-grid classes is presented as a total for Skåne and Halland in table 4.5. It total, roughly 13 000 ha of forest and agriculture on organic soils are available within 5 km, 8 500 ha within 2.5 km and, 4 000 within 1.2 km.

Table 4.5
Area of land use associated with organic soils in total for Skåne and Halland, within the three distance classes. Data from NLCD: forest on wetland (SEPA, 2024) and SBA: arable land (SBA, 2024b). Forest includes final fellings as well as forest notified for clear-felling.

Land use	**Size (ha)**	**Share (Percentage)**
Total arable land within 5 km	429 409	100,0%
Arable land, organic overlap, 5 km	9 798	2,3%
Arable land, organic overlap, 2.5 km	6 560	1,5%
Forest, total on wetland within 5 km	48 835	100,0%
Forest, felled or up for felling, 2.5 km	2050	4,2%
Forest, felled or up for felling, 1.2 km	1065	2,2%

In figure 4.6, an example illustrating an area of organic soil (red), overlapping a larger plot of arable land which also consists of mineral soils can be visualised. The figure also includes a satellite image of the same piece of land, as an overview of the modelled area.

Figure 4.6
Overview of organic soils close to Himleån, Halland. Satellite imagery (©Google) to the left and results from the modelling exercise to the right.

4.7 Economic analysis

The varying economic conditions between different GMPV cases, depends on distance to power line and land cover. In the following chapter, results of the economic analysis of the eight GMPV cases described in the method chapter are presented.

4.7.1 New power lines

Cable dimensions for different GMPV cases are shown in Table 4.7. Costs omitted due to Non-Disclosure Agreement (NDA) between author and Swedenergy who provided the cost data. Relative costs are shown anonymised (scaled with undisclosed scalar) and normalised to enable comparison between cases with respect to same-as-above commitment.

Table 4.7
Cable dimensioning for each PV park case. Data from NKT Cables (2015) and Swedenergy (2023a).

Park Capacity (MWp)	**Voltage U (V)**	**Current I (A)**	**I per cable (A/Cable)**	**Closest cable (mm^2, A)**	**Cable ducts (number)**	**Cable (units)**	**Cable name, Swedenergy (2023a)**
5	12 000	241	241	120, 270	1	1	G146, 25 PEX 3x150 12 kV
25	12 000	1203	401	300, 450	1	3	G146, 06 PEX 3x300 12 kV
40	12 000	1925	385	240, 400	1	5	G146, 26 PEX 3x240 12 kV
63	12 000	3031	433	300, 450	2	7	G146, 06 PEX 3x300 12 kV
5	24 000	120	120	35, 130	1	1	G146, 14 PEX 3x50 24 kV
25	24 000	601	301	150, 310	1	2	G146, 15 PEX 3x150 24 kV
40	24 000	962	241	70, 260	1	4	G146, 16 PEX 3x95 24 kV
63	24 000	1516	379	240, 400	1	4	G146, 16 PEX 3x240 24 kV

Figure 4.7 shows the cost, normalised to the lowest overall cost and anonymised with factor, due to the NDA for cost data on power cables, of constructing a new power line per installed MW capacity for the eight cases. For the 12 kV cases the cost decreases with scale up to 40 MW, beyond (i.e., 63 MW case) the high nominal currents results in a slight cost increase per MW. This effect is not observable in the 24 kV case, where a strict decrease of cost with increased installed capacity can be observed.

As Swedenergy (2023a, 2023b) expresses average total costs for new power lines built the previous year in Sweden, the increasing cost in the 12 kV scenarios is a sign of the movement away from the use of common equipment

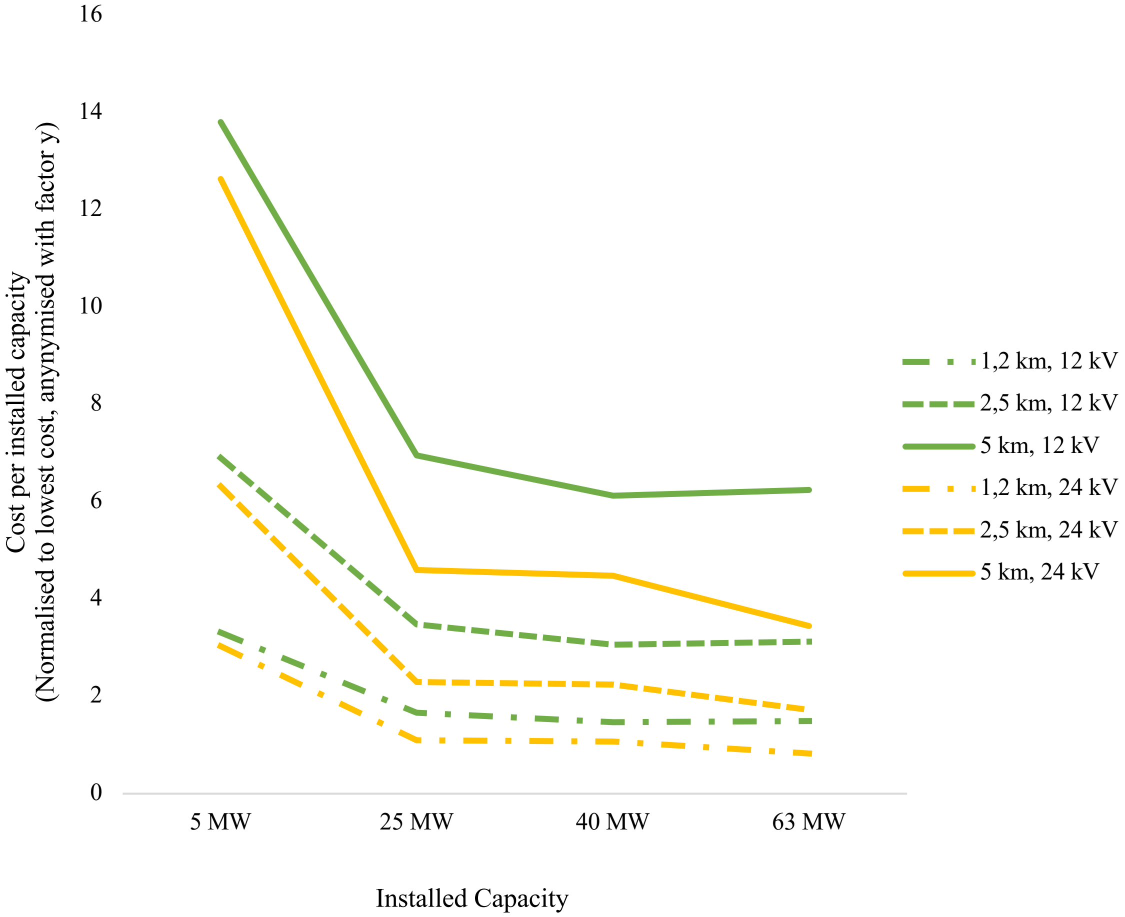


Figure 4.7
Cost of power line per installed capacity (SEK / MW), as a function of distance to power line, voltage, and PV park size. Normalised to case of lowest cost and scaled to anonymise results due to NDA. Source: Swedenergy (2023a).

The average cost of a new power line, based on the eight cases, compared to other initial investments can be seen in figure 4.8. Two effects can be observed, first that there is a clear effect of scale with a distinct decrease in cost with an increase of installed capacity. Secondly, the overall lower nominal currents in the 24 kV case led to the overall use of more common, less expensive, smaller cross-section cables which implies lower overall costs. Overall, opting for building larger GMPV, in higher voltage conditions allows to minimize investment costs for new power lines.

Figure 4.8 also visualises the total initial investments for new GMPV in Sweden. The legend "grid connection" reflects the actual average cost of new power lines built when establishing the GMPV. Considering the Swedish average distance-to-grid today of roughly 1 km and an average, installed capacity of roughly 3.5 MW (Lindahl, 2021), the average cost emerging from this thesis aligns well with actual costs.

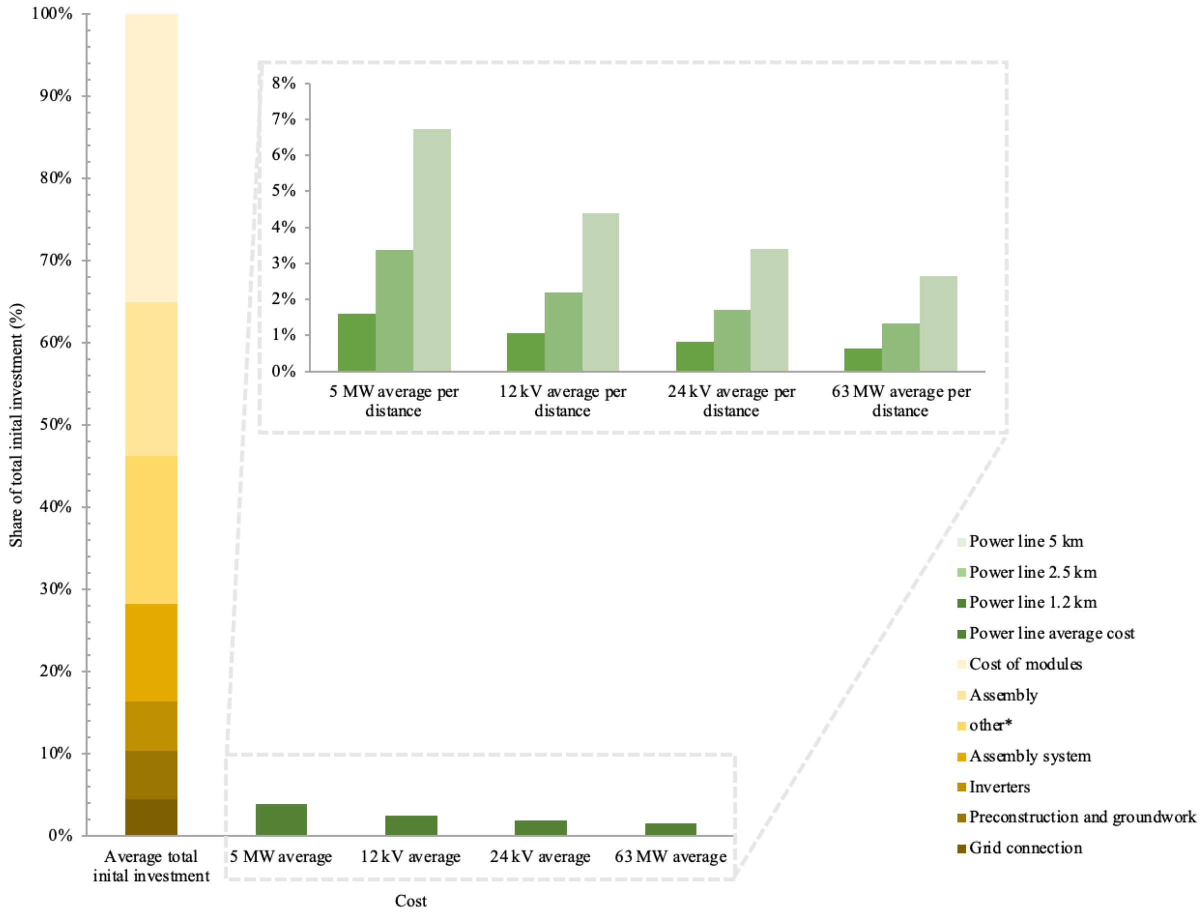


Figure 4.8
Average cost of GMPV components, as share (yellow) of total initial investment per installed capacity (Lindhal, 2021) . The cost of land is omitted. Green established cost for new power lines. Other* includes: *"cables and other electronics, transformer substation. safety and surveillance system, material and work on AC-side, system and production guaranties, signs, service building and fibre installation"* (Lindhal, 2021).

4.7.2 Cost of land

Costs associated with different land use as a function of total initial investment of an average GMPV (Linahl, 2021) are shown in figure 4.9. The employed discount rate becomes of increasing importance with increasing yearly land rents, but does not significantly change the comparison between different land covers and is excluded in the figure. The lowest land rent are associated with pasture, however use of national average could imply that rent is lower than in reality. The highest land rents are given by the highest rents paid by GMPV developers on arable land according to Lindahl (2021), about 25 000 SEK per ha and year. The cost of forest differs as it reflects a purchasing price and not a summarized rent, as such the two components should not be directly compared to each other. The purchasing cost of forest still serves a purpose as it illustrates that it is an alternative to arable land with high rent.

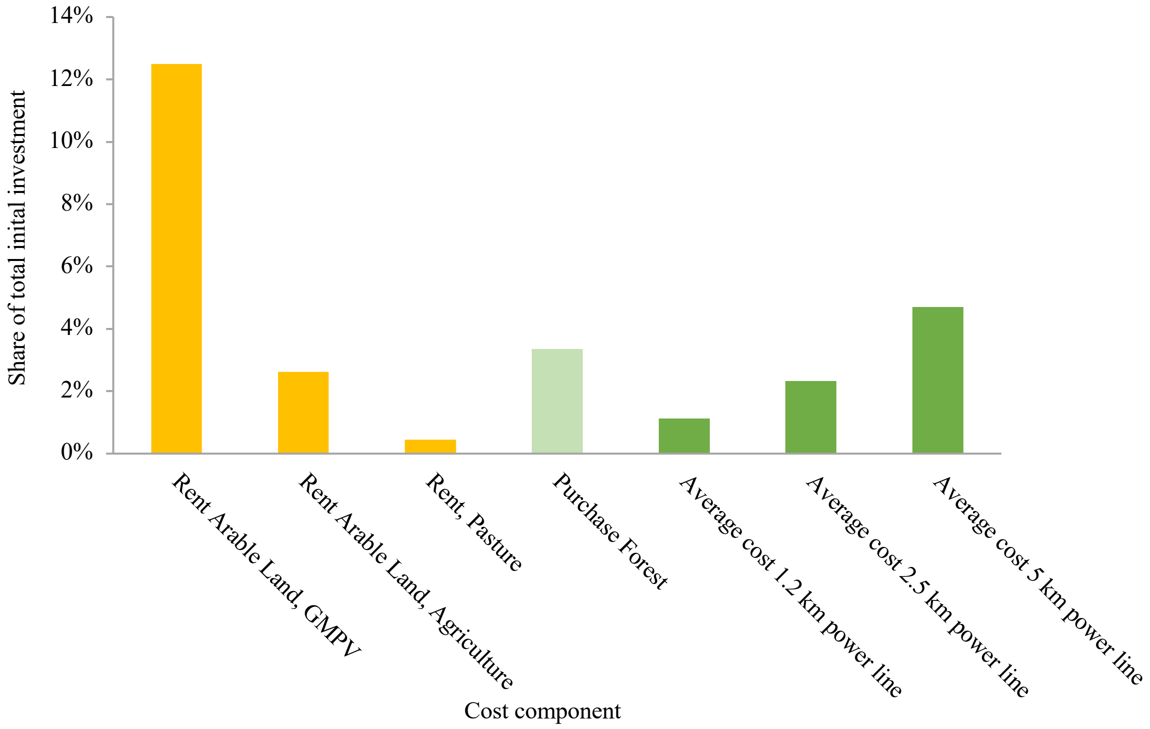


Figure 4.9
Net present value of rents (yellow) compared to cost of purchase of forest (light green) and average cost (dark green) of power lines for each distance, as a share of total investment. Rents summarised in discounted form over lifetime (30 years), 1 and 2 percent discount rate. Source: SBA (2023a), Lindhal (2021)

In figure 4.9 is shown that the variation between the cost of arable land and the price of arable land is larger than average cost of any new power line. Figure 4.9 illustrates a trade-off for GMPV developers, balancing paying a higher land rent to secure a specific plot (the higher rent needed to convince land owner to accept GMPV establishment) of land, or building a longer new power line to an already available plot of land (where no high rent is needed to convince land owner).

4.8 Opportunities for multi-functional land use

The positioning of GMPV in the region of Skåne and Halland have as of today mainly been decided by available agricultural land, in close connection (<5 km) to the regional grid, with swift access to the land, i.e., one current landowner which facilitate acquisition (OX2, 2023; Rise, 2021). However, recent court rulings (MMD, 2023) have shown that these lands are hard to claim for electricity production, due to the legal status of agricultural land declared *National Interest*. Instead of claiming agricultural land, win-win scenarios of multi-functional land use could help enable the continued growth of solar power in Sweden. Two such scenarios are described in this section, together with an estimate of available land, shown accessible by new power lines in the previous section.

4.8.1 Omni-functional use of wetland

One way to achieve increased land use efficiency is to move PV to re-wetted parts of arable land that is on organic soils. When organic soils are rewetted, CO2 emissions reported in the LULUCF (LandUseLandUseChangeForestry) category can be reduced and if combined with wetland photovoltaics WLPV, farm profitability can be increased. This occurs in multiple ways, both as a replacement for any revenue lost (albeit organic soils are associated with relatively low revenues) if the re-wetted arable land was previously productive, and the financial interest on farm-level resulting from the WLPV and its diversified revenues, compared to the financially unattractive wetland.

WLPV can promote the creation of wetlands, an opportunity for increased biodiversity dependent on the biota. Policy measures for re-wetting sufficient organic land to attain GHG emissions reduction targets are in place (SEPA, 2023b), but today the financial risk for farmers when re-wetting is a barrier. The revenue from WLPV could help make up for the revenue lost when re-wetting organic arable land, acting as an incentive to adhere to the policy scheme. This could in turn allow to attain GHG emissions reduction targets for the agricultural sector. It is however unclear to what extent GMPV impact wetland biota and biodiversity (e.g., physical barriers, reflections). An initial strategy to minimise negative impact can involve aiming WLPV developments towards areas with relative low nature values.

The concept of re-wetted organic soils is well understood, but dependent on on-site characteristics. For the concept to be effective, areas of interest should be tested for organic content to make sure that climate mitigation is ensured. This is especially important step during the development stage as data on organic soil is approximative and old. Further research could help identify organic "hot-spots", so that the avoided emissions can be adequately approximated in line with GHG emission reduction targets for the agriculture sector.

In WLPV, either complete fields can be claimed for PV, or patches situated on organic soil with high carbon content (see figure 4.5). There is an interest in focusing on deploying the concept on relatively large fields, partly re-wetted, which provides an opportunity for increased renewable electricity, reduced GHG emissions and continuous agriculture as primary land use, resulting in an omni-functional use of land. Total land available for creating wetland GMPV from re-wetted organic arable land is 3 200 – 9 700 ha, and from felled forestry another 1 000 – 3 900 ha can be found (see table 4.5 for figures in detail). If wetland according to the NLCD is included, limited by possible, socio-cultural constraints, another 4 000 – 14 000 ha can be identified of relevance for GMPV development.

4.8.2 Agrivoltaics

AV systems in the southern part of Sweden have the potential to be a cost competitive source of electricity, but with a negative impact on crop yields. Some argue that AV could deblock the use of arable land for electricity generation, but no proof of eligibility with the Swedish legal framework have been made so far. Crops such as potatoes, forage, sugar beets and grass shows promise as they react positively to increased shade. However, as crops are grown in rotations, the success of an AV system is dependent on the integration of less promising crops as well. Considering initial result from field trials, successful integration of shade sensitive crops such as wheat and maize is challenging. For a successful AV system, a balance between low enough GCR to allow for sufficient solar radiation reach crops, but high enough GCR for an attractive LCOE (Willockx et al., 2022) have to be made. One way of achieving the latter could be tilt axis modules, which have been shown has a higher efficiency at relevant latitudes (B&B, 2023). Lastly, minimising soil compaction by careful land protection measures during installation is vital to maintain yield levels on the food-producing land (Welsh Government, 2023).

Using the GCR while designing the AV system allows for an improved way to control and limit yield losses due to reduced solar radiation, without the need for reference plots and weighting of harvest (Dupraz, 2023). While AV systems are associated with losses during "normal conditions", during hot and dry years the effects could be reversed and lead to gains, specifically for shade-tolerant crops such as potatoes and sugar beets (Weselek et al., 2021; Reher et al, 2024).

The concept of replacing "maize-for-fuel" with "PV-for-Electric Vehicle (EV)" have a big potential for increasing energy efficiency for the propulsion of personal vehicles, by increasing "field-to-fuel" efficiency (Dupraz, 2011; Chatzipanagi et al., 2023). Combining crops with a low solar radiation need, with an AV scheme with an adequate GCR, could in southern Sweden imply a low LCOE (Willockx, 2022). A low LCOE allows for a good potential of profitability, which could help increase PV development and deploy the quick transitions needed to achieve PV and electrification policy targets. In Sweden, maize for fuel is not grown in large scale, where instead other crops, for example some wheat is cultivated for ethanol (and feed co-products) and rapeseed can be cultivated for RapsMetylEster (RME) production (and feed co-products). However, maize, wheat and rapeseed is not only used for fuel, but also as fodder and food, which limits the possibility of substitution. One research question for future work emerging from this conclusion is how many hectares of crops-for-fuel that could be substituted for PV-for-EV in the Swedish context, and what policy requirements such a system change would need. The result from such investigations would show to what extent the pressure on land use could be relieved by switching to a more energy efficient mode of transport.

Overall, AV could enable food and energy production at the same plot of land. However, only pilot-scale projects exist so far, and many knowledge gaps need to be filled before large-scale development. Major challenges that need to be resolved are how to deal with the physical obstacles and its financial consequences, shading effects and its consequences, both on crop yields and for soil characteristics as well as its eligibility with the Swedish law. If AV is to be implemented, local acceptance and thus feasibility of the project is in areas less constrained by possible, socio-cultural factors. In the studied region such areas total 2 000 ha in the least restricted case, and 35 000 ha less restricted case (see table 4.3 for detailed numbers). The total area available strongly depends on proximity to existing population, and what distance is chosen to it (500m, 100 m respectively for the two cases).

4.9 Identifying risks in future climate

Erosion, leading to losses of soil and nutrients most important phosphorus (P), is a major land degradation process that risks to increase in a future climate. As shown in the background, GMPV establishment risk increased soil erosion. An erosion risk assessment on different land covers in Skåne and Halland is shown in Figure 4.10, with present situation (left) and two future scenarios based on rain patterns in two future climate scenarios. RCP2.6 and RCP4.5 (Panagos et al. 2022).

Included in the figure is the baseline erosion assessment (RUSLE2016 of Panagos et al., 2015), with the regional grid superposed (The Land Survey, 2024), followed by the percentual change of the R-factor in two future climate scenarios: RCP2.6 and RCP4.5 (Panagos et al., 2022). Some coastal areas are left out in the R-factor modelling, compared to RUSLE, due to cell size difference. A larger format of the figure is available in appendix V. In both IPCC scenarios, some increase of R-factor is expected, with a maximal change in the central region of Halland (Both RCP2.6 and RCP4.5). In scenario RCP4.5, larger changes are expected with two major zones of change, the same central Halland zone and in the southern point of Skåne.

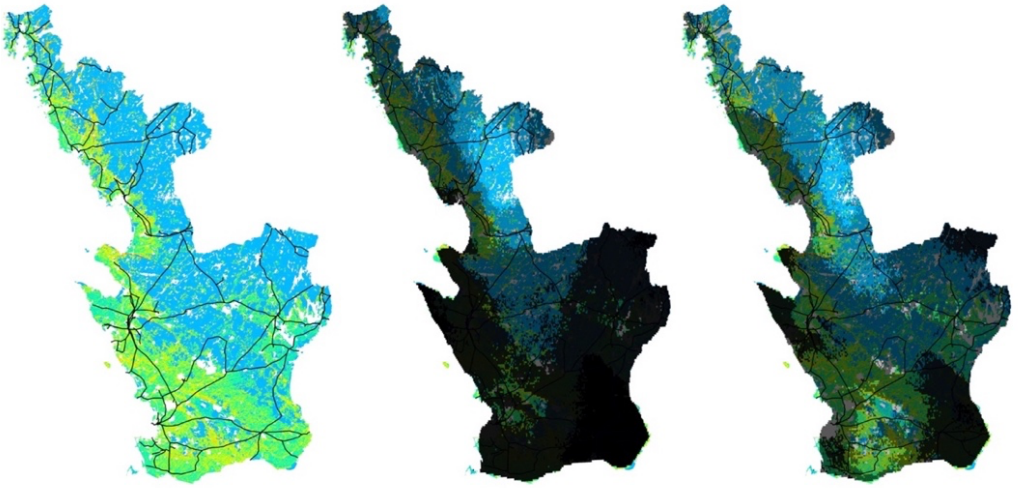


Figure 4.10
Left, baseline soil loss from water erosion in Halland and Skåne in the year 2016 (Panagos et al, 2015), regional grid superposed in black (Lantmäteriet ©). Blue indicate low relative erosion, green moderate, yellow high and red very high. From right, two maps of areas with high potential R-factor change, based on two IPCC scenarios: RCP2.6 and RCP4.5. Dark areas equal less than 40% change, slightly lighter 40-60%, light 60-80% and transparent over 100% change of R-factor (Panagos et al, 2022). As erosion is dependent on rainfall (R-factor), any change (areas in transparency) would imply a risk of increased erosion in the area.

Erosion, associated land use and eutrophication risk areas are visualised in figure 4.11. Land use assessed in relation to erosion consists of agricultural activities (i.e., plots with applications to the EU CAP scheme), and forestry. As visualised by the agricultural fields (in pink) correlating with high erosion (yellow and red) in figure 4.11, areas with relatively high erosion are associated with agricultural activities. As areas of forestry (black) instead are correlating with areas of low erosion (blue), forest are shown associated with erosion. One explanation for this is that land cover is one of the parameters used in the RUSLE2016 equation, and the strong correlation shown above imply land use as dominant factor in case of erosion in the region. Eutrophication in the region is strongest on the western part (left in figure), and a clear correlation of eutrophication and agricultural activities can be observed.

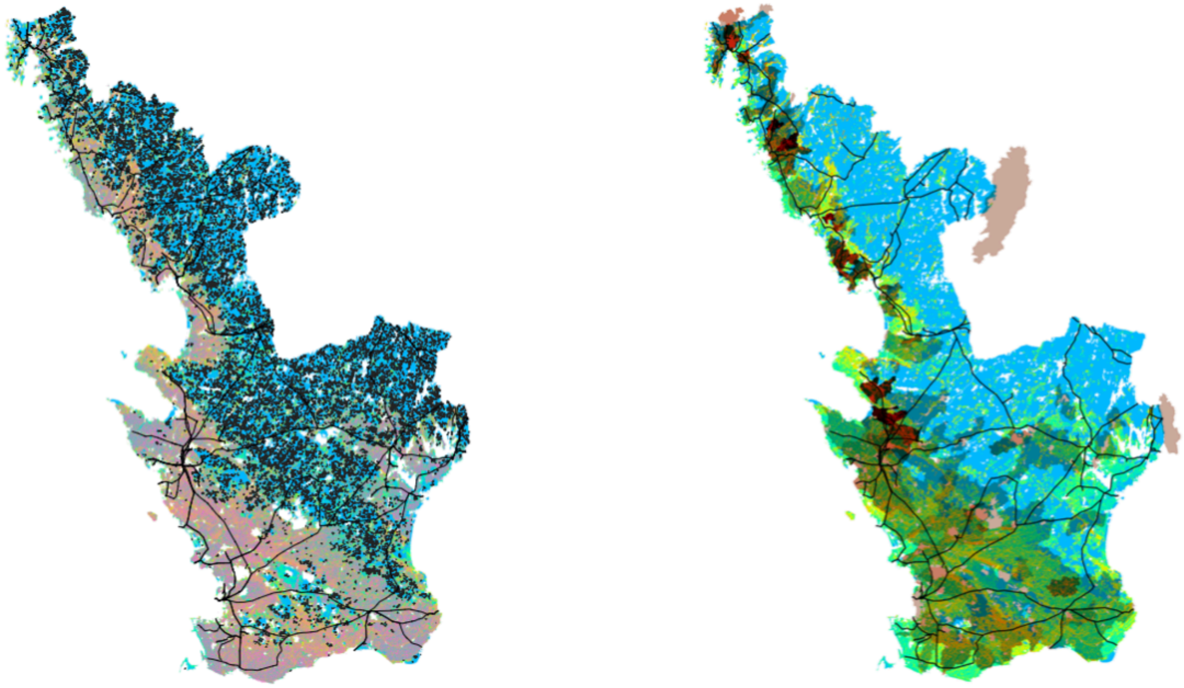


Figure 4.11
Left, baseline soil loss from water erosion in the year 2016 (Panagos et al, 2015) and associated land use (pink agriculture, SBA, 2023, black forestry, Swedish Forest Agency, 2024). To the right, baseline soil loss from water erosion in the year 2016 (Panagos et al, 2015), and Phosphorus reduction need. The redder area, the higher reduction needed, expressed in kg P per hectare and year (VISS, 2024). Black lines indicate regional grid (©Lantmäteriet, 2024).

5. Discussion

5.1 Land use

In this section, implications regarding land use of relevance for the study are discussed.

5.1.1 Land use change

As made visible in the section 4.9 , any change of forestry into open land for GMPV development is likely to increase both erosion and eutrophication due to its correlation with open and agricultural land. If occurring in an area of relatively large potential change of R-factor, that is especially central Halland and in some cases also the southern part of Skåne that effect over time will be amplified. The clear surface below a GMPV system risks increased leakage of nutrients, since less vegetation is available to absorb them and to prevent runoff. There is also a risk that runoff, taking nutrients with it, could be increased by the resulting rivulets beneath the GMPV.

In the case of development of GMPV on arable land, any lost food production must be replaced from other sources. The alternative source in this case is either the intensification of land use, where yields are increased for example by increasing nitrogen input to compensate, or new land is claimed for food production either locally or internationally. The latter thus represent indirect land use change, as the establishment of GMPV indirectly (as well as directly of the arable land) changes the land use in an area different to that of the system.

5.1.2 Changing climate and volatile yields

Further uncertainties lie in the changing climate. Yield levels vary depending on factors like nitrogen input, crop variety, solar irradiation and precipitation. In a future climate where prolonged periods of drought as well as intensified precipitation patterns are increasingly common (Bowles et al., 2018), yields are likely more volatile since drought and floodings have negative impact for yield levels. Therefore, food security is threatened due to risk for fluctuating yields, putting increased pressure on the food production system. While some argue that AV could provide protection against extreme weather events, the dominating effect in Swedish conditions is most likely a reduced production capacity associated with the conversion of arable land and shading effects. This effect, combined with volatile yields have negative consequences for food independence, in a time when much of politic attention is directed toward improving it (SOU 2024:8, 2024).

5.1.3 Implications for land governance

GMPV development in southern Sweden can be seen as a rapid alternation of land use in agricultural landscapes. Land previously governed by farmers (as the actors that is occupying and using the land) becomes governed by energy producers which outcompetes the farmer by deploying a larger financial capacity. In this context, the effect of farmer de-governing is caused by the higher rent energy producers can pay, in Sweden up to almost five times and in Europe as much as 10-50 times (Dupraz, 2023a). The Swedish Environmental Code has until now to some extent protect arable land for agriculture and thus the primary activity of farmers, but not categorically. It is still a highly subjective legal zone, where different CABs can evaluate and weight different societal needs differently, with no legal directives for guidance (CAB Skåne, 2024). Therefore, if GMPV projects continue to establish on arable land, albeit at a planning stadium, it implies a risk for increased cost of land for farmers and the local community, which in turn impact the economic conditions of the residents local to a GMPV establishment.

Further, a GMPV/AV developer could argue that the possibility to pay a higher rent equals a more rational use of land, but many of the negative externalities (that is decreased property values for neighbours, reduced intrinsic natural value etc) that many actors associate with an industrialisation of the landscape (Ketzer et al., 2019, Biro-Varga et al., 2024), is not reflected in that price. To ensure a fair use of land, where the cost of externalities is compensated in a fair way, it is thus important to include impacted actors, for example in a co-ownership were part of the revenue generated of the PVs are shared within the local community.

However, not only farmers and the local community are impacted of the changing land governance. The many GMPV project stopped due to the legal status of arable land shows that the change is also a problem for developers within the technology. If renewable energy targets are to be reached, such barriers must be overcome, and this thesis has shown that using other land than arable land is an option. If arable land however is deemed needed for higher prioritized societal interests, as is the case for current GMPV that have been allowed on arable land, another option would be to minimize the change of land governance. One example of how to achieve the minimization of land governance can be by imposing a new, adapted, legal framework. For example in French projects, where GMPV developments are explicitly banned from arable land, a clear focus on achieving a farmer's green transition can be identified by helping to integrate energy production within farm activities, i.e., the creation of a AV system (OX2, 2024). In contrast, Swedish projects focus on large-scale GMPV on arable land (ibid.), competing with farm activities. One potential explanation of the Swedish development is the lack of regulation, a second could be the import dependence of the Swedish PV market (Andersson et al., 2021). This dependence has in turn led to a development driven by entrepreneurial forces. Hence the focus from GMPV developers on arable land with minimal distance to the grid, which is argued the most cost-effective "rational" method. Such forces dominating development is not without implications for land governance, as GMPV developers are new "agents" using the agricultural landscape, imposing new economic conditions.

Overall, companies and regional authorities alike have the need of a common definition and legislation, for guidance. However, rushing the development might benefit specific actors and expose others. One risk is that if not based on thorough understanding, there might be backlash from unforeseen consequences. It is thus important to include actors from multiple disciplines and minimise change in land governance so that food and energy production can exist in synergy rather than compete against one and another.

5.1.4 Possible approach for detecting relevant land areas

To include a multi-disciplinary perspective, the result of the method developed in this thesis can be used to assess potential use of land with an associated potential for PV capacity in a region. Figure 5.1 shows the total area of the different land covers in Skåne and Halland. Each part of the pie-chart has a specific radius, equalling the size of the land cover category. Inside the pie-parts, potentially used shares (green) are shown. As illustrated in figure 5.1, the used shares provide an opportunity for regional actors to, following a bottom-up methodology, assess available land and associated potential installed capacity. By doing a focused inventory of each land cover category, not only could a realistic amount of available land be identified by including relevant actors. Examples of this could be farmer led AV-schemes with local acceptance, in which case energy and food production and resulting revenue is included in local activities, or a locally co-owned GMPV on open wetland with low nature value, where (some of the) revenue is recirculated in operational costs of both the GMPV and the maintaining of the wetland.

One challenge consists of finding a standard for designating which land is readily available, as grid distance and availability, as well as busbar slot availability often are characteristics that are not publicly disclosed by PV developers and the DSOs respectively. The publication of such information is unlikely due to security reasons, it is thus highly important to also include these actors in the planning phase. By including both actors, the PV developer have the possibility to provide input for the selection of relevant land (i.e., distance from grid/transformer) and the DSO in turn might work in parallel on grid reinforcements.

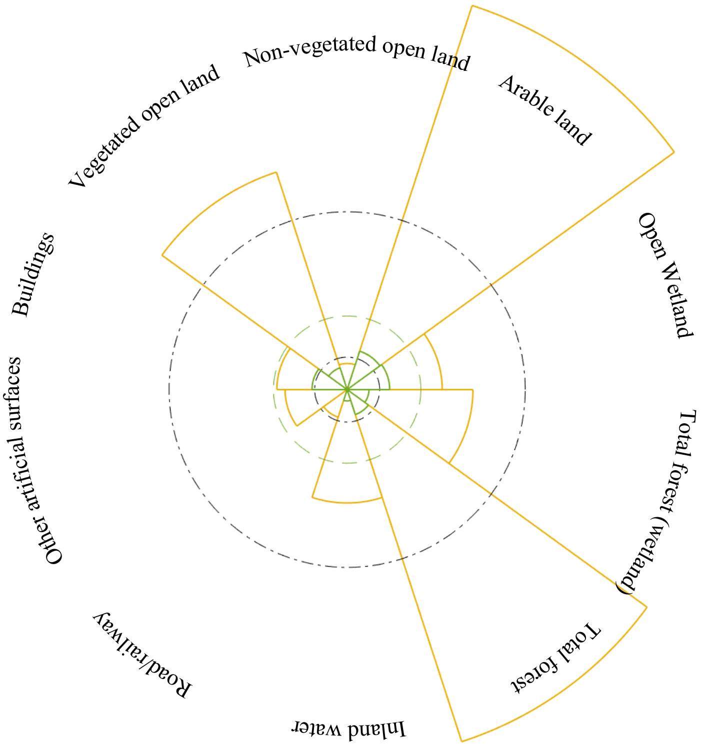


Figure 5.1
Land cover share(yellow) and used fraction(green). Radius equals relative land cover size. Dash-dot black circle indicates land requirements for 1 and 30 GW, respectivel. Dashed green circle indicates resulting capacity from used shares in the example (about 5 GW).

Shifting the focus from exclusive use of arable land, figure 5.1 shows an example based on land cover within 2.5 km of the regional grid, resulting in roughly five GW of installed capacity in the region of Halland and Skåne. The example illustrated in Figure 5.1 is not given to illustrate any optimal GMPV establishment on various land cover, but to illustrate an example of how of the result of the thesis project can be applied. In table 5.1 the parameters used to obtain figure 5.1 are listed. *Power densities* and *total areas* are based on findings for Skåne and Halland from this thesis project, while *shares used* is part of the total area dedicated to PV’s and is chosen arbitrarily to illustrate the exemplified methodology for policy design.

Table 5.1
Land cover 2.5 km distance-to-grid class, used share and power density for proposed policy design example.

Land type	Total area (ha)	Share used (%)	Power density (MW / ha)	Comment
Open Wetland	15 720	20%	1.84	GHG mitigation
Arable land	284 650	1%	0.8	Using constrained, organic and abandoned land
Non-vegetated other open land	1 190	0%	0	Unknown potential due to input data quality.
Vegetated other open land	91 250	1%	1	On anthropogenic land (GMPV) and pasture (AV)
AS*, building	8 590	25%	2	In line with regional rooftop-PV potential
AS*, not building or road/railway	6 710	0	2	Industrial sites, not available
AS*, road/railway	1 470	0%	0	Not possible due to owner structure of land
Inland water	22 430	1%	1.84	Floating PV
Total forest (outside wetland)	239 140	0.5%	1.84	Recently felled forests, constrained
Total forest (on wetland)	27 528	3%	1.84	GHG mitigation, recently felled forests, constrained

* Artificial Surfaces

By establishing the shares of available land cover that could be deployed in practice, using the proposed bottom-up methodology from above, a snapshot of a region's PV potential can be visualised. When established, the snapshot can be used by relevant actors such as the government, solar power developers and/or local DSO's to understand needs and challenges, as well as possibilities. At national level, regional assessments can be integrated to form an understanding of overarching themes and policy needs.

An illustrative example can be made by considering a region where the CAB identifies low availability for PV on buildings. As a result, the CAB may conclude that deploying PV on arable land or VOOL is the only viable land cover option. They would then update regional planning accordingly, focusing on areas with low competing interests. Simultaneously, the DSO in the same region could gain a better understanding of the future grid needs, informed by the CAB's work, working to facilitate the deployment of GMPV in the region by updating the electrical grid.

In contrast, suppose a second region has a large amount of roof space on buildings compared to arable land and VOOL. Here, a different potential is identified. In such a region, aiming for multi-functional land use and minimal land use change, solar power development is more likely to occur on rooftops than GMPV with high energy density. These examples illustrate how different available land covers have implications for a region's specific needs, highlighting the importance of considering regional effects when designing potential policies on a national scale.

One specific area of use of the proposed approach is in the "investigations of localisation" (Swedish: *"lokaliseringsutredning"*). The investigations are often the barrier on which a permit application is denied, as in the case in the court of appeal (MMD, 2024). However, the design of the investigation and what it should consist of is still very much an open question. Here the proposed approach can be used to establish a methodology for executing the investigation by assessing the land cover characteristic of a region, missing today and in demand from both developers and regional authorities (CAB Halland, 2024a).

Developers might initially be reluctant to long lead times of more participatory-based project. However, current conditions where non-participatory, un-regulated/-governed planning and development which are ultimately rejected for legal reasons, leads to uncertainties. This is illustrated by the debate where concerns for slowing down are heard. A participatory-based project thus implies a trade-off for developers, where some control would be sacrificed for increased probability of the project to materialise. Further studies are needed to show how initial inclusion of local actors and place-specific characterist in the project planning phase influence local resistance during development phase compared to a project governed by less internal actors, and how local acceptance eventually impacts a projects possibility to materialise.

5.2 Very large-scale GMPV parks

To assess the economic dynamic involved with increasing distances between GMPV and the regional grid, two key preconditions of the regional grid where assumed: distribution power lines operating at either 10 (12), 20 (24) kV and substations with transformers rated at either 40 or 63 MVA with space at busbar for connection available. Up until now, the largest GMPV parks of Sweden does not surpass maximum capacity assessed in this work (63 MW), but many applications currently on the desks of regional authorities in Skåne and Halland are bigger (CAB Halland, webinar, April 24). If these very large-scale GMPV (VL-GMPV), of more than 63 MW installed capacity, are established, their connection to current grid will imply a big change. Such parks would surpass the capacity that current substations can handle and thus would need updated or new substations. Any new transformer would likely be placed on the VL-GMPV plot, which implies a different cost structure compared to when connecting to an existing transfomer (Jimmy Ehnberg, Chalmers University of Technology, pers. Comm., mars 24). From a technology perspective, the two (GMPV and VL-GMPV) are in a Swedish context best understood as two different technologies, like on and offshore wind, as the electrical infrastructure and preconditions vary to such an extent.

Considering the previous chapter, establishment of GMPV as of today (<63 MW installed capacity) would be in close proximity to not only the regional power lines, but also close to existing transformers. Thus, a focus on land cover within a specific distance to existing transformers could be argued as more suitable as evaluation criteria compared to regional power lines. The distance from the GMPV to the regional power line is however still the most important, as it reflects potential future developments. Another way of framing the methodological choice is that focusing on existing transformers would allow to assess where land more *probable* to be used, whereas focusing on land area around existing regional power lines results in a study where *potential* land is assessed. The methodology eventually used aims to be a combination of both, by assessing the *potential* land that could in theory be used, by focusing on the most *probable* technology to do so.

As initial investments are a large share of overall costs associated with the development of a PV park (Lindahl, 2021), any big increases of these cost can have implications for the LCOE, and thus PV park profitability. A brief assessment of price guidelines for electrical infrastructure development (Swedenergy, 2023b) , indicates that building a new powerline, either 20 kV or 130 kV, and connecting it to an existing substation is far cheaper than building a new substation and powerline. However, the cost structure of connecting on a higher voltage is different. Higher voltage implies lower losses, reducing costs, and tariffs from DSO are different. The trade-off depends then on both needed infrastructure and associated cost and is probably a thesis work in its own.

Judging from applications for work permits, VL-GMPV developers are ready to gamble on the risk that a project will bring with it reinforcements of the grid in the concerned area, which in turn will enable the project to be developed at full scale. If no such parks are envisioned, reinforcements will probably not be made which would have been able to support such solar capacity. This in turn does not create any possibilities for VL-GMPV and following this logic any establishment would have to create its own need for reinforcement of the grid (be it improved, digitalised transformers and sub stations, energy storage or transmission capacity).

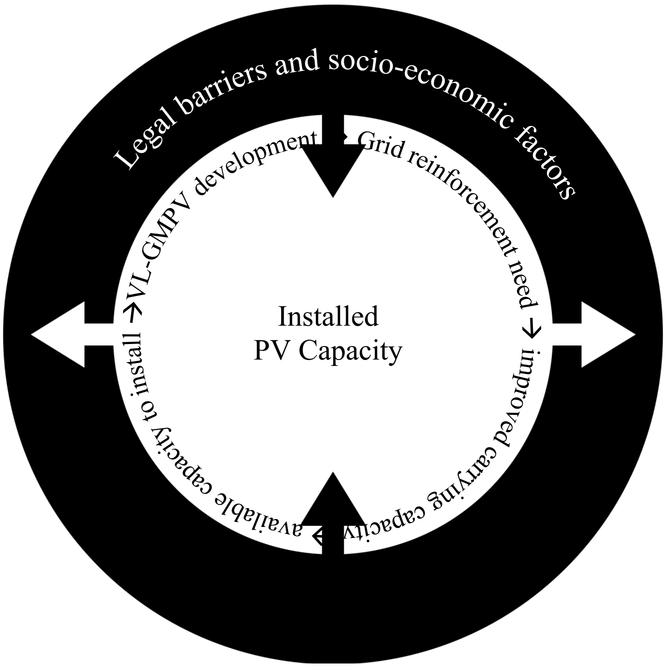


Figure 5.2
Proposed interaction society – energy producer – grid operator, result, needs and opportunities. Growth of GMPV capacity depends on interaction between internal factors (grid operator and GMPV developer), as well as external (local demand, acceptance, and legal conditions).

The interaction between DSO and PV developers described above explain why in work applications developers seek to establish VL-GMPV, even if limitations of the current grid does not allows any installed capacities over the closest transformer's power rating. As previously touched upon, and further motivated here, the question of how any new investments in infrastructure would be split between actors is a highly relevant area for future research. Another aspect is the role of regional authorities, as developers are also dependent on construction and environmental permits. Any findings from an analysis based on system perspective, linking the roles of actors such as grid operators, energy producers in the region and its authorities would without doubt be highly relevant for future research. A framework for future studies is suggested in figure 5.2 which shows growth of PV as a function of technological (internal) factors and land governance as well as policy/political (external) factors.

5.3 Technologic opportunities

In this section, potential technologies identified as relevant for the study and opportunities that arise with them are discussed.

5.3.1 Combined emission reduction, crop, and electricity production in wetland PV

Establishing GMPV on organic soil re-wetted to create a wetland allows for a synergy effect. It allows farmers to establish PV on land that is hampered by low profitability due to soil conditions, remove a source of GHG emissions and conserve integrally the part of the arable land that is productive for food production. It could be included in the AV concept as an example of land sparing, removing food production from directly underneath the PV's, to replace with another function in climate mitigation, while maintain full food production outside the PV's. Thus, decreased yield on a field level is limited to only part of it, arguing for a new form of AV. A visualisation of the concept can be seen in figure 5.3, showing the sequence going from organic arable land, to AV, to WLPV.

While the use of agricultural land for GMPV is seriously restricted, to not say forbidden, according to rulings in the Land and environmental court of Appeal (M 13461-22, 2024), PV on wetland is potentially legal. By changing the land use from arable land on organic soil to re-wetted wetland for climate mitigation, a second use of the wetland could be to produce renewable solar electricity. The PV modules can be mounted on piles anchored in the wetland, which have been shown to be feasible and cost-competitive at least in one instance with a LCOE of 87$ per MWh, roughly 93 SEK per kWh (Javeed et al, 2023).

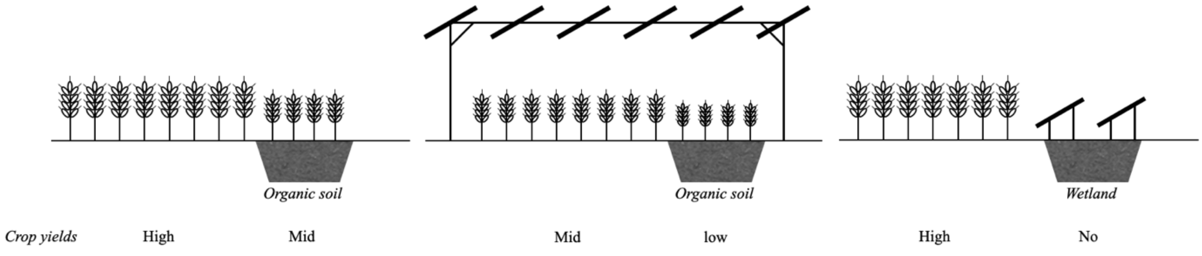


Figure 5.3
Illustration of proposed WLPV concept. Initial conditions to the left with low-yielding crop on organic arable land. Second from left integration of elevated AV system, lowering yields due to decreased solar irradiation at plant level. Right, high-yielding crop on non-organic soil maintained, with organic soil re-wetted to create wetland followed by GMPV system integration.

Considering that the practice of re-wetting Organic soil is understood to be the most effective measure to reduce GHG emissions associated with such soils, an interesting opportunity can be noted. Current policy scheme is deemed sufficient for attaining the target of 10 000 ha, which roughly corresponds to the amount of Organic arable land in the region of Skåne and Halland. However, without financial support, the target is not likely to be met as farmers are reluctant to adopting re-wetting. Integrating a new revenue stream from the WLPV system could be the lever that enables the achievement of the re-wetting target. The loss of value from land and harvest, would be compensated by the sale of electricity from the WLPV system,

Establishment of WLPV still consists of land use change. In countries where a legal definition of AV exists, a law could prove the concept of PVs on re-wetted arable land ineligible with the AV concepts, as is the case French law on Agrivoltaics Art. L. 314-36. – II– 2° . The law stipulates that while AV is a measure for adaptation to climate change, it must be coupled with agricultural production being the principal activity of the land. However, this allows for some flexibility as the term land does not clearly delimit what should be considered. It might be that if a sufficiently small share of the arable land is converted, agricultural production would still be the principal activity of the land. As illustrated in figure 5.3, it is possible to construct a scenario with a wetland of a size so that the where the high-yielding non-AV, non-wetland field produces more total yield than the AV system, whose yields are impacted negatively from both the shadow effects of the AV system, and soil quality of the organic land.

Even without resigning to legal frameworks, agricultural practices are *de facto* abandoned when re-wetting land. While some food-production is lost, organic soils are often associated with unprofitable agriculture, and therefore they might represent an opportunity to reduce carbon emissions from the agricultural sector, which is a challenge considering the hard-to-abate emissions. To resume, making sure any GMPV built on arable land is built on re-wetted organic soils allows to compensate for lost food production not only by providing renewable electricity, but also to reduce GHG emissions of the agricultural sector in a cost-efficient way. Further, the target of re-wetted land in some cases have already “acted” an associated reduction of food-production – hence the opportunity to make a case for even more land use efficiency gains.

5.3.2 Agrivoltaics

Crops are grown in rotations, to minimise diseases, fungi, and negative soil impacts. It is thus not possible to grow, for example, exclusively organic potatoes as conditions would quickly deteriorate with dramatic negative consequences for yields. So, while in theory, as suggested by early literature on the subject, an AV system could be designed to maximise PV electricity production and potato or sugar beet yield, in real-world conditions, potatoes or sugar beet would only be grown every x year. Depending on rotation, the rest of the time other crops, such as cereals or rapeseed, would occupy the field. Crop rotations are a result of generations of gathered knowledge of farmers, and deviating from them can risk the spread of deceases, fungi and poor soil conditions. It is thus very unlikely that any AV scheme focused on only shade tolerant species would provide reasonable yields on the long run, as decease and fungi build-up in the soil as well as decreased soil quality would drastically reduce yields after a few growing seasons.

To prove the AV concept, longer studies are needed to assess what shading effect implies over long term. If gains during hot, dry weather are larger than losses during corresponding conditions, the net benefit could be improved yields. However, there is a risk that the relatively large potential losses compared to potential gains leads to an overall net-decrease in yields. This is, of course, dependent on the ratio of hot and dry conditions compared to “normal” years. Further, scaling to larger fields and commercial production will likely imply technical challenges, AV systems must be made sure compatible with agricultural machinery and practices. Irrigation and access to, as well as physical clearance of machines such as harvesters, are important aspects that could seriously impact the feasibility of a AV project.

Table 5.2
Preliminary crop areal (total ha) and share of total arable land per region for the year of 2023, for Skåne and Halland. Summarised for crop type. Source: SBA (2024b).

	Skåne	Share	Halland	Share	Total	Share
Cereals	205 217	47%	42 734	40%	247 951	46%
Rapeseed	47 854	11%	5 286	5%	53 140	10%
Sugar beets	27 815	6%	649	1%	28 464	5%
Potatoes	11 100	3%	1 823	2%	12 923	2%
Lay	102 459	24%	43 741	41%	146 200	27%
Fallow	7 122	2%	2 618	2%	9 740	2%
Peas and other leguminous	10 501	2%	3 448	3%	13 949	3%
Maize	8 059	2%	3 839	4%	11 898	2%
Vegetables, etc.	8 859	2%	632	1%	9 491	2%
Energy forest	1 744	0%	125	0%	1 869	0%
Other	2 463	1%	779	1%	3 242	1%
Total arable land	433 193	100%	105 674	100%	538 867	100%

The inclusion of AV in crop rotation is not the only technical challenge. No commercial scale AV scheme exists today, and small trials are of limited relevance for today's large-scale agriculture with highly specialised machinery. Commercial scale AV likely to be deployed on large fields (multiple hectares) for scale effect, and modern agricultural machinery such as harvesters, drillers and fertilizers are not developed to incorporate structures within the field it operates on. Further, AV have social implications as well. Ketzer et al (2023), shows that it is important to include locals at early stage, as acceptance is not granted only because agricultural activates are continued.

One way of achieving such acceptance is stakeholder interaction (Ketzer et al., 2021, Sirnik et al., 2024), so that key conditions are identified. Another way to improve acceptability could be sharing of revenue from electricity sales in a co-ownership scheme. Including the impacted stakeholder of the project, local acceptance might be higher as a "price" of implementation becomes a "trade-off" between lost nature value and new source of income. As no fixed cost is imposed on the project, but instead that a share of profit is redirected, the model minimises risk as no payments must be done when the plant is not producing.

5.3.3 From "Maize-for-fuel" to "biomass-for-fuel"

Maize as an energy crop is potentially impacted by the electrification of society (as suggested in Dupraz, 2023a), where GMPV could play a substitutional role. In a Swedish context, the main energy crops are instead wheat for ethanol, rapeseed for RME, and wood as bioenergy source. Wood as a biomass energy source often is focused on use of by-products (such as wood chips), the potential revenue that a GMPV park is associated with could possibly surpass that of wood production and use of by-products. One example of impact is the intended use of biomass for bio-energy with carbon capture and storage (BECCS), where an increase demand on limited biomass due to energy demand from capture processes is expected, putting the forests under pressure. If part of these processes could be electrified instead of using biomass as energy source, and that the electricity comes from a GMPV system on recently felled land, it would result in a possibility of a BECCS system with smaller impact on biomass availability. Therefore, less biomass would be used for process energy, lowering the total needed biomass for energy. An interesting question for future work would then consists of how and if a substitution of energy source, from biomass to GMPV, to the expense of a share of forests, in a BECCS plant is possible.

However, as in the case of AV, one precondition that poses problem for the idea of substituting the energy pathway, is that wheat and rapeseed are components in a crop rotation. Thus, while some wheat and rapeseed would be substituted, other crops grown in the rotation for food or fodder would need to be replaced, putting pressure on food production and on arable land. For the concept to be successful, careful planning and design of the system would have to be made to enable the new energy pathway without losing involuntarily associated food production.

One factor that could influence the relevance of the concept of substituting crops for energy with PV for electricity is the recently decreased reduction duty (Swedish: “reduktionsplikt”) of fossil fuel carried out by the Swedish government in 2023. This reduced reduction duty in theory decreases demand on energy crops, and argue for a transition from energy deficient “field-to-fuel” based on internal combustion to a more efficient AV-electricity-EV on associated land. While substituting wheat and rapeseed would increase energy efficiency of the transport sector, it does not provide any solution to the competition on land that GMPV development on arable land results in. Wheat and rapeseed are crops that on a yearly basis can be either planted or not according to a crop rotation, whereas a PV park have a lifetime spanning multiple decencies with risks of negative impacts on soil quality.

6. Conclusions

In this chapter, conclusions based on findings from the thesis try to answer the four research questions stated in the beginning of the report. The conclusions are initially formulated as a bullet list with key results: Then follows four themes, one for each research question, that captures the most important findings corresponding to each research questions. In the end a last theme addresses potential future studies identified. The key results are:

- GMPV establishment today has a clear focus on arable land close to regional grid.
- Two potential multifunctional land uses were identified: Agrivoltaics on less constrained land, and re-wetted organic arable land.
- Less constrained land in the region count at least 8 000 ha, organic agricultural land 4 000 ha.
- Accessing less constrained plots is possible, as cost of new longer power cable is compensated by lower land rent.
- Physical planning can identify suitable land for GMPV with low competing interests.

6.1 Characteristics of GMPV in Halland and Skåne

GMPV of large scale (installed peak capacity in the range 1-63 MW) in the region of Halland and Skåne have up until now been built on arable land, near electrical infrastructure of the regional grid. Development is governed by factors such as cost/rent of land and proximity to grid, with less regard to natural values. Within the scope of the thesis, all assessed GMPV have been built on arable land, at an average distance from the regional power lines of 800m, with a corresponding average distance to the closest electrical sub-station of 1800 m. A typical installed capacity of GMPV in Skåne and Halland ranges from 1 to 25 MW, with panels mounted either in portrait or landscape on a steel structure. The structure itself anchored to the ground with steel beams.

The results from the quantitative assessment of this thesis are also backed by findings in the literature review. The results indicate that a majority (50%) of GMPV developers considered *cost of land* and *proximity to grid* as a governing factor during the design phase. A relatively small share of developers considered *acceptance from locals* (30%), *consideration to valuable arable land* (20%), *consideration to valuable natur*e (20%) *and increased profit for landowner* (10%). Thus, overall, a qualitative perspective on land use have been missing in the current GMPV development, instead focusing solely on techno-economic aspects (with some marginal consideration for biodiversity and livestock integration). The importance of addressing the perspective is further motivated by the status of valuable arable land as *national interest*, eventually causing the rejection GMPV projects on such land.

Considering applications for future GMPV, a focus on bigger parks is visible, with parks of installed capacities from 50, 150 or even 600 MW having been identified. As shown in chapter 4.1, this trend likely leads to an increased focus on arable land, as it is the only land cover that includes continuous plots of large size (>10 ha). If established, these projects would have large implications for the electrical grid, both on demands for increased carrying capacity to cope with increased power, as well as for substations, where transformers today are not rated for such high power. A second future trend identified is the shift of focus from arable land to include other land covers. Examples of projects in planning phase of large scale GMPV (>63MW) have been identified, both on cleared forest, and on wetland. One pilot plant believed to be in the region of 6 MW, of AV have been identified. While this thesis has not investigated any total potential for GMPV, assuming an energy density of solar parks of 1.84 ha / MW would result in the need of allocating nationally roughly 30 000 hectares for GMPV to be in line with SVK's long term market analysis. This can be compared to the total available area of arable land, forests and wetland that, using possible constraints, amounts to 6 000 ha (>500 m to closest population) to 60 000 ha (>100m).

Table 6.1

Description and characteristics of land cover sub-classes. Sub-Classes used stemming from NLCD (SEPA, 2024). Relevant areas corresponds to findings in study.

Land type	1.2 km	Total area 2.5 km	(ha) 5 km	Energy density	Relevant area (1000 ha)	Cluster	Population density	Typical current land use	"Win-win"	Comment
Open Wetland	8 745	15 750	26 621	Average	5 – 20	Environmental mitigation	n/a	carbon sequestration / emittance	WLPV	Except Nature Reserves
Arable land	167 784	284 658	432 003	Low-Avg.	5 – 50	All three	high	Food production	GHG mitigation	Organic and/or less constrained land
Non-vegetated other open land	597	1 208	2 685	0	n/a	-	low	Anthropogenic activity	-	Remote (?) Industrial sites
VOOL*	49 670	91 285	143 691	Low	20 – 120	Land Use Efficiency	High	Grassland, pasture, lawns, golf courses and roadsides	Increased land efficiency	Low energy density due to need of low GCR
AS**, building	4 381	8 580	11 855	High	n/a	Land Use Efficiency	n/a	Roofs	Increased land efficiency	High energy density due to high GCR
AS, not building or road/railway	3 608	6 675	9 023	Average	n/a	Land Use Efficiency	low	Airports, parkings, pits and mines	Increased land efficiency	Marginal use possible but not studied
AS, road/railway	917	1 468	2 223	0	n/a	-	n/a	Physical road excluding roadsides	-	Unfeasible due to land ownership
Inland water	11 353	22 413	45 360	Average	Not assessed	Environmental Mitigation	high	Lakes and waterways	e.g., Decreased evaporation	Floating PV
Total forest (outside wetland)	126 266	239 140	406 948	Average	11 – 36	Energy Efficiency	low	Forestry	Increased energy efficiency?	Limited to final fellings, and notified for clear-felling, of forest
Total forest (on wetland)	14 299	27 528	48 835	Average	3 – 10	Environmental mitigation	low	Forestry	WLPV, GHG mitigation	Limited to final fellings, and notified for clear-felling, of forest

* Vegetated Other Open Land, ** Artificial surfaces

6.2 Overview of GMPV on different land covers, benefits, and trade offs

One inherent challenge to GMPV development is the proximity to the population. The challenge is that the condition for land, to be in proximity to grid to be relevant for GMPV, also hold for the population. 91% of the region's population lives within a 5 km buffer around regional power lines, and 86-89% of arable land in that buffer is within a 100 m distance to closest population. Secondly, any new requirement on land usage in the region, dominated by anthropogenic activates, will lead to either intensified use of limited land, or land use change to arable in an area where other land is available, an example of indirect land use change.

A third challenge, which is due to the current use of arable land for GMPV is changing land governance. By allowing a competition on land, were one actor (energy producers) has more financial power than the other (farmer), the control of arable land risks to change from the food to the energy production section. This in turn can impact food production in two ways, both by losses in food yield and land, but also by denying farmers (new/old) access to land on financial grounds, triggered by the uneven playing field.

Table 6.1 presents in a summarised form land covers and usages within the three distance-to-grid classes 1.2, 2.5 and 5 km, which have been shown relevant for GMPV development in this study. Energy density compares to Swedish GMPV average of 1.84 MW / ha and is based on deployed solar power technology. In the column "win-win", three clusters of land covers named Environmental Mitigation, Land Use Efficiency and Energy Efficiency are shown. In the clusters potential win-win scenarios, that is a clear multi-functional use of more than electricity generation, have been identified.

Environmental Mitigation includes three land covers, Open Wetland, Arable Land and Forests. Carbon emissions can be restricted when organic agricultural land is re-wetted to wetland, and wetland can benefit from increased resilience induced by shadow effects from GMPV. For inland water, panels can help reduce evaporation, increasing water availability, both being of increasing importance considering an in the future changing climate. For forestry, only partly covered in the study due to time constraints, it is likely that current felling practices would have to change to enable GMPV establishment. This is due to the of small size of plots from finally felled forests, compared to GMPV need. For reference, an GMPV park of average size (installed capacity of 3.5 MW) would require almost 7 ha, and with current felling practices about 10% of plots are larger than 7 ha. Removing forests from production results in change in carbon stock, increasing GHG emissions from electricity stemming from forestry-GMPV. Further, forests are associated with low(er) solar irradiation due to higher levels of shadowing and cloud formation, limiting electrical efficiency.

Land use efficiency is achieved by increasing the total use of land, on land where anthropogenic activities are already dominating. The prime example of the cluster is roof-top PV. Further areas of interest include artificial grassland and lawns, with some potential for combination with AV systems on pasture and arable land. However, pasture and arable land, are directly involved with a competition on land for food production. Considering impacts on carbon stocks, converting arable land to pasture involves some carbon sequestration. The increase of carbon stock is however limited to the lifetime of GMPV system, and is lost if reconverted to agricultural use. Challenges associated with establishment of GMPV on agricultural land identified includes: risk for increased runoff, negative impacts on soil organic carbon, mechanical compaction during construction and deconstruction as well as leakage of nutrients. Adding the risk of change in land governance when energy producers can compete with farmers, a thorough understanding of impacts, effects and consequences on food production and security should be established before large-scale GMPV deployment on agricultural line to limit conflict of interests.

The last cluster, emerging from the literature review and with expanded scope in a Swedish context is Energy Efficiency. By technological substitution of an energy system of low energy efficiency, such as the case *"maize-to-fuel"* (Dupraz, 2023b), in a Swedish context updated to *"biomass-for-fuel",* for a high energy efficiency equivalent to *"PV-for-EV"* (ibid.), electricity can be generated and reduce pressure on biomass at the same time. More research is needed to fully understand the potential impact and challenges for this specific technology, but the transition is seen of high potential for the transport sector, where electrification involves much higher efficiencies going from energy to propulsion.

6.3 Economic consequences

Due to the low operational costs of GMPV compared to total initial investment, it is possible to focus on the latter to understand and assess economic consequences, when varying key parameters such as distance to grid and land cover. For eight cases of GMPV dimensioned on current grid characteristics in the region of Skåne and Halland, the cost of a new power line is lesser than the variation in rents paid by developers. Hence, a trade-off is imaginable where less expensive lands on plot further from the power lines can compensate for the higher total initial investment of new longer power lines.

Two criteria were shown to imply the lowest investments costs, higher voltage condition (in the studied region equalling 24 kV), and bigger scale. Bigger scale, from around 25 MW and above led to a reduction of costs per installed capacity for both mid-high (24 kV) and mid-low (12 kV) voltage conditions. In the 12 kV case this effect was reversed in the 63 MW scenario, as the nominal currents in power lines meant the need to resort to "overly" expensive cables. However, as shown in the background, it is not possible to select voltage according to preference on a specific plot. Instead, it is the local preconditions of the regional power lines that dictates what voltages are relevant for the GMPV.

6.4 Ways forward

To build upon the results presented in this study, a thorough assessment of costs for preparing the different land covers for establishment of GMPV (e.g., trunk and stone removal in forests) would enable a further dimension to the thesis. Including land covers available, cost for a new power line on a specific distance, and for the land covers specific cost for preparing the land would enable, coupled with assumptions on availability of land and total demand, an analysis of total GMPV system cost. This analysis could be made in two ways, either aiming at a specific target of installed solar capacity and optimising for lowest cost or assessing the available land and establishing the resulting energy supply and cost.

As GMPV on cleared forest land is thought to represent a likely pathway for solar development in Sweden, further investigations of challenges and opportunities are needed. Such challenges and possibilities includes: land use and change, covering but not limited to impact on carbon sinks and biodiversity; the potential substitution of biomass for energy and its impact on both other techno-economic systems (such as BECCS), and overall pressure on biomass.

One possible approach for establishing the assumptions on availability on land, is to use the bottom-up assessment proposed in this thesis. By involving relevant actors for each specific land cover at this stage, a share of land available for GMPV development can be identified before any specific projects are developed. This identification of zones for GMPV, not unlike the zone designated for wind energy projects, can help private endeavours to materialise, minimising the risk of project failure due to the legal incompatibility of some land covers and GMPV, as is currently the case with establishment on arable land.

References

Andersson, J., H., Hellsmark, B., Sandén, (2021), *Photovoltaics in Sweden – Success or failure?*, Renewable and Sustainable Energy Reviews, Volume 143, 110894, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.110894.

Biró-Varga, K., I., Sirnik, S., Stremke, (2024), *Landscape user experiences of interspace and overhead agrivoltaics: A comparative analysis of two novel types of solar landscapes in the Netherlands*, Energy Research & Social Science, Volume 109, 103408, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2023.103408.

Björnsson L.H., Pettersson, I., Morell, K. & van Noord, M., (2022), Solar PV parks in Sweden 2021 *[Solcellsparker i Sverige 2021 – en kartläggning]*, RISE Rapport 2022:64, ISBN 978-91-89711-04-4, RISE Research Institutes of Sweden.

Bolinger, M., G., Bolinger, (2022), *Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density,* in IEEE Journal of Photovoltaics, vol. 12, no. 2, pp. 589-594, doi: 10.1109/JPHOTOV.2021.3136805.

Bowles, T.M., S.S., Atallah, E.E., Campbell et al., (2018), *Addressing agricultural nitrogen losses in a changing climate*. Nat Sustain 1, 399–408 https://doi.org/10.1038/s41893-018-0106-0

Bushra Javeed, S., A., Shah, A., Najib, E., Abbas Jafri, S., A. Khan, (2023), *Techno-economic analysis of incorporating up to 20% of wetland for the installation of a photovoltaic powerplant*, Sustainable Energy Technologies and Assessments, Volume 57, 103212, ISSN 2213-1388, https://doi.org/10.1016/j.seta.2023.103212

Campana, P., E., (2023*), Evaluation of the first agrivoltaic system in Sweden*, Project report, Swedish Energy Agency,

Cherp, A., Vinichenko, V., Tosun, J., Gordon, J., Jewell, J., (2021), *National growth dynamics of wind and solar power compared to the growth required for global climate targets*, nature energy, vol 6, 742–754, https://doi.org/10.1038/s41560-021-00863-0

County Administrative boards, (2023), *Built solar photovoltaic parcs over 0.5 MW,* https://ext-dokument.lansstyrelsen.se/gemensamt/geodata/ShapeExport/lst.LST_Uppforda_solcellsparker_over_05_MW.zip

County administrative board of Halland, 2024a, webinar

County administrative board of Halland, 2024b, https://www.lansstyrelsen.se/halland/natur-och-landsbygd/livsmedel-och-foder/livsmedelsstrategi.html

Décret n° 2024-318 du 8 avril 2024 relatif au développement de l'agrivoltaïsme et aux conditions d'implantation des installations photovoltaïques sur des terrains agricoles, naturels ou forestiers [Law n°2024-318 of April 8, 2024 related to development of Agrivoltaics and conditions for implementation of photovoltaic installations on arable, natural or forest land], Journal Officiel de la République Française [J.O.] [Official Gazette of France], Apr. 8, 2024

Dupraz, C., H. Marrou, G. Talbot, L. Dufour, A. Nogier, Y. Ferard, (2011), *Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes,* Renewable Energy, Volume 36, Issue 10, Pages 2725-2732, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2011.03.005.

Dupraz, C., (2023a), *Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity*. Agroforest Syst. https://doi.org/10.1007/s10457-023-00906-3

Duprez, Christian, (2023b), presentation slides

Elkadeem, M. R Zainali, S., Ma Lu, S.,Younes, A., Abido, M. A., Amaducci, S., Croci, M., Zhang, J., Landelius, T., Stridh, B., Campana, P. E., (2024) *Agrivoltaic systems potentials in Sweden: A geospatial-assisted multi-criteria analysis*, Applied Energy, Volume 356, 122108, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2023.122108

Erlandsson Lampa, M., J., Pettersson F., Engene, N., *Water agency calculations on eutrophication mitigation need [Vattenmyndigheternas beräkningar av åtgärdsbehovet för övergödning]*, Vattenmyndigheten, https://viss.lansstyrelsen.se/ReferenceLibrary/55066/Metod%20beting.pdf

Erlander, M., *Planning of operation of regional grid [Planering av regionnätsdrift: Begränsning av subtransitering genom radialläggning av maskade ledningar],* Master's thesis, Division of Industrial Electrical Engineering and Automation Faculty of Engineering, Lund University, https://www.iea.lth.se/publications/MS-Theses/Full%20document/5401_full_document.pdf

Geological Survey of Sweden, (2018), *Product: Soiltype 1:25 000 – 1:100 000 [PRODUKT: JORDARTER 1:25 000-1:100 000]*, Dataset, not published

Goetzberger, A., A., Zastrow, (1982), On the Coexistence of Solar- Energy Conversion and Plant Cultivation, International Journal of Solar Energy, 1:1, 55-69, DOI: 10.1080/01425918208909875

Gorjian, S., H. Sharon, H., Ebadi, K., Kant, F., Bontempo Scavo, G., Marco Tina, (2021), *Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems*, Journal of Cleaner Production, Volume 278, 124285, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.124285

Göteborgs Energi, (2023), [informative plate on site], Solinavium, Solar Park, Göteborg Energi, accessed 09-02-24.

Ilmatar Solar, (2023), *Underlag för avgränsningssamråd inför etablering av solcellspark på fastigheterna horshult 1:5 och flymossen 1:1, värnamo kommun, jönköpings län [Basis for permit application process for the establishment of solar powerplant in Jönköping county]*, Report

Kakoulaki, G., N., Taylor, S., Szabo, R., Kenny, A., Chatzipanagi, A., Jäger-Waldau, (2024), *Communication on the potential of applied PV in the European Union: Rooftops, reservoirs, roads (R3)*, EPJ Photovoltaics 15, 2

Ketzer, D., N., Weinberger, C., Rösch, S., B. Seitz (2020), Land use conflicts between biomass and power production – citizens' participation in the technology development of Agrophotovoltaics, Journal of Responsible Innovation, 7:2, 193-216, DOI: 10.1080/23299460.2019.1647085

Laub, M., Pataczek, L., Feuerbacher, A., Zikeli, S., Högy, P., Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis. Agron. Sustain. Dev. 42, 51 (2022). https://doi.org/10.1007/s13593-022-00783-7

LC energi, (2023), Underlag för samråd inför uppförande av solcellspark inom fastigheterna Ryssebo 1:5 och Skuru 1:5 i Eksjö kommun, Jönköpings län, Report, AFRY

Ljungström, Viktor, Åke, Svensson, (2021), *Exploatering av jordbruksmark 2016–2020*, Metria AB, Swedish board of agriculture, Rapport 2021:08, ISSN 1102-3007, ISRN SJV-R-21/08-SE

Ljungström, M., J., Hörnelius, *Ecovoltaics in Sweden: Views on integrating measures for biodiversity in solar parks*., Report no. E2023_085, Department of Technology Management and Economics, Chalmers University of Technology

Lindahl J., (2021), *Appendix to Cost of new Electricity [Bilaga till el från nya anläggningar]*, Energiforsk, Report 2021:714, Report, https://energiforsk.se/media/30709/bilagor-till-rapporten-el-fran-nya-anlaggningar.pdf

Lindahl, J., C., Stoltz, (2017), *National Survey Report of PV Power Applications in Sweden 2017*, Report, Swedish Energy Agency, https://iea-pvps.org/wp-content/uploads/2020/01/Swedish_NSR_2017.pdf

Liu, H., Wu, C., Yu, Y., Zhao, W., Liu, J., Yu, H., et al. (2023). *Effect of solar farms on soil erosion in hilly environments: A modeling study from the perspective of hydrological connectivity*., Water Resources Research, 59, e2023WR035067. https://doi.org/10.1029/2023WR035067

Ludvig & Co, (2024), *Skogsprisrapporten helår 2023 – Skog*, report. Retrieved mars 20, 2024, https://kunskap.ludvig.se/rapport-skogsmarkspriser-helar-2023

LRF, (2024), *food supply questions in Skåne [Livsmedelsfrågor i Skåne]*, Lantbrukarnas Riksförbund Skåne, retrieved April, 2024, https://www.lrf.se/regioner/skane/det-har-gor-lrf-skane/livsmedelsfragor-i-skane/

Markensten, T., L., Reiter, P., Bodin, K., Per Hasund, E., Svensson, M, Nyberg, (2018), *Re-wetting organic arable land as climate mitigation [Återvätning av organogen jordbruksmark som klimatåtgärd]*, Report, Swedish board of Agriculture

Nilsson, S. (2020), *Marknadsplats För Skogsarrende - att hyra eller hyra ut skog,* Report, Sveriges Lanbruksuniversitet SLU

OX2, (2023), *Permit application Brunskog-Stjärnarp solar park [Samrådsunderlag Brunskog-Stjärnarp solpark, Halmstads kommun],* Report, OX2

Panagos, P., Borrelli, P., Matthews, F., Liakos, L., Bezak, N., Diodato, N., & Ballabio, C. (2022). *Global rainfall erosivity projections for 2050 and 2070*. Journal of Hydrology, 610, 127865. https://doi.org/10.1016/j.jhydrol.2022.127865

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., & Alewell, C., (2015), *The new assessment of soil loss by water erosion in Europe*. Environmental Science & Policy, 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012

Parvin, N., E., Coucheney, I-M., Gren, H., Andersson, K., Elofsson, N., Jarvis, T., Keller, (2022), *On the relationships between the size of agricultural machinery, soil quality and net revenues for farmers and society*, Soil Security, Volume 6, 100044, ISSN 2667-0062, https://doi.org/10.1016/j.soisec.2022.100044

Paulsson, K., (2015), *Restoring valuable nature [Restaurering av en värdefull naturtyp, MYREN: Erfarenheter från projektet Life to ad(d)mire]*, Booklet, County administrative boards of Dalarna, Jämtland, Jönköping, Kronoberg, Skåne, Västernorrland and Östergötland

Petersson, I., M., Allard, K., Jansson, S., Berg, (2024), *Food security for a new time [Livsmedelsberedskap för en ny tid: Betänkande av Utredningen om en ny livsmedelsberedskap]*, report, SOU 2024:8, Swedish Government Official Reports, Swedish Government

Pringle, A., N., Handler, R., M., Pearce, J., M., (2017), *Aquavoltaics: Synergies for dual use of water area for solar photovoltaic electricity generation and aquaculture*, Renewable and Sustainable Energy Reviews, Volume 80, Pages 572-584, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2017.05.191

QGIS.org (2024*). QGIS Geographic Information System*. Open-Source Geospatial Foundation Project. http://qgis.org

Reher, T., C., Lavaert, B., Willockx, Y., Huyghe, J., Bisschop, J., A. Martens, J., Diels, J., Cappelle, B., Van de Poel, (2024), *Potential of sugar beet (Beta vulgaris) and wheat (Triticum aestivum) production in vertical bifacial, tracked, or elevated agrivoltaic systems in Belgium*, Applied Energy, Volume 359, 122679, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2024.122679.

Roos, C., (2024), *Electrification of Sweden [Elektrifieringen av Sverige - Var ser vi tillväxten idag, och vad tror vi om imorgon? Kommer elnätet bli fullt?]*, E.On energy distribution, presentation, https://www.elmia.se/globalassets/bilder/massor/solar/for-besokare/13-feb_11.00_framtidens-elnat_christian-roos_e.on.pdf

Sirnik, I., D., Oudes, S., Stremke, (2024), *Agrivoltaics and landscape change: First evidence from built cases in the Netherlands*, Land Use Policy, Volume 140, 107099,ISSN 0264-8377, https://doi.org/10.1016/j.landusepol.2024.107099.

Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., Goetzberger, A., Weber, E., (2020), *Implementation of agrophotovoltaics:Techno-economic analysis of the price-performance ratio and its policy implications*, Applied Energy, Volume 265, 114737, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.114737.

Schoeck, M. (2023, May 9). *Silicon Ranch plans to appeal ruling in 100 MW solar property damage case.* Pv Magazine USA. https://pv-magazine-usa.com/2023/05/09/silicon-ranch-plans-to-appeal-ruling-in-100-mw-solar-property-damage-case/

Skåne Capacity Commission, *Pathways for Skåne's power electrical supply 2030*, 2023, report, https://utveckling.skane.se/siteassets/publikationer/fardplan-for-skanes-elforsorjning-2030.pdf

Svea Court of Appeal, land and environment court of appeal, (2024), M 13461-22, [unpublished]

Statistics Sweden, *Population in Sweden 31 December 2023 - Municipal comparative figure*, (2024), Online, retrieved April 2024, at https://www.scb.se/en/finding-statistics/statistics-by-subject-area/population/population-composition/population-statistics/pong/tables-and-graphs/population-statistics---summary/population-in-sweden-31-december-2023-municipal-comparative-figures/

Swedenergy, (2023a), EBR cost catalogue 2023: Distributional grid 0.4-24 kV and optogrid, [unpublished]

Swedenergy, (2023b), EBR cost catalogue 2023: regional grid 24-130 kV, [unpublished]

Swedish Environmental Protection Agency, (2023a), *Product description: National Land Cover Data 2018 Baselayer [Produktbeskrivning, Nationella Marktäckedata 2018 basskikt]*, online, https://geodata.naturvardsverket.se/nedladdning/marktacke/NMD2018/NMD_Produktbeskrivning_NMD2018Basskikt.pdf

Swedish Environmental Protection Agency, (2023b), *Basis for re-wetting wetland [Underlag för återvätning utav våtmarker]*

Swedish Environmental Protection Agency, (2024), *National Land Cover Data 2018 [Nationella Marktäckedata 2018],* Datastet, online, retrieved feb- 24,]https://geodata.naturvardsverket.se/nedladdning/marktacke/NMD2018/NMD2018_basskikt_ogeneraliserad_Sverige_v1_1.zip

Swedish Environmental Protection Agency, (n.d), *Effects of climat change on Swedenı*, (online), https://www.naturvardsverket.se/amnesomraden/klimatforandringar/klimatet-i-framtiden/effekter-i-sverige/

Swedish Forest Agency, (2024a), *Application for felling*, online, retrieved april 2024 https://www.skogsstyrelsen.se/globalassets/sjalvservice/blanketter/avverkning/anmalan-om-avverkning.pdf

Swedish Forest Agency, (2024b), *Forest care law*, online, retrieved April 2024 https://www.skogsstyrelsen.se/lag-och-tillsyn/skogsvardslagen/

Swedish Forest Agency, (2024c), *Felling applications, geodata format*, dataset, online, https://geodpags.skogsstyrelsen.se/geodataport/feeds/AvverkAnm.xml, retrieved mars 2024

Swedish Forest Agency, (2024d), *Acted felling, geodata format*, dataset, online, https://geodpags.skogsstyrelsen.se/geodataport/feeds/UtfordAvverk.xml, retrieved mars 2024

The Swedish board of agriculture, (2023a), *Rents on arable land after crop and production area year 2009 – 2022 [Arrendepris på jordbruksmark efter ägoslag och produktionsområde. År 2009-2022]*, Jordbruksverket statistic database

The Swedish board of agriculture, (2023b), *Rents of agricultural land 2022 [Arrendepriser på jordbruksmark 2022]* https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2023-02-28-arrendepriser-pa-jordbruksmark-2022, retrieved 20-03-2024

The Swedish board of agriculture, (2024a), *Preliminary crop areal by region and crop, year 2018-2023* [*Preliminära grödarealer efter län och gröda. År 2018-2023 [Preliminairy crop areals sorted by region and crop. Year 2018-2023]*, Online, https://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets%20statistikdatabas/Jordbruksverkets%20statistikdatabas__Arealer__Preliminar%20arealstatistik/JO0104C01.px/

The Swedish board of agriculture, (2024b), Agricultural block 2023, dataset, online, https://jordbruksverket.se/e-tjanster-databaser-och-appar/e-tjanster-och-databaser-stod/kartor-och-gis#h-Laddanerkartskikt

Toledo, C., A., Scognamiglio, (2021), *Agrivoltaic Systems Design and Assessment: A Critical Review, and a Descriptive Model towards a Sustainable Landscape Vision (Three-Dimensional Agrivoltaic Patterns)*, Sustainability, 13, 6871 https://doi.org/10.3390/su13126871

Trommsdorff, M., I., S., Dhal, Ö., E., Özdemir, D., Ketzer, N., Weinberger, C., Rösch, (2022), *Chapter 5 - Agrivoltaics: solar power generation and food production*, Editor(s): Shiva Gorjian, Pietro Elia Campana, Solar Energy Advancements in Agriculture and Food Production Systems, Academic Press, Pages 159-210, ISBN 9780323898669, https://doi.org/10.1016/B978-0-323-89866-9.00012-2.

Turney, D., V., Fthenakis, (2011), *Environmental impacts from the installation and operation of large-scale solar power plants*, Renewable and Sustainable Energy Reviews, Volume 15, Issue 6, Pages 3261-3270, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2011.04.023

van Aken, B., A., Binani, A., K., Cesar, (2021). *Towards nature inclusive east-west orientated solar parks*. https://publications.tno.nl/publication/34638414/WHhRMg/TNO-2021-R11087.pdf

Råberg, T., van Noord, M., Björnsson L.H., Pettersson, I. & Zinko, U. (2021) *Solar PV parks, biological diversity and ecosystem services [Solcellsparker, biologisk mångfald och ekosystemtjänster – Påverkan och möjligheter för multifunktioner*, RISE Rapport 2021:52, ISBN 978-91-89385-93-1, RISE Research Institutes of Sweden.

Vattenfall, 2024, *Historical prices of market electricity price [Prishistorik över Rörligt elpris]*, retrived mars-24,
https://www.vattenfall.se/elavtal/elpriser/rorligt-elpris/prishistorik/

Weselek, A., Bauerle, A., Hartung, J. et al., (2021), *Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate*, Agron. Sustain. Dev. 41, 59
https://doi.org/10.1007/s13593-021-00714-y

Wallén, U., (2021), *Competence supply for the climate transition [Kompetensförsörjning för klimatomställningen]*, Report, Svenskt Näringsliv, retrieved jan 23,
https://www.svensktnaringsliv.se/bilder_och_dokument/rapporter/9f5oys_rapport_klimatkompetens_webbpdf_1175402.html/Rapport_Klimatkompetens_webb.pdf

Welsh Government, (2023), *The impact of solar photovoltaic (PV) sites on agricultural soils and land. Work Package Three: Review of Impacts*, ADAS

Willockx, B., B., Herteleer, B., Ronsijn, B., Uytterhaegen, J., Cappelle. (2020*). A standardized classification and performance indicators of agrivoltaic systems*. In EU PVSEC Proceedings. WIP.

Willockx, B., B., Ronsijn, B., Herteleer, J., Capelle, (2020), *A Standardized Classification and Performance indicators of Agrivoltaic Systems*, Research Group Energy & Automation, Faculty of Engineering Technology, KU Leuven

Willockx, B., C., Lavaert, J., Cappelle, (2022), Geospatial assessment of elevated agrivoltaics on arable land in Europe to highlight the implications on design, land use and economic level, Energy Reports, Volume 8, Pages 8736-8751, ISSN 2352-4847,
https://doi.org/10.1016/j.egyr.2022.06.076

Zhang, P, C., Yue, Y., Li, X., Tang, B., Liu, M., Xu, M., Wang, L., Wang, (2024), *Revisiting the land use conflicts between forests and solar farms through energy efficiency*, Journal of Cleaner Production, Volume 434, 139958, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2023.139958

Zheng, J., Y., Luo, R., Chang, X., Gao, (2023), *An observational study on the microclimate and soil thermal regimes under solar photovoltaic arrays*, Solar Energy, Volume 266, 112159, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2023.112159

Appendix I

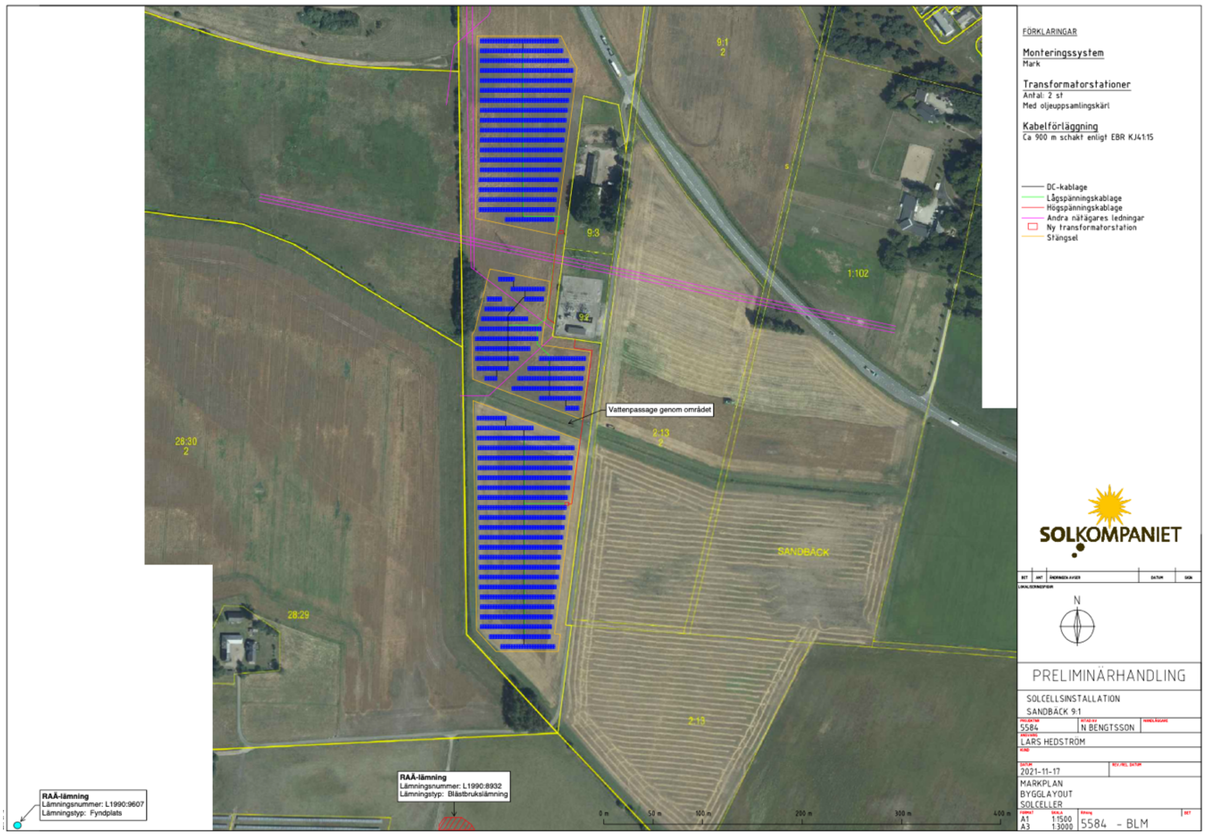


Figure I.I
Technical drawing of solar park, with connection to substation at plot boundary with passing regional power lines over plot. category: “close to existing electric infrastructure” (source: Solkompaniet)

Figure I.II
PV park Varberg Norra and supposed connection to new substation less than 500 m away (C google Earth). Corresponding to category “new infrastructure”.

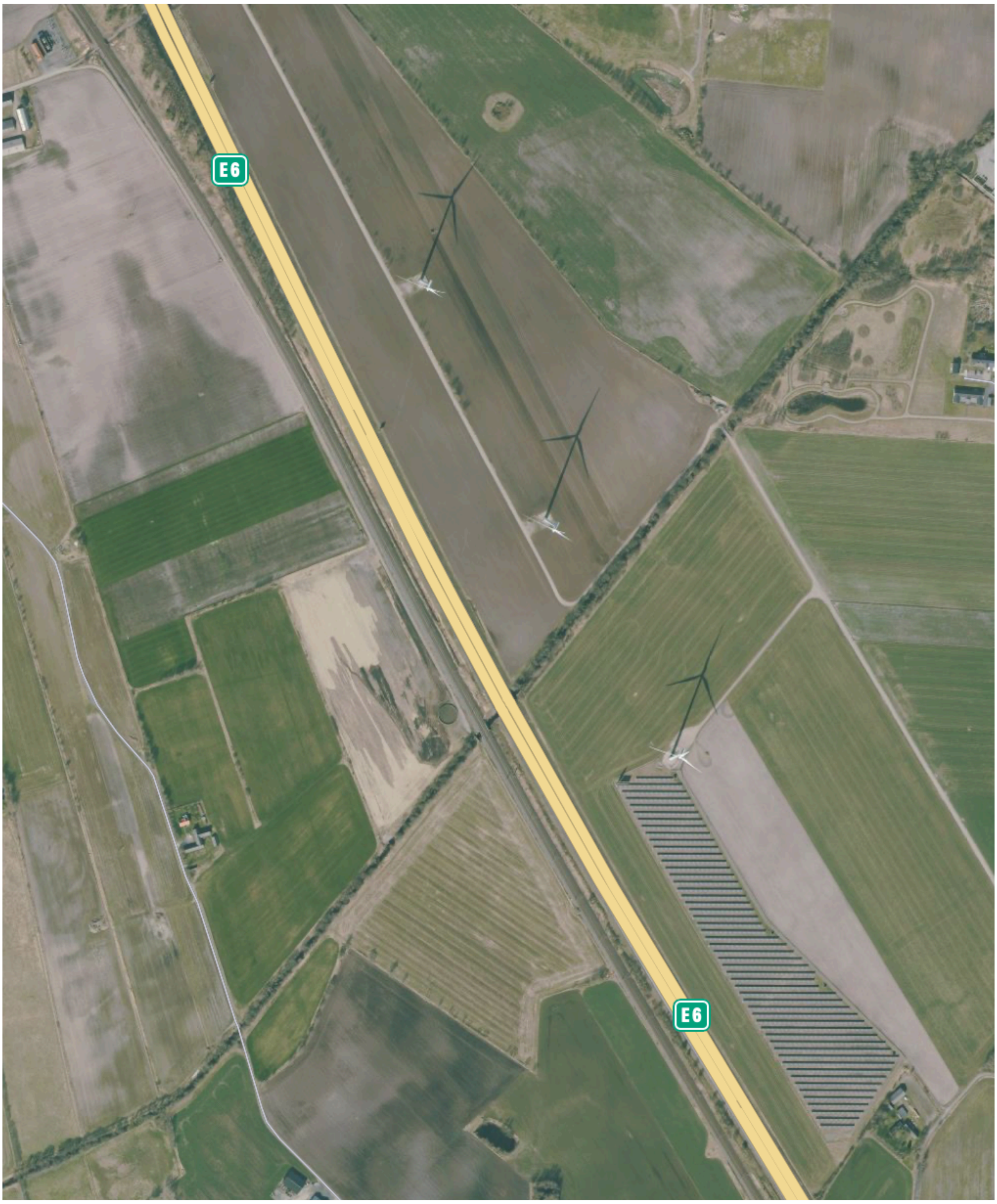


Figure I.III
PV park(bottom right) Varberg södra with supposed connection to an existing substation (top left) at roughly 1 300 m. (C Apple maps). Corresponds to “close to existing electrical infrastructure”

Appendix II

Table II.I

Preliminary crop areal per region for the year of 2023. Source: SBA(2024)

Crop	Skåne	Halland
Höstvete	106596	16720
Vårvete	4206	1490
Råg	10897	1163
Höstkorn	4705	992
Vårkorn	63894	14225
Havre	9825	6325
Höstrågvete	4608	1597
Vårrågvete	284	27
Blandsäd (stråsäd)	203	195
Summa spannmål	205217	42734
Ärter, åkerbönor m.m.	4590	1641
Konservärter	2879	607
Bruna bönor	..	..
Majs	8059	3839
Grönfoderväxter	3032	1200
Slåtter- och betesvall som utnyttjas	95818	42947
Vall för fröskörd	6641	794
Matpotatis	5638	1807
Potatis för stärkelse	5462	16
Sockerbetor	27815	649
Höstraps	47549	5133
Vårraps	260	135
Höstrybs	40	18
Vårrybs	4	..
Summa raps och rybs	47854	5286
Oljelin	223	0
Trädgårdsväxter	8859	632
Andra växtslag	1124	379
Energiskog	1744	125
Träda	7122	2618
Ospecificerad åkermark	1116	400
Total åkerareal	433195	105674
Betesmark	51914	15101
Slåtteräng	2133	163
Skogsbete	81	57
Fädbodbete	..	..
Alvarbete	..	..
Mosaikbetesmarker	49	410
Ospecificerad betesmark	800	232
Total betesareal	54978	15963
Total jordbruksareal	488173	121637

Appendix III

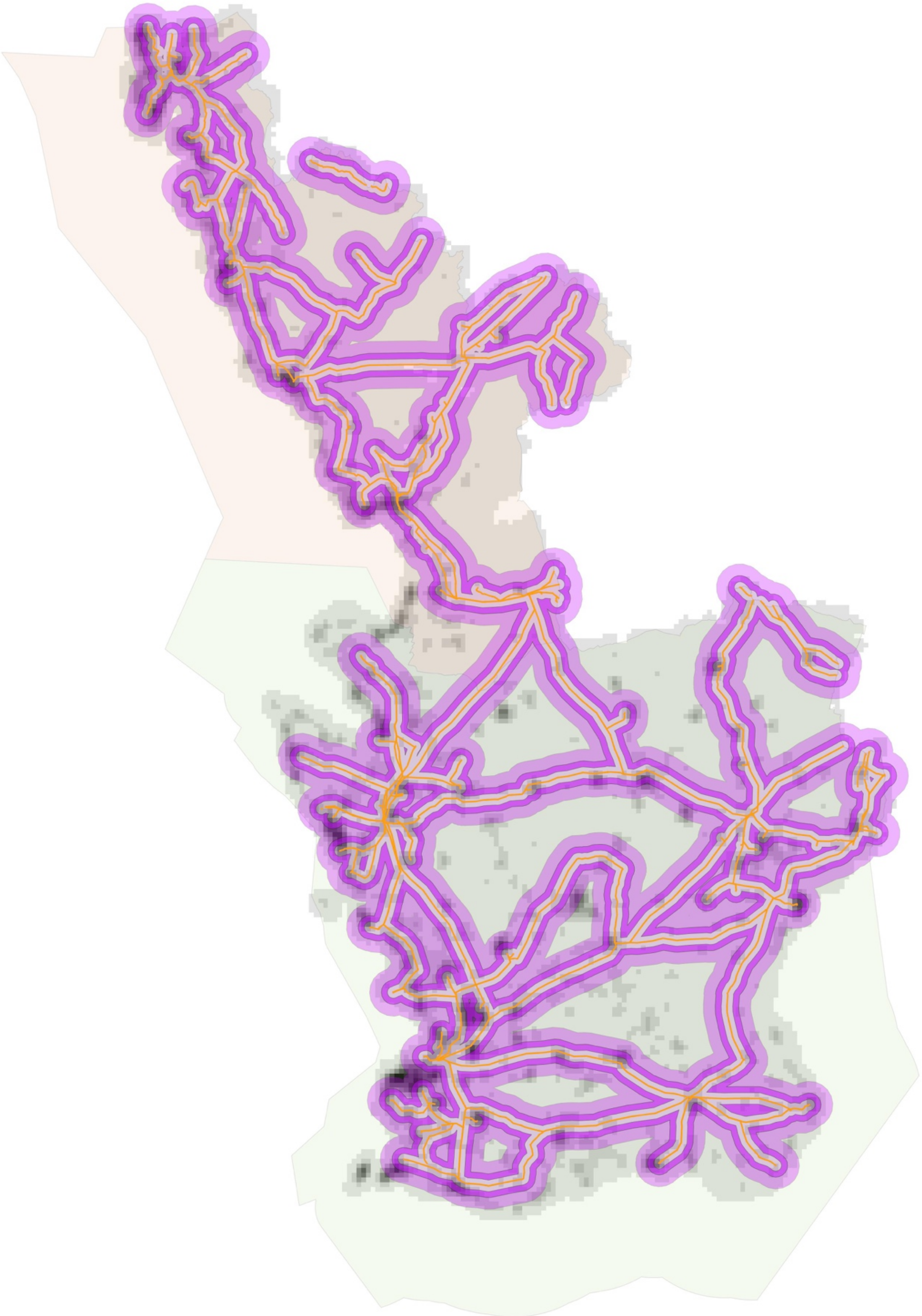


Figure AA
Map of Skåne and Halland, population density in whole region (greyscale) and in relation to within a specific distance class to regional grid (1.2, 2.5 and 5 km, purple hues). Regional grid depicted in orange. Source: statistics Sweden, Lantmäteriet.

Appendix IV

	Halland			Skåne			Total		
Type of land	1.2 km	2.5 km	5km	1.2 km	2.5 km	5 km	1.2 km	2.5 km	5 km
Open wetland	3946	6744	10405	4799	9006	16216	8745	15750	26621
Agricultural land	35332	50447	62224	132452	234211	369779	167784	284658	432003
Non-vegetated other open land	242	499	1410	355	709	1275	597	1208	2685
vegetated other open land	12919	22096	31730	36751	69189	111961	49670	91285	143691
Artificial Surface, building	543	941	1100	3838	7639	10755	4381	8580	11855
Artificial Surface, not building or road/railroad	851	1346	1595	2757	5329	7428	3608	6675	9023
Artificial Surface, road/railroad	347	545	759	11951	22761	1464	12298	23306	2223
Lake and waterway	7562	13013	16914	3791	9400	28446	11353	22413	45360
Pine forest (Outside wetland)	8916	14668	21310	6441	13890	25090	15357	28558	46400
Sprouce forest (Outside wetland)	12010	21299	35936	11149	23631	44708	23159	44930	80644
Coniferous forest (Outside wetland)	2085	3742	5930	1033	2324	4437	3118	6066	10367
Coniferous forest mixed with deciduous (Outside wetland)	6091	10592	16085	6823	13774	24622	12914	24366	40707
Trivial deciduous forest (Outside wetland)	4777	8532	12715	10398	20611	35749	15175	29143	48464
Noble deciduous forest (Outside wetland)	9793	16723	24165	20163	39387	70099	29956	56110	94264
Trivial deciduous forest w/ patches of noble (Outside wetland)	669	1158	1627	670	1407	2235	1339	2565	3862
Temporarily not forest (Outside wetland)	13423	22737	36860	11825	24665	45380	25248	47402	82240
Total forest outside wetland	57764	99451	154628	68502	139689	252320	126266	239140	406948
Pine forest (On wetland)	4880	8790	14079	2018	4134	8860	6898	12924	22939
Sprouce forest (On wetland)	351	662	1067	264	616	1215	615	1278	2282
Coniferous forest (On wetland)	251	480	765	136	319	678	387	799	1443
Coniferous forest mixed with deciduous (On wetland)	1164	2164	3654	952	2151	4087	2116	4315	7741
Trivial deciduous forest (On wetland)	1587	2792	4580	2202	4434	8093	3789	7226	12673
Noble deciduous forest (On wetland)	5	9	13	19	36	61	24	45	74
Trivial deciduous forest w/ patches of noble (On wetland)	0	0	0	0	1	2	0	1	2
Temporarily not forest (On wetland)	258	429	668	212	511	1013	470	940	1681
Total forest on wetland	8496	15326	24826	5803	12202	24009	14299	27528	48835

Appendix V

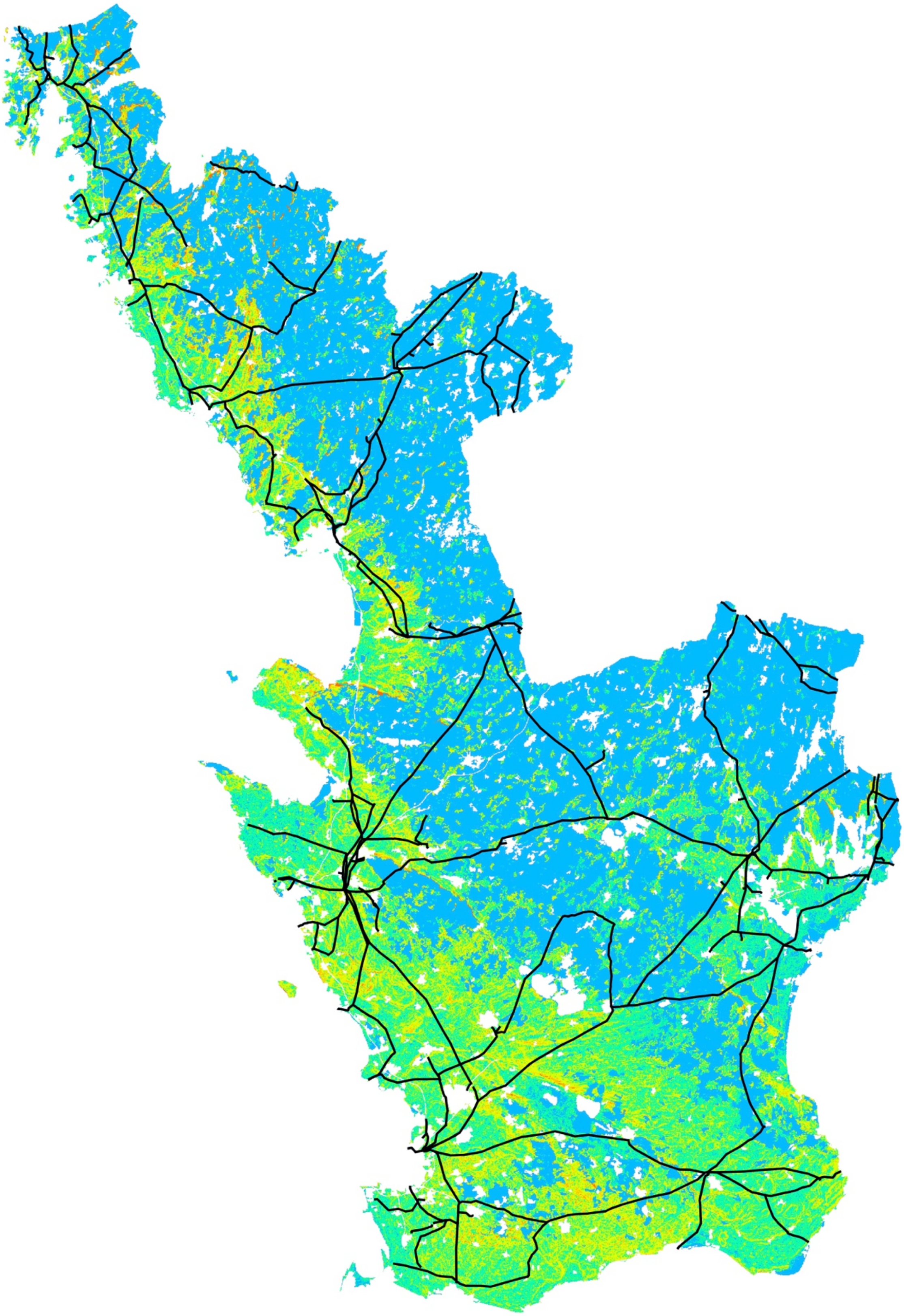
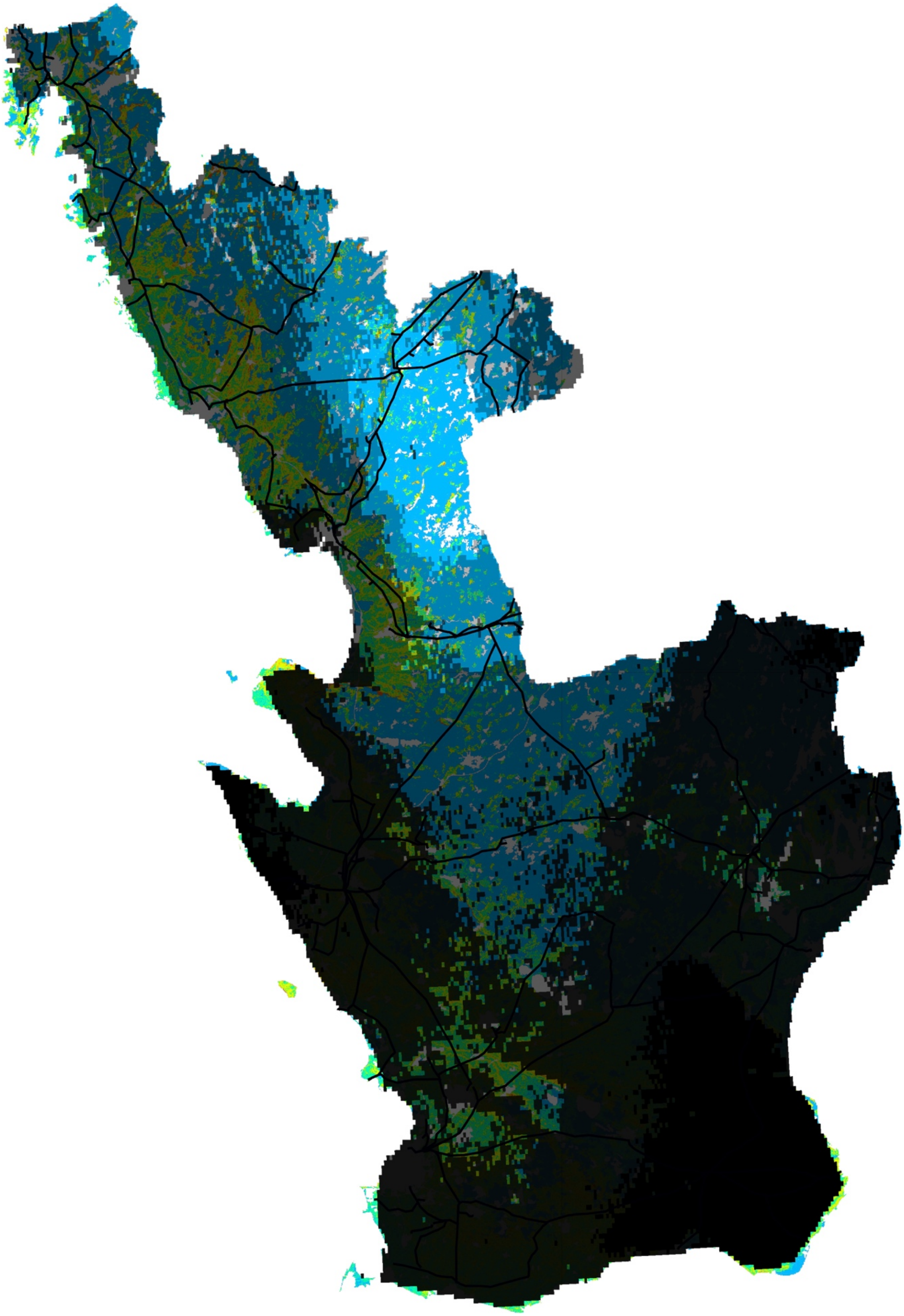


Figure V.I
Maps of soil loss due to rain erosion in Halland and Skåne, Relative change in R-factor with direct implications on simulated soil loss in the year 2050. Source: Panagos et al. (2022), Property map, ©The Land Authority



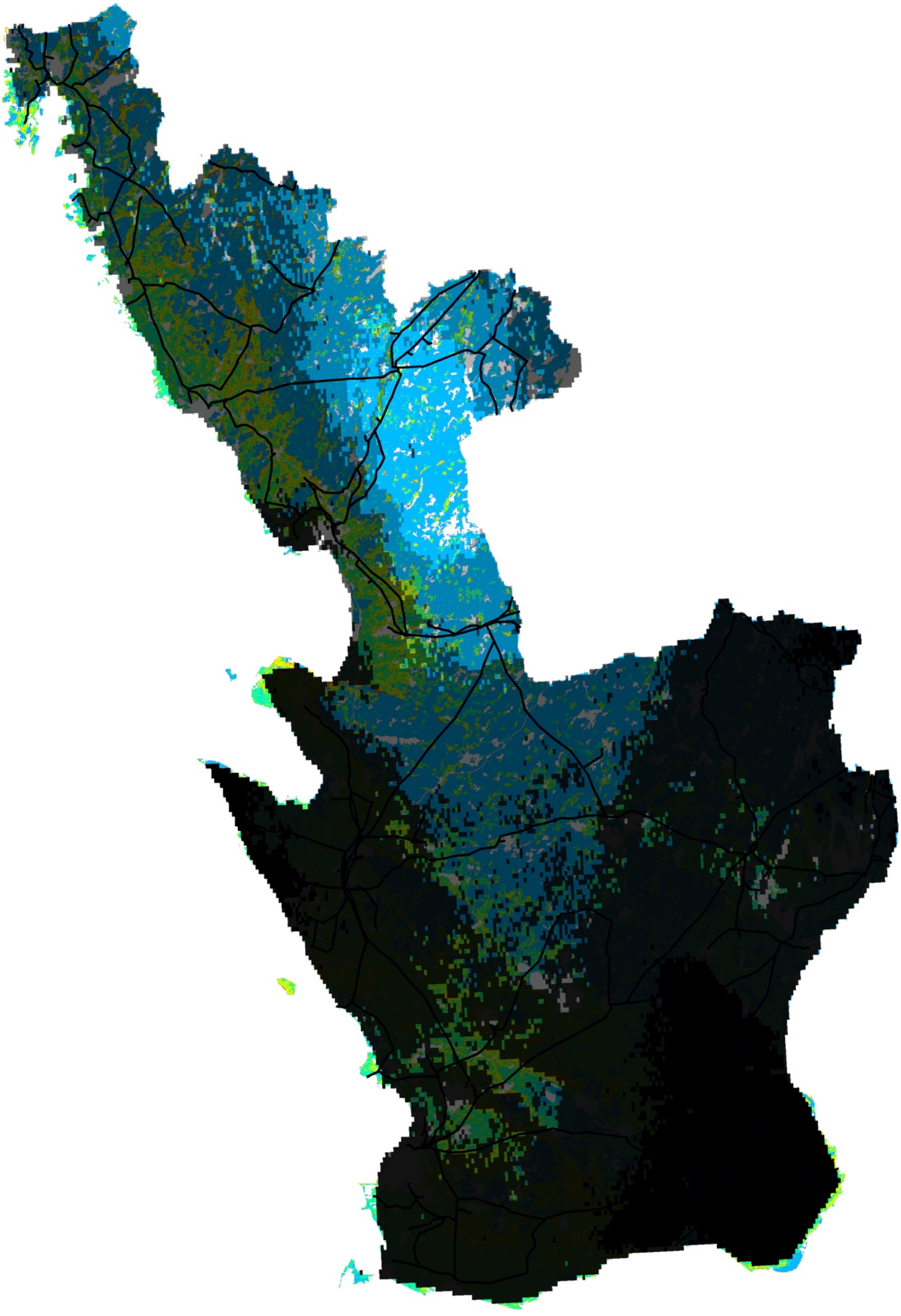


Figure V.II
Maps of soil loss within IPCC scenarios, 2.5. Relative change in R-factor with direct implications on simulated soil loss in the year 2050. Source: Panagos et al. (2022), Property map, ©The Land Authority

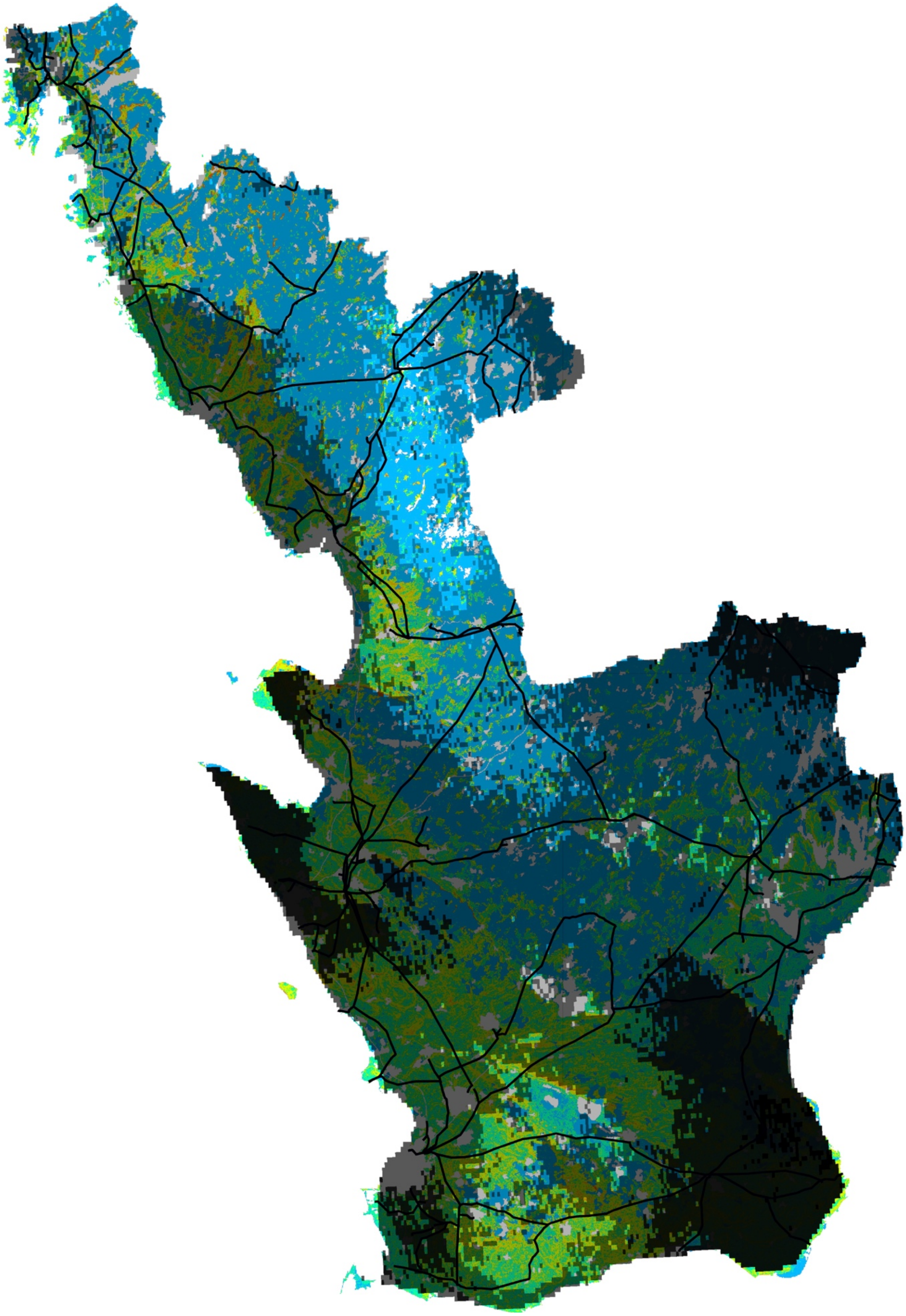


Figure V.II
Maps of soil loss within IPCC scenario 4.5. Relative change in R-factor with direct implications on simulated soil loss in the year 2050. Source: Panagos et al. (2022), Property map, ©The Land Authority

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This thesis investigates land use associated with the establishment of ground-mounted photovoltaics (GMPV) in Skåne and Halland, southern Sweden. It shows examples of efficient use of land, that could help promote local, renewable electricity generation. Up until now in Sweden, establishment of GMPV have focused on fields of arable land, close to existing electrical infrastructure. As a consequence is a competition on land, as the land of another essential societal interest, arable land and its associated food production, is permanently claimed.

The results of the thesis shows that the access to other land is a financially sound option, paving the way for a shift of focus away from productive arable land. Instead, it is shown that an important electricity demand could be met by focusing on two examples of efficient multi-functional land use. First, organic agricultural soils re-wetted to wetland includes electricity and greenhouse gas emission reduction. Secondly, land areas isolated from the local population can host GMPV with low competing interest, including arable land in combined food and energy production, so called Agrivoltaic systems.

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