Norwegian University
of Life Sciences

Master's Thesis 2024 30 ECTS
Faculty of Landscape and Society (LANDSAM)

Exploring the potential of agrivoltaics to integrate energy production, agriculture and wildlife

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CONTENTS

ABSTRACT

The world faces pressing challenges in reducing greenhouse gas emissions and mitigating the impacts of climate change. Failure to address these issues could result in global average temperatures surpassing the 1.5-degree goal set by the United Nations, leading to severe consequences. Simultaneously, land use change and loss of nature pose significant threats to biodiversity and ecosystem services. Agrivoltaic systems, which integrate solar energy production with agricultural activities, could serve as a valuable approach in addressing these challenges. This thesis explores the design considerations for agrivoltaic systems, focusing on their impact on wildlife, agricultural production, and electricity generation. The research aims to provide insights into optimizing agrivoltaic system design to minimize negative impacts on wildlife while ensuring efficient agricultural and renewable energy production. The analysis of various solar panel configurations and their suitability for different agricultural practices reveals the potential of agrivoltaics to enhance crop production, particularly in dry conditions. The thesis presents several design proposals and principles, such as prioritizing site selection, incorporating wildlife-friendly features, and adapting row spacing and panel height, to address the different considerations. However, the lack of comprehensive studies and empirical data specific to Norway and temperate regions presents challenges in fully understanding the potential and limitations of agrivoltaic systems in these contexts. The thesis emphasizes the importance of further research, field trials, and long-term monitoring to assess the performance, challenges, and opportunities of agrivoltaic systems under local conditions.

1 INTRODUCTION

Climate change is arguably the greatest threat our civilisation has ever faced (Attenborough, 2021). Following the release of the third Intergovernmental Panel on Climate Change (IPCC) working group report last year, UN General Secretary António Guterres said the following in a video speech:

> "We are on a fast track to climate disaster. Major cities under water. Unprecedented heatwaves. Terrifying storms. Widespread water shortages. The extinction of a million species of plants and animals. This is not fiction or exaggeration. It is what science tells us will result from our current energy policies." (Guterres, 2022, 00:22).

Since the preindustrial era, the global average temperature has increased by over 1.1 degrees Celsius (GISTEMP Team, 2023). In 2023, the greenhouse gas (GHG) emissions set a record, again, when the carbon dioxide levels reached 424 parts per million (ppm) in the atmosphere (NOAA, 2023).

The consequences of climate change we already face include, among others, more frequent and intense extreme weather events such as cyclones, floods, and droughts; melting glaciers and polar ice causing sea levels to rise; ocean acidification; and declining biodiversity (IPCC, 2022). If left unaddressed, the consequences of climate change could be devastating and "cause significant disruption to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable" (Ripple et al. 2019, p.10).

The majority of the global GHG emissions come from electricity and heat (Ritchie et. al, 2020). This is why renewable energy production is the largest contributor to emission reduction in the "Net Zero Emissions by 2050 scenario" and plays an essential role in halting the current anthropogenic climate change that is threatening "(…) human wellbeing and the health of the planet" (Pörtner, 2022, p.3 in IPCC Press release).

As the demand for clean energy alternatives continues to rise as an urgently needed mitigation strategy, countries have intensified their focus on renewable energy production (COP28, 2023). At the COP28 conference, nations signed the Global Renewables and Energy Pledge, committing to triple the current renewable energy capacity by 2023, aiming to add at least 11 terawatts (TW) of new renewable energy Solar, wind, and other renewable energy sources have demonstrated tremendous potential in reducing greenhouse gas emissions and decarbonizing the global energy sector and will play a crucial role in alleviating the detrimental consequences of climate change.(Androniceanu & Sabie, 2022).

The widespread deployment of renewable energy technologies comes with its own set of challenges, however. One significant concern is land scarcity. This can lead to conflicts of interest and competing demands for this limited resource (Santangeli et al., 2015). In particular, the expansion of renewable energy infrastructure can encroach on agricultural lands, natural habitats, and other critical land uses, potentially exacerbating existing pressures on local habitats and ecosystems (Sánchez-Zapata et al., 2016). Land use change caused by human activity, primarily deforestation, is estimated to account for 12-20% of global greenhouse gas emissions, and hence is a major contributor to climate change (Watson and Schalatek, 2020).

One example of conflict between renewable energy production and competing interests is the Three Gorges Dam power station, which has had significant negative impacts on local habitats, species, and ecosystems in the area. The dam has been associated with habitat fragmentation, altering the landscape pattern and habitat quality in the region (Chu et al., 2018). The modified river flows, changes in sediment composition

(Yang et al., 2007), and the barrier effect of the dam have significantly impacted habitats for flora, fauna, and microorganisms in riparian, riverine, and coastal ecosystems (Fu et al., 2010).

Another example is The Fosen Wind Farm. Among Europe's largest onshore wind farms located in central Norway, it has sparked significant controversy, particularly regarding its environmental impact and infringement on indigenous rights (Skogvang, 2024). The project aims to contribute substantially to Norway's renewable energy goals but has faced criticism for disrupting traditional Sámi reindeer herding, leading to legal challenges alleging insufficient consultation and violation of cultural rights under international conventions. Environmentalists have also raised concerns about wildlife disruption and habitat degradation (Michelsen, 2003). Despite mitigation efforts by developers, the Norwegian Supreme Court ruled that parts of the project violated Sámi herding rights, prompting discussions on compensation and potential dismantling of affected areas. In 2024, agreement on compensation was finally reached, over two years after the Supreme Court ruling. This example highlights the challenging balance between developing renewable energy and protecting both indigenous rights and the local environment, which can lead to conflict and competition for the land.

To address these challenges, innovative solutions that minimize land use conflicts and promote sustainable development are necessary. This thesis explores the potential of one such solution – agrivoltaics. Agrivoltaics combines renewable energy production, specifically solar photovoltaics, with agricultural production and presents a promising opportunity (Dupraz et al., 2011). By co-locating solar panels and agricultural operations, agrivoltaics has the potential to optimize land use and enable renewable energy generation without severely compromising food production, local habitats, or ecosystems.

Habitat loss is primarily driven by the expansion of agricultural land, urban development, and the increasing demand for resources (Martinuzzi et al., 2015). As habitats shrink and become fragmented, species struggle to adapt to the altered landscape, leading to shifts in their distribution, behavior, and interactions with other species (Gonzalez et al., 2011). These changes can have cascading effects on ecosystems, ultimately decreasing biodiversity and compromising their overall stability and resilience. In fact, agricultural land use the primary cause of global biodiversity loss (Baan et al., 2015). Worldwide, around five billion hectares (50 million km^2) of land are dedicated to agricultural activities, or 38% of the land surface, accounting for a substantial part of the Earth's habitable land (FAO UN, 2020).

The Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Agriculture Agency have recommended developing solar power generation on so-called "grey areas", i.e., already developed areas such as rooftops of buildings, industrial sites, parking lots, and other urban spaces (NVE, 2024; Landbruksdirektoratet, 2024). These areas are preferred because they do not require additional land use changes and do not compete with agricultural land or natural habitats.

However, relying solely on these grey areas may not be sufficient for reaching Norway's ambitious renewable energy goals. Norway has set a goal to build 8 TWh (terawatt hours) of solar power by 2030 (NVE, 2024). According to NVE's estimates, ground-mounted solar power plants have the most competitive Levelized Cost of Electricity (LCOE) at 63 øre/kWh (kilowatt-hour) when compared to other solar power generation options. Rooftop solar installations on flat-roofed commercial buildings have the second lowest LCOE at 76 øre/kWh, while residential rooftop solar systems have the highest LCOE at 116 øre/kWh. The LCOE is a metric used to assess and compare the cost of producing a single unit of electricity across different power generation technologies (Bansal et al., 2023). Unless the government implements serious subsidies, it is unlikely that that the 8 TWh goal will be reached by building on grey areas alone.

Given the lower costs of ground-mounted solar power plants, it may be necessary to consider using agricultural land for solar power generation. This could help accelerate the deployment of solar power and contribute to meeting the 8 TWh target by 2030. In fact, building on just 1% of the EU's utilized agricultural area could exceed the EU's 2030 solar energy generation targets of 720 GW direct current (Chatzipanagi, 2023).

In this context, this thesis will investigate the potential of agrivoltaic systems to integrate food and energy production while minimizing negative impacts on wildlife and local ecosystems. By leveraging concepts from landscape ecology, it aims to develop agrivoltaic design ideas suitable for temperate climates, that consider the needs of both human societies and the natural environment, ultimately contributing to more sustainable land use practices.

The questions explored are:

- What are the key factors to consider when deciding on potential sites for agrivoltaics?
- How can agrivoltaic systems be designed to reduce impacts on wildlife while also ensuring efficient production of food and electricity?
- What design principles or best practices can be applied to achieve this?

While there is a rapid increase in solar power in the world, the research on its impact on wildlife is limited (Cock, et al. 2020). This thesis therefore recognises that the implementation of agrivoltaics systems on agricultural land is not without its challenges. As with any large-scale land use change, it has the potential to impact wildlife and natural habitats. It is therefore necessary that any use of agricultural land should be carefully planned to balance the need for renewable energy with food production and environmental conservation.

This thesis will first investigate the existing literature on agrivoltaics, focusing on the impacts of solar power on wildlife and the use of shade-tolerant crops. It will also explore relevant online resources to supplement this research. Subsequently, the study will develop principles for site selection and propose design ideas for agrivoltaic systems. These proposals will consider factors such as wildlife impact, agricultural productivity, and energy production.

2 Contextual overview

Chapter 2 establishes a contextual backdrop important for understanding the topics discussed later. It introduces key concepts from landscape ecology that are fundamental for understanding the results and subsequent chapters. Additionally, this chapter will outline the current political climate in Norway and the EU regarding the adoption of agrivoltaics.

2.1 Concepts from landscape ecology

Landscape ecology is a field of study that focuses on the interactions between spatial patterns and ecological processes across different scales (Wu and Hobbs, 2008). It recognizes that the arrangement and composition of habitats, resources, and other landscape elements can have a significant influence on the distribution, abundance, and behavior of species, as well as the functioning of ecosystems (Turner et al., 2001). Key concepts from landscape ecology that are important to consider include habitat fragmentation, connectivity, and heterogeneity.

Habitat fragmentation refers to the process by which large, adjoining areas of habitat are divided into smaller, more isolated patches (Fahrig, 2003). This can occur as a result of human activities such as land-use changes, which can negatively impact wildlife populations by reducing the quantity and quality of available habitat, restricting movement and gene flow, and increasing edge effects (Haddad et al., 2015). *Edge effects* refer to the changes in environmental conditions and ecological processes that occur at the boundaries between different habitats or land-use types. It can extend varying distances into the adjacent habitats depending on the type and intensity of the edge (Ries et al., 2004).

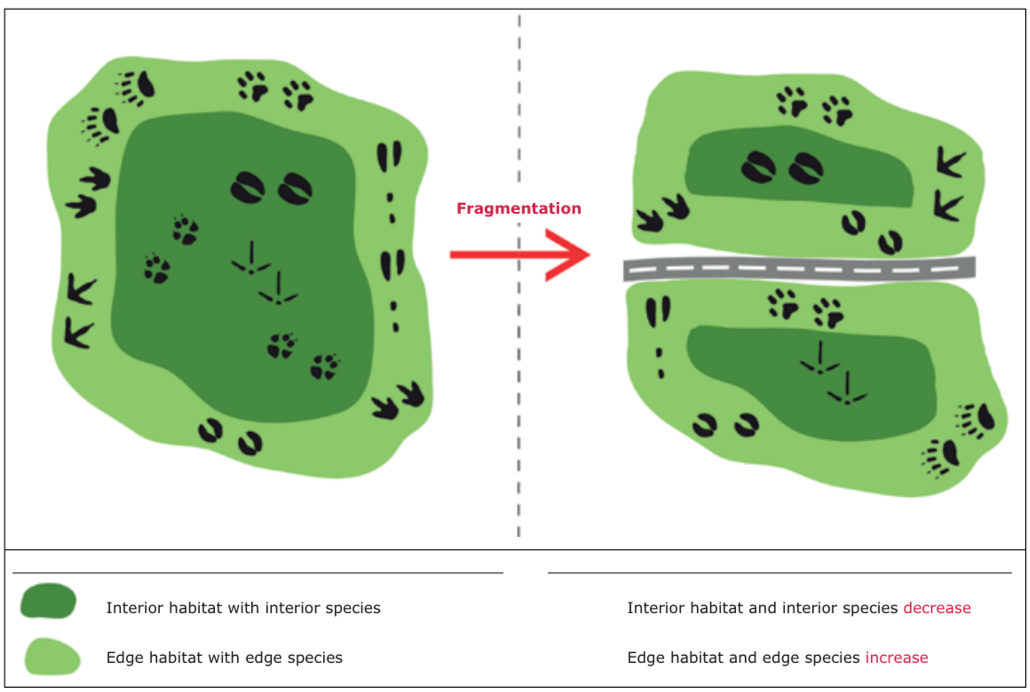

Figure 1. European Environmental Agency (2011). Illustration of the loss of core habitat (or interior habitat) caused by road construction cutting through a patch of habitat. *EEA Report No 2/2011*, p. 12. Available at: https://www.eea.europa.eu/publications/landscape-fragmentation-in-europe (accessed: 01.03.2024).

CONNECTIVITY refers to the degree to which the landscape facilitates or impedes the movement of species and ecological processes between habitats (Taylor et al., 1993).

CORRIDORS, which are linear landscape elements that connect patches of habitat, play a crucial role in maintaining connectivity (Hilty et al., 2019). These corridors can take many forms, such as riparian buffers, hedgerows, or wildlife overpasses, and can help to facilitate the dispersal and migration of wildlife, as well as the flow of nutrients, water, and other resources across the landscape (Hess and Fischer, 2001).

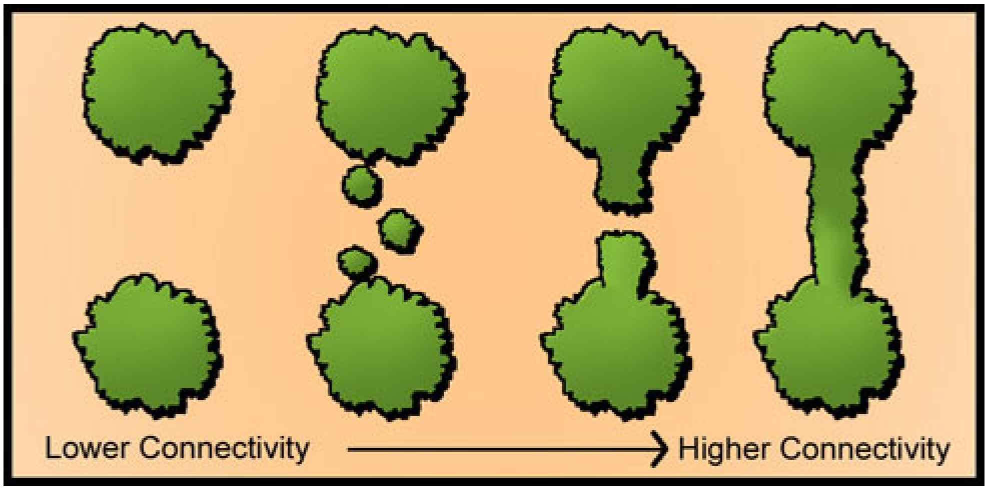

Figure 2. Bentrup, G. (2008). The c*oncept of connectivity.* Conservation buffers: design guidelines for buffers, corridors, and greenways. Gen. Tech. Rep. SRS 109. Asheville, NC: USDA, Forest Service, Southern Research Station. Available at: https://www.fs.usda.gov/nac/buffers/guidelines/2_biodiversity/3.html (accessed 01.03.2024).

While *ecological corridors* are generally considered beneficial for maintaining connectivity between habitats and facilitating species movement, there are also potential negative effects to consider. One concern is that corridors may facilitate the spread of invasive species, diseases, or disturbances, leading to homogenization of species composition within the connected habitats (Haddad et al., 2014). This is particularly problematic if the corridors are dominated by a few generalist or invasive species, which can outcompete native species and reduce overall biodiversity (Beier and Noss, 1998).

Additionally, it is crucial to distinguish between *structural connectivity* and *functional connectivity*, illustrated in *Figure 3* (Benstrup, 2008). Structural connectivity refers to the physical arrangement of habitat patches and corridors. Functional connectivity considers the actual movement and ecological processes of species within the landscape (Taylor et al., 1993). A corridor that appears to provide structural connectivity may not necessarily facilitate the desired ecological processes or support the target species' requirements, leading to a mismatch between conservation goals and outcomes (Tischendorf and Fahrig, 2000).

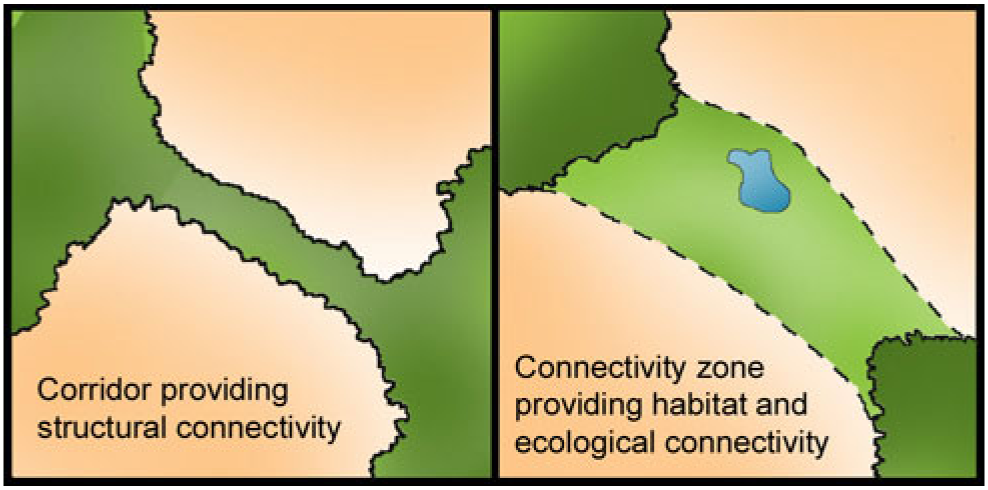

Figure 3. Bentrup, G. (2008). *Corridors with structural vs functional connectivity*. Conservation buffers: design guidelines for buffers, corridors, and greenways. Gen. Tech. Rep. SRS 109. Asheville, NC: USDA, Forest Service, Southern Research Station. Available at: https://www.fs.usda.gov/nac/buffers/guidelines/2_biodiversity/4.html (accessed 01.03.2024)

HETEROGENEITY refers to the diversity and complexity of habitats and other landscape elements within a given area (Pickett and Cadenasso, 1995). Heterogeneous landscapes typically support higher levels of biodiversity and ecological function than homogeneous ones, as they provide a greater variety of niches and resources for different species (Tews et al., 2004).

These landscape ecology principles provide a lens for considering the impact that agrivoltaic systems can have on local wildlife, species health and ecosystems. Taken together, these concepts inform the proposed design approaches outlined in Chapter 4 and 5.

2.2 POLITICAL CLIMATE

2.2.1 NORWAY

In Norway, the ambitious target of 8 TWh new solar energy production by 2030 has been set (NVE, 2024). The political climate, however, is not all positive in terms of building on agricultural land (Landbruksdirektoratet, 2024).

Despite the legal protection of agricultural land in Norway, concerns in the last decade have emerged regarding excessive construction approvals on such land by local governments (Yset & Sund, 2013). In 2021, the Norwegian parliament passed an updated national land protection strategy, setting a goal to limit the annual repurposing of cultivated land nationwide (Statsforvalteren i Oslo og Viken, 2022). However, statistics reveal that a significant amount of cultivated and cultivable land was still approved for repurposing in 2021, highlighting the ongoing challenge of balancing development with agricultural land preservation.

To build on land designated as *agricultural* by the local municipality's zoning plan, a temporary exemption is needed. This exemption is only valid for specific uses. However, permanently changing the zoning plan can convert agricultural land to industrial land. Both renewable energy developers and farmers might use this route to construct large-scale agrivoltaic systems. Farmers also have the option to use their right to implement necessary operations on agricultural land, such as agrivoltaic systems, if the electricity produced is primarily used on the farm (Landbruksdirektoratet, 2024).

2.2.2 The European Union

The political climate in the EU is increasingly focused on addressing climate change and promoting the adoption of renewable energy sources. The European Green Deal, launched in 2019, sets the ambitious goal of making the EU climate-neutral by 2050 and increasing the share of renewable energy to 40% by 2030. This overarching policy framework demonstrates the EU's commitment to transitioning towards a more sustainable and low-carbon economy.

Within this context, the EU's Renewable Energy Directive II (2018/2001) specifically promotes the use of renewable energy in the agricultural sector and encourages Member States to develop policies and measures to support the deployment of agrivoltaics. This directive recognizes the potential of agrivoltaics to contribute to both renewable energy production and sustainable agriculture.

Furthermore, the EU's Common Agricultural Policy (CAP) for 2021-2027 introduces "eco-schemes," which are voluntary environmental measures that farmers can adopt to receive additional payments. Some Member States have already included agrivoltaics in their CAP Strategic Plans, indicating a growing interest in this technology to support sustainable farming practices and contribute to renewable energy targets. The regulations and incentives for agrivoltaics may differ across Member States, as they are afforded the flexibility to tailor policies within the wider EU legislative framework. To facilitate the adoption of agrivoltaica in Norway, it may be beneficial to consider insights from the regulatory practices within the European Union (EU), although the effectiveness of such adaptations could vary.

3 Methodology

The literature survey was conducted between January 2023 and May 2024, using multiple search engines and databases to ensure a comprehensive coverage of relevant research papers and articles. The primary sources included the NMBU library database Oria, Google Scholar, and Google.

The search process involved using a combination of keywords related to the research topic. The main search terms used were "agrivoltaic", "agrophotovoltaic", "landscape", "landscape ecology", "shade tolerant plants agriculture", and "solar farms impact on wildlife". These keywords were used individually and in various combinations to capture relevant literature from different perspectives. The search process was iterative, with the keywords and search strategies being refined based on the relevance and quality of the results obtained. The reference lists of the identified papers were also examined to find additional relevant literature that may have been missed in the initial searches.

In addition to scholarly articles and research papers, non-scholarly sources such as reports, news articles, and websites were also consulted to gain a broader understanding of the topic and its practical applications. These sources were found through Google searches and by following relevant links from the initial search results.

The literature search aimed to gather a diverse range of perspectives and evidence on the potential impacts of agrivoltaics on wildlife and agricultural production, in addition to strategies and mitigation measure to reduce the potential impacts. The information obtained from this search formed the basis for the literature review and helped to identify key themes, knowledge gaps, and areas for further research.

In addition, most of the figures used in this paper are under *Creative Commons (CC)* license or similar copyright protection, where the reproduction and use are allowed, when properly cited. The remain figures are from Trommsdorff et al. (2021) and permission to reuse the figures have been obtained.

4 ANALYSIS OF VARIOUS DESIGN CONSIDERATIONS

This chapter discusses key design considerations relevant to agrivoltaics, focusing on their impact on wildlife, agricultural production, and electricity generation. Each topic is briefly summarized, highlighting the findings crucial for an integrated agrivoltaic system design. These considerations are further explored in the following chapter.

4.1 IMPACT ON WILDLIFE

This section provides a proposal for the optimal design of agrivoltaic systems that minimize negative incursions on wildlife and native species. Where possible, the design elements integrate concepts from landscape ecology. Furthermore, it also explores similarities and differences between reducing wildlife impacts in agrivoltaic systems compared to conventional solar farms. While many of the same principles apply, the unique context of agrivoltaics presents both challenges and opportunities for supporting wildlife conservation efforts. By understanding and addressing these considerations, we can work towards designing agrivoltaic systems that contribute to sustainable energy and food production while fostering wildlife and ecological resilience.

The following pages explores how to optimize agrivoltaic system design to reduce impacts on wildlife. Drawing from research from traditional solar farms, the discussion covers both macro-level landscape considerations and micro-level site-specific factors that should inform agrivoltaics planning and design.

At the macro scale, there is an emphasis on strategies that avoid natural habitats and fragmentation, maintain wildlife corridors, and prioritize development on degraded and species-poor agricultural land. At the micro scale, site-specific design elements can create wildlife-friendly environments within the agrivoltaic system itself. Such elements include the integration of native vegetation, the use wildlife-permeable fencing, protection of water resources, and the implementation of erosion control measures (Walston et al., 2018). By carefully planning and managing these site-level factors, agrivoltaic systems can provide valuable habitats and resources for local wildlife species (Peschel, 2010). Figure 4 below provides an overview of factors to avoid (in red) and embrace (in green) when designing agrivoltaic systems that minimize negative impacts on wildlife.

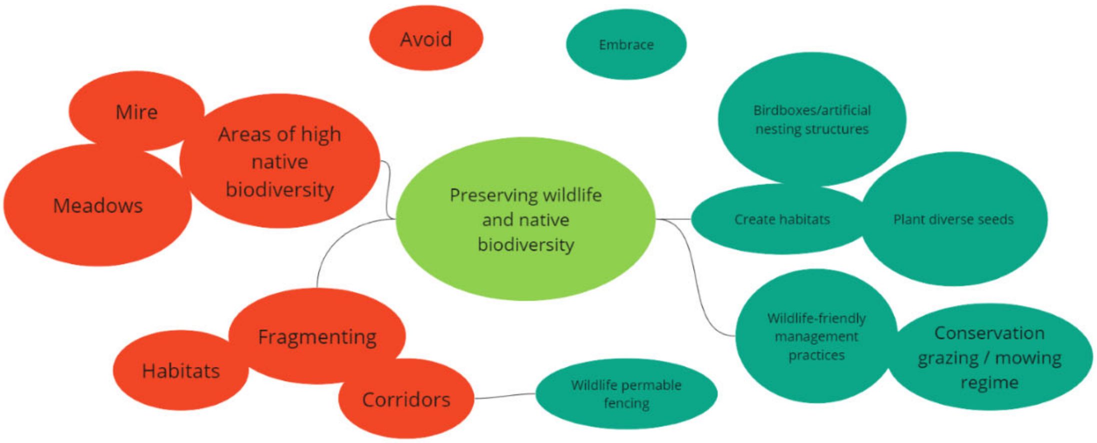

Figure 4. Diagram of how to select and design for wildlife and biodiversity considerations.

4.1.1 *Lessons from traditional solar farms and differences to agrivoltaics*

The discussion within this chapter is adapted from the principles and practices developed by The Nature Conservancy for traditional solar farms in North Carolina (TNC, 2020). Their guidelines provide a useful benchmark on how to site and design solar energy facilities in a manner that minimizes impacts to natural ecosystems and biodiversity. Their key principles and practices for solar farm planning are summarized in Figure 5 below.

Summary of Principles and Practices: See TNC's NC Solar Siting Webmap for spatial data

PRINCIPLE	SITING	DESIGN[7]
1. Avoid areas of high native biodiversity and high quality natural communities	Avoid siting in resilient areas	
2. Allow for wildlife connectivity, now and in the face of climate change	Avoid siting in and fragmenting climate corridors	Where appropriate, use wildlife-friendly fencing or unfenced wildlife passage-ways
3. Preferentially use disturbed or degraded lands	Preferentially site on degraded lands with little vegetation and/or poor soil quality	Retain or plant vegetation/trees in buffers or outside of perimeter fence
4. Protect water quality and avoid erosion	Do not site in floodplains	Buffer streams and wetlands
5. Restore native vegetation and grasslands		Integrate the planting of native and/or pollinator vegetation where appropriate
6. Provide wildlife habitat		Protect and restore on-site wildlife habitat features (e.g., wetlands, vege-tated buffers); provide supplemental habitat as appropriate

[7] There is no "one size fits all" approach to solar facility design. Each solar facility needs to be evaluated based on natural landform and hydrology, native plant and wildlife species presence, and ecosystem functions. For example, wildlife corridors may be most relevant for an installation in a forested matrix, whereas pollinator habitat may be more appropriate in an agricultural setting. The NC Solar Siting Webmap can help identify solar facilities that are candidates for best design practices based on their position on the landscape.

Table 1. Bruns, C. (2019). Summary of Principles and Practices for Solar Siting. The Nature Conservancy. Available at: https://www.nature.org/content/dam/tnc/nature/en/documents/ED_TNCNCPrinciplesofSolarSitingandDesignJan2019.pdf (accessed 05.05.2024).

Compared to conventional solar farms, the unique integration of agricultural activities within agrivoltaic systems presents both challenges and opportunities for supporting wildlife. For example, the presence of crops or pasture beneath the solar panels can create a more diverse range of microhabitats and resources for wildlife compared to the relatively homogeneous environment of a conventional solar farm (Montag et al., 2016). However, the differences would be much less when compared to a solar farm following TNC's principles.

On the other hand, the additional complexities of managing both solar energy production and agricultural activities within an agrivoltaic system may require more careful planning and coordination to ensure that wildlife considerations are adequately addressed. For example, the timing and intensity of agricultural practices, such as planting, harvesting, and grazing, may need to be adjusted to minimize disturbance to wildlife (Schindler et al., 2018).

Furthermore, the potential for increased human presence and activity within an agrivoltaic system, due to the agricultural component, may require additional measures to minimize wildlife disturbance compared to a conventional solar farm (Harrison et al., 2017). This could include implementing buffer zones around sensitive habitat areas or restricting certain activities during critical breeding or migration periods.

Despite these challenges, the integration of agricultural activities within agrivoltaic systems also presents unique opportunities for supporting wildlife conservation efforts.

4.1.2 Macro perspective – Site selection considerations

In terms of impact on wildlife and biodiversity, agricultural areas with low biodiversity are ideal for agrivoltaics. For example, pastures with few species or monocultures could benefit from an agrivoltaics design approaches that integrates strategies for improving wildlife and biodiversity.

Habitat fragmentation and connectivity are crucial factors that can influence the movement and survival of wildlife populations (Fahrig, 2003). If not carefully planned, agrivoltaic systems may contribute to habitat fragmentation and decreased connectivity via the creation of barriers or altered land-use patterns. When selecting a site for agrivoltaics, it is therefore important to avoid areas of high native biodiversity protected habitats and areas of high native biodiversity. Examples of such sites to avoid are meadows and mires.

Meadows for example, known as *slåttemark* in Norwegian, are semi-natural grasslands that have been shaped by centuries of traditional hay cutting (Norderhaug and Svalheim, 2009). These species-rich habitats are among the most diverse in Norway and Europe, but also among the most threatened - it is estimated that only 1% remain today.

Meadows support a wide range of plant species and provide essential habitats for many threatened species. They are characterized by nutrient-poor soils, which have developed due to the regular removal of biomass through hay-cutting and the absence of fertilization. This low-nutrient environment prevents individual species from dominating and allows a high diversity of species to coexist. Unlike pastures, meadows contain unique vegetation types and species that cannot survive under grazing alone.

Mires are habitats that form peat and provide crucial ecosystem services like carbon storage and water regulation, have been extensively degraded and ditched in Norway for agricultural and forestry uses over the years (Kyrkjeeide et al.,2021). While these degraded mires release carbon, ecological restoration efforts can reinstate the water table and revive their ecosystem services, and arguably should be prioritized above other land-uses.

The above considerations and examples highlight how crucial it is to give special attention to site suitability early in the agrivoltaic system design process. It is vital to understand the ecological habitats, potential corridors and connectivity zones that run through or are in proximity of the area. If the impacts of intervention are severe, alternative sites should be explored. At a minimum, sufficient site-specific mitigation measures can be put in place. Such measures are discussed further in the following section.

4.1.3 *Micro perspective – Site specific*

While the site selection considerations lay the groundwork for a successful wildlife friendly agrivoltaic system, site-specific design elements play a crucial role in creating suitable habitats that minimise disturbances to local wildlife populations. Such design elements include vegetation management and habitat creation, microhabitats and wildlife permeable fencing. These are discussed in turn below.

By integrating native vegetation and pollinator-friendly plants, agrivoltaic systems can provide valuable foraging and nesting resources for a wide range of species (Walston et al., 2018). For example, research conducted by Montag et al. (2016) found that solar farms have the potential to increase the diversity and abundance of broadleaved plants, grasses, butterflies, bumblebees, and birds.

The extent to which solar farms benefit biodiversity is largely dependent on the site's management practices. Within the 2016 study, sites with a greater focus on wildlife management exhibited higher levels of biodiversity. Solar farms that achieved the highest wildlife value shared several key characteristics: they were seeded with a diverse seed mix upon completion of construction, employed limited use of herbicides, provided ample marginal habitat for wildlife, and implemented a conservation grazing or mowing regime (Montag et al, 2016). These findings highlight the importance of integrating wildlife-friendly, site-specific management practices into the design and operation of solar farms to maximize their potential for enhancing local biodiversity.

Research indicates a minimal risk of birds colliding with solar panels, according to carcass searches around solar PV installations detailed in scientific and grey literature (Harrison et al., 2017). However, associated infrastructure like overhead power lines could pose greater risks. The literature also advises against selecting protected or nearby areas for new solar developments, although precise guidelines are not well-defined. Notably, engineering studies highlight indirect signs of avian interactions, such as bird droppings, which affect the design of solar panel cleaning technology. Another ecological consideration is the polarized light reflected by solar panels, which attracts certain insects and can mislead birds into perceiving the panels as water sources, potentially influencing their behavior and biology. The varied responses of different bird and bat species to solar farms, dictated by their specific behaviors and ecological needs, underscore the necessity for tailored environmental assessments in planning solar energy projects.

In addition to vegetation management, the creation of microhabitats and refuges within the agrivoltaic system can further support wildlife populations. This can include the incorporation of bird boxed/artificial nesting structures that provide shelter and breeding sites for various species (Cowan et al., 2021). If possible, these microhabitats could potentially be placed in areas that do not interfere with solar panel functioning or agricultural activities, thereby maximizing the co-benefits for wildlife.

Fencing and perimeter design is another critical consideration for wildlife-friendly agrivoltaic systems. Traditional fencing can create barriers to animal movement and increase the risk of entanglement or injury (Hanophy, 2009). These can reduce connectivity and have negative consequences for local species. Solar facilities have started testing 'wildlife permeable fences' that feature larger openings than standard chain-link fences, enabling medium-sized animals to move through (Kallies, 2023). These permeable fences could play a crucial role in reducing the impacts of solar development on wildlife. Equally important is the establishment of unfenced wildlife 'corridors' within large facilities, which permit larger mammals such as deer to move freely through the area.

To ensure the effectiveness of these site-specific design elements in supporting wildlife populations, long-term monitoring and evaluation are essential (Montag et al., 2016). Regular surveys of flora and fauna within and around the agrivoltaic system can provide valuable insights into the presence, abundance, and diversity of species over time. This monitoring data can be used to assess the success of wildlife-friendly design features and to inform adaptive management strategies. For example, if monitoring reveals a decline in certain species or a lack of use of artificial nesting structures, adjustments can be made to the design or management of the agrivoltaic system to better support wildlife.

Furthermore, monitoring can help identify any unintended consequences or negative impacts on wildlife that may arise from the agrivoltaic system (Pozo et al., 2020). By detecting these issues early, mitigation measures can be implemented to minimize harm to wildlife populations. This iterative process of monitoring, evaluation, and adaptation is crucial for ensuring that agrivoltaic systems continue to provide suitable habitats and resources for wildlife throughout their operational lifetime.

In conclusion, while site selection considerations are essential for minimizing impacts on wildlife, site-specific design elements and long-term monitoring and evaluation are also crucial for creating and maintaining wildlife-friendly agrivoltaic systems. By integrating these micro-level considerations into the planning, design, and management of agrivoltaic projects, the potential for these innovative land-use strategies to support wildlife conservation can be maximized.

4.2 Agricultural production

This chapter discusses various considerations for designing an agrivoltaic system in terms of agricultural output. Firstly, it outlines practical considerations such as lost area and row spacing. Secondly, it examines the research on the suitability of various crops in semi-shaded environments similar to agrivoltaic systems.

There are several factors as to why agricultural areas can be considered for agrivoltaics, including the potential for increased land productivity. To compare the land use efficiency of conventional agriculture and solar energy systems with agrivoltaic systems, the use of Land Equivalent Ratios (LER) has been proposed. Depicted in Figure 5 (Trommsdorff et al., 2020)., LER is a ratio that traditionally comes from comparing the relative land area required for a monoculture to produce the same yield as a polyculture.

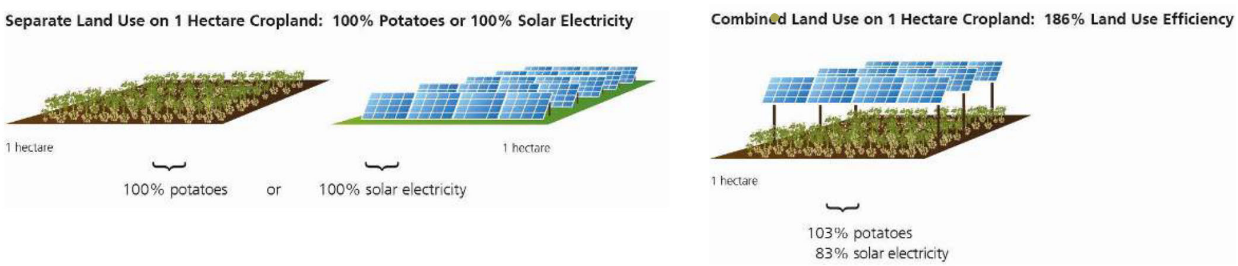

Figure 5. Trommsdorff, M. (2020). Exampled of LER in an agrivoltaics setting with potatoes. Performance Indices for Parallel Agriculture and PV Usage - Approaches to quantify land use efficiency in agrivoltaic systems. EU PVSEC 2020, Online conference. Available at: https://iea-pvps.org/wp-content/uploads/2020/09/07_M.-Trommsdorff_A (accessed 11.05.2024).

In the context of agrivoltaics, LER compares the area needed to produce the same amount of agricultural produce and electricity, either co-located as in agrivoltaics or on separate areas, and gives it as a ratio. A LER value greater than 1 indicates that the agrivoltaic system is more productive than a separate sole crop system and a ground mounted PV farm, demonstrating the potential for increased land productivity (Thompson et al., 2020; Sekiyama & Nagashima, 2019; Pascaris et al., 2020).

A 2021 study from Sweden based on computational modelling, Campana et. al. showed that for the locations investigated, the implementation of and agrivoltaic system for crops such as oats and potatoes gave an LER of above 1.2. Similar studies conducted further south in Europe in countries such as Italy and Germany have also modelled promising LER values (Campana et. al, 2021). However, the study concluded that LER cannot be used as the main and only parameter for designing agrivoltaic systems, as maximizing the LER alone may reduce electricity production drastically.

The selection of suitable crops and their spatial arrangement within the agrivoltaic system is essential for maximizing agricultural output. Studies have demonstrated that shade-tolerant crops are particularly well-suited for agrivoltaic systems. The integration of solar panels can lead to increased economic value and an over 30% improvement in farm productivity compared to conventional agriculture (Dinesh & Pearce, 2016). Additional potential benefits include increased water-use efficiency, improved soil moisture, and more pollinators which can positively impact agricultural productivity (Adeh et al., 2018; Campana et al., 2021).

4.2.1 AREA LOST TO INFRASTRUCTURE IN AGRIVOLTAICS

A common cause of resistance to agrivoltaics on agricultural land is the perceived loss of land to infrastructure. The extent to this lost area varies according to the design principles used and can be minimised. Some examples of different configurations are provided in **Error! Reference source not found.**Figure 5 (Macknick et al. 2022).

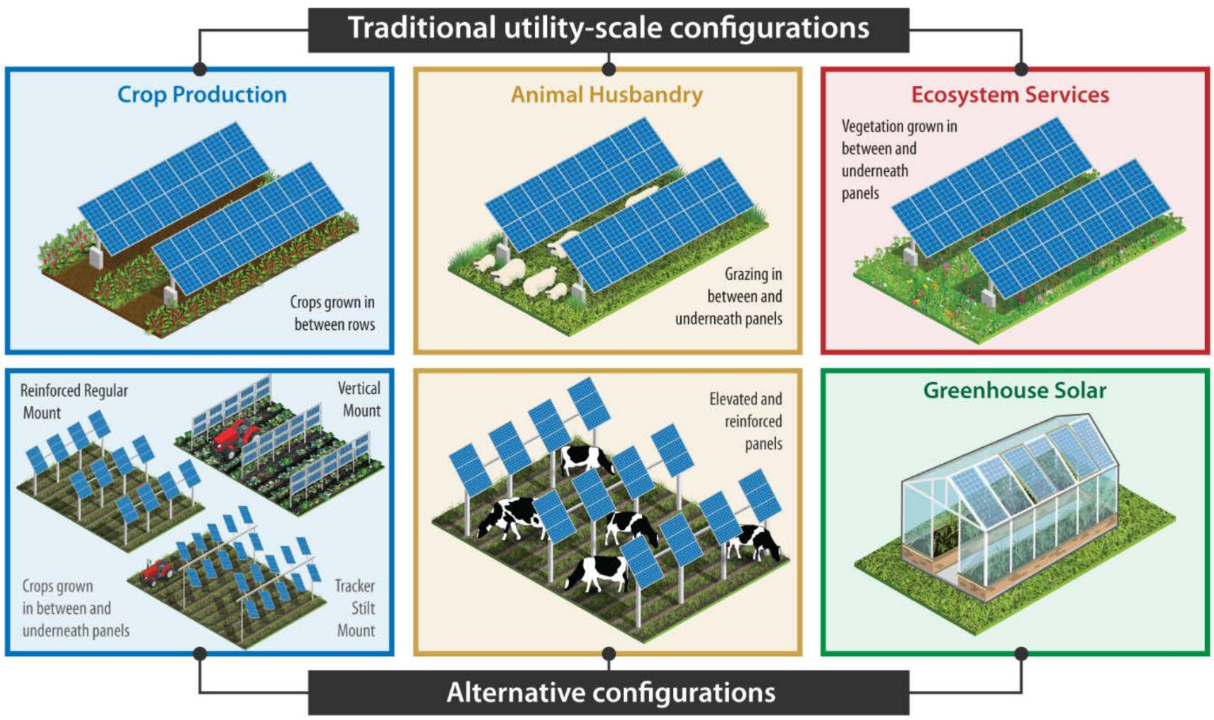

Figure 6. Macknick et al. (2022) Various types of utility-scale agrivoltaics configurations that have been deployed commercially.*The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study*. NREL/TP-6A20-83566. National Renewable Energy Laboratory (NREL). Available at: https://www.nrel.gov/docs/fy22osti/83566.pdf (accessed: 10.05.2024).

The Norwegian Agriculture Agency (Landbruksdirektoratet) examined the consequences of ground-mounted solar power plants on agricultural and forestry land in a recent report (Landbruksdirektoratet, 2024). The report considered row spacings ranging from 3 to 30 meters and estimated the total area lost due to accompanying infrastructure and buffer zones. The findings suggested that with a 3-meter row spacing, approximately 20% of the land would be occupied by infrastructure and buffer zones. However, as the row spacing increased, the percentage of land lost gradually decreased, reaching 10% for a 30 m row spacing.

The Norwegian Institute of Bioeconomy Research (NIBIO) examined six agrivoltaics projects currently in the planning stages in Norway (NIBIO, 2024). The projects featured row spacings ranging from 4 to 10 meters. The investigation revealed that, on average, 90% of the land area within the solar panel arrays was maintained as green space, with the remaining 10% allocated for technical infrastructure and access roads. For areas surrounding transformer stations, NIBIO recommended assuming a default green space allocation of 25%, which is the standard distribution for developed areas.

Next2Sun are according to their website a "(…) technology leader in vertical bifacial photovoltaics" and considered a pioneer in agrivoltaics (Emir, 2024). They advertise that the panels take than 10% of the area, leaving over 90% of the area for agricultural activies (Next2Sun, 2024).

Similarly, Trommsdorff et al. (2021) investigated an agrivoltaics research facility in Germany installed on stilts. It had a vertical clearance of 5 meters and a width clearance of up to 19 meters to accommodate agricultural machinery. The study revealed that the supports for the solar panels and accompanying infrastructure occupied approximately 8.3% of the total land area, leaving 91.7% of the land available for crop production.

4.2.2 Practical row width for agricultural machinery

According to research conducted by the Norwegian Institute for Bioeconomy (NIBIO, 2024), a row width of 12-15 meters should be sufficient to use agricultural machinery between the widths. There may be some difficulties regarding the ploughing, and the cable ditches need to be at a sufficient depth to avoid damage. It was also mentioned that fertilizing equipment might be up to a 20 meters width, and the fertilizer could possibly soil the panels, requiring additional labour to clean them afterwards.

4.2.3 Grass, pasture, and feed production

Further research by NIBIO (2024) found that any shading, given optimal water and nitrogen availability, reduced the herbage yield. The results of NIBIO's plant growth modelling using a software called NORNE, showed that grass growth is highly dependent on weather, with yields varying significantly between years and locations. These results are shown in Figure 7 and 8 (NIBIO, 2024).

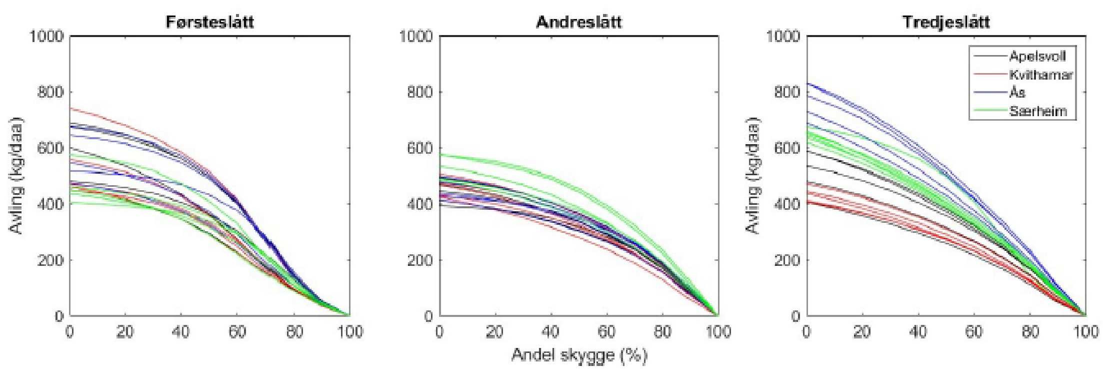

Figure 7. NIBIO (2024). 1. 2. and 3. dry cut yield with optimal water and nitrogen, and varying degree of shading, at the four sites studied between 2018 and 2022. *Solkraftverk på jord- og skogareal*. NIBIO-rapport vol. 10 nr. 9, 2024, s. 19 kapittel 4.3.

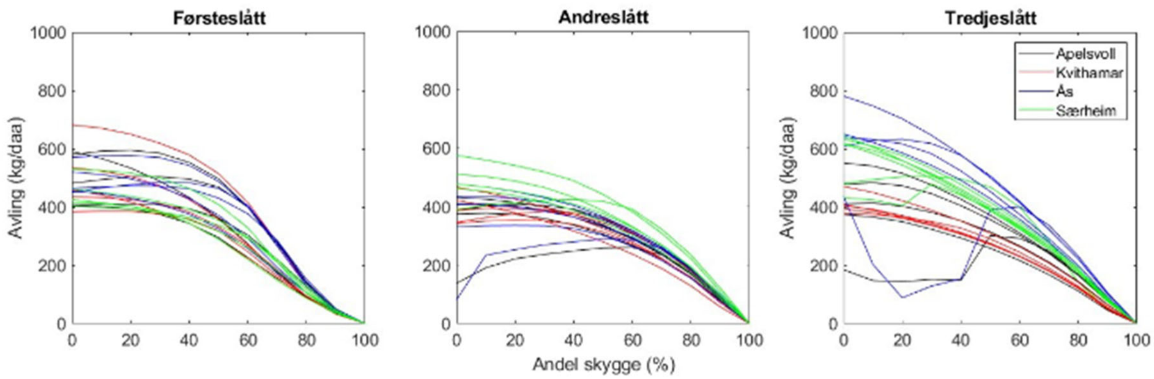

Figure 8. NIBIO (2024) 1. 2. and 3. Dry cut yield with optimal nitrogen, and varying water availability

and degree of shading at the four sites studied between 2018 and 2022. *Solkraftverk på jord- og skogareal*. NIBIO-rapport vol. 10 nr. 9, 2024, s. 19 kapittel 4.3.

As depicted above, shading was first simulated assuming optimal water and nitrogen availability, revealing that shading's effect on plant growth is not linear but follows a sigmoid curve, with stronger effects as shading increases from 50% to 100%. On average, first cut yields decreased by 3-29% with 10-50% shading, with similar patterns observed for second and third cuts. When the model's water availability module was included, shading's effect varied, sometimes leading to increased yields, particularly in years with drought stress, as shading reduced evaporation. In the model, it was assumed a uniform shading over the whole area, actual field conditions with a given row and panel width would result in alternating strips of shaded and unshaded areas.

The study concludes that solar energy shading will reduce grass yield potential if water and nutrients are optimal, consistent with other research. Reductions ranged from 3-5% with 10% sunlight reduction to 26-36% with 50% reduction. In drought years, shading could mitigate yield loss due to better soil water status.

They conclude that the study by Honningdalsnes (2022) did a fair assumption by ignoring water availability, as most sites in Norway do have sufficient water availability most years. However, in certain years like 2018 where drought stress due to low rainfall and high evaporation was an issue, the shading effect could decrease crop loss. With climate change, this might be the case in certain locations in Norway in the near future and warrants further investigation of ideal sites where droughts are more likely.

In Oregon, an agrivoltaics pasture system was investigated and compared to an open pasture to evaluate its impact on pasture and lamb production (Andrew et al., 2021). The experimental setup had solar panels installed above the pasture, creating shaded and partially shaded areas. It was found that solar pastures yielded lower herbage compared to normal pastures. However, lamb growth did not differ, despite the lower herbage production on the solar pasture. Chemical analysis of the pastures' nutritional content revealed that the overall quality was superior in the agrivoltaic system compared to conventional pastures.

Pasture production was lower in fully shaded areas, suggesting that light availability was a critical factor for plant growth. Despite lower pasture availability in shaded areas, lamb liveweight gain was comparable between solar and open pastures, potentially due to higher forage quality in shaded pastures. Lambs utilized shaded areas extensively for ruminating and idling, which may have reduced heat stress and maintenance energy requirements. Water intake by lambs was similar or lower in shaded pastures compared to open pastures. The Land Equivalent Ratio (LER) for the agrivoltaic system indicated that combining sheep grazing and solar energy production on the same land was more productive than using the land for a single purpose.

The study concluded that agrivoltaics can sustainably produce both lamb and energy, with the dual-use system not diminishing the land's production value. However, the reduced pasture yield under fully shaded areas was a concern, suggesting that careful selection of shade-tolerant and trampling-resistant pasture species, as well as strategic grazing management, are important for optimizing agrivoltaic systems.

Trommsdorff et al. (2021) also investigated clover grass production in their agrivoltaic system in Germany. In 2017, clover grass was the best performing crop under the PV modules, with a yield reduction of only 5% compared to the reference area. However, in 2018, clover grass was the poorest performing crop, with an 8% decrease in yield under the agrivoltaic system. Interestingly, clover grass showed similar results for both years, suggesting that the agrivoltaic system did not provide an advantage to clover grass even in the drier year of 2018, unlike the other crops studied.

There is a notable gap in research concerning pastures, grass and feed production within agrivoltaics settings (Andrew et al., 2021). While some studies have touched on aspects related to livestock production and foraging behavior in agrivoltaic systems, the direct examination of grass species and their influence on feed production within these settings is an area that warrants more attention.

4.2.4 Grain production

The review of the literature revealed limited research on grain production in an agrivoltaics setting. However, some site-specific physical experiments have investigated wheat production in areas around Europe. The results from these experiments are summarised below and provide useful learnings for grain production via agrivoltaic systems.

One such example is an experiment conducted in Germany, near Lake Constance within the research project APV-RESOLA by Fraunhofer Institute for Solar Energy Systems ISE, which has been cited in the clover grass discussion(Trommsdorff et al., 2021).

Figure 9. Trommsdorff et al., (2021). Picture of the agrivoltaics at Heggelbach.*Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany.* Renewable and Sustainable Energy Reviews, 140. https://doi.org/10.1016/j.rser.2020.110694

Their research on the viability of winter wheat in agrivoltaic systems presents an informative perspective on the effects of weather and climate on the yield. In the initial assessment during 2017, winter wheat exhibited a reduction in harvestable yield under the agrivoltaic system compared to the reference area, with a notable 19% yield decrease. However, this trend was reversed in 2018. Marked by improved crop performance, the yield was notably 3% higher than the reference area. The shift towards higher harvestable yields under the agrivoltaic system in 2018 can be attributed to specific environmental conditions, particularly a warmer and drier summer climate. The reduced water stress experienced by winter wheat due to shading from the solar panels in the agrivoltaic setup likely also played a crucial role in the crop's improved productivity. The dry and warm weather conditions prevalent in 2018 also created a favorable environment for winter wheat cultivation within the agrivoltaic system, leading to increased crop yields and overall land use efficiency. The cultivation area is pictured in Figure 10 (Trommsdorff et al., 2021) and Figure 10 (Pataczek, 2022).

Figure 10. Pataczek (2022). Winter wheat grown in Heggelbach under agrivoltaics. *Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis*. Agronomy for Sustainable Development, 42, 51. https://doi.org/10.1007/s13593-022-00783-7

As shown in Figure 11 (Trommsdorff et al., 2021) below, the mean Land Equivalent Ratio (LER) for winter wheat in the agrivoltaic system ranged from 1.56 in 2017 to 1.78, which was higher than predicted conservative values ranging from 1.19 to 1.43 (Dupraz et al., 2011). The higher LER of the agrivoltaic system may result from the use of bifacial modules and higher vertical clearance, compared to earlier estimated LER values.

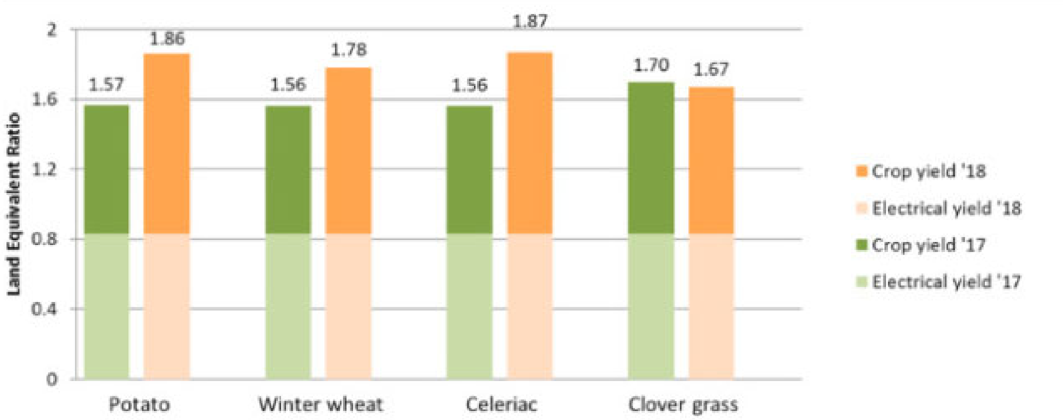

Figure 11. Trommsdorff et al. (2021). LER values of the different crops measured during 2017 and 2018, at Heggelbach. *Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany*. Renewable and Sustainable Energy Reviews, 140. https://doi.org/10.1016/j.rser.2020.110694

Campana et al. (2021) explored the potential of vertically mounted agrivoltaic systems for the cultivation of oats in Sweden. Their study used a crop model to simulate the growth and productivity of the crop under different row spacing of vertical agrivoltaic system designs in Swedish climatic conditions. They found that if the aim was minimum a 70% crop yield, i.e. up to 30% reduction in crop yield, the row spacing would be 9 m. The design of their system is shown in Figure 12 (Campana et al., 2021), and the LER values are shown in Figure 13 (Campana et al, 2021) below.

Figure 12. Campana et al. (2021). Bifacial photovoltaic modules in a vertically mounted agrivoltaic system at Kärrbo Prästgård, Västerås, Sweden. *Optimisation of vertically mounted agrivolatic systems.* Journal of Cleaner Production, 325, p.18 s. https://doi.org/10.1016/j.jclepro.2021.12909

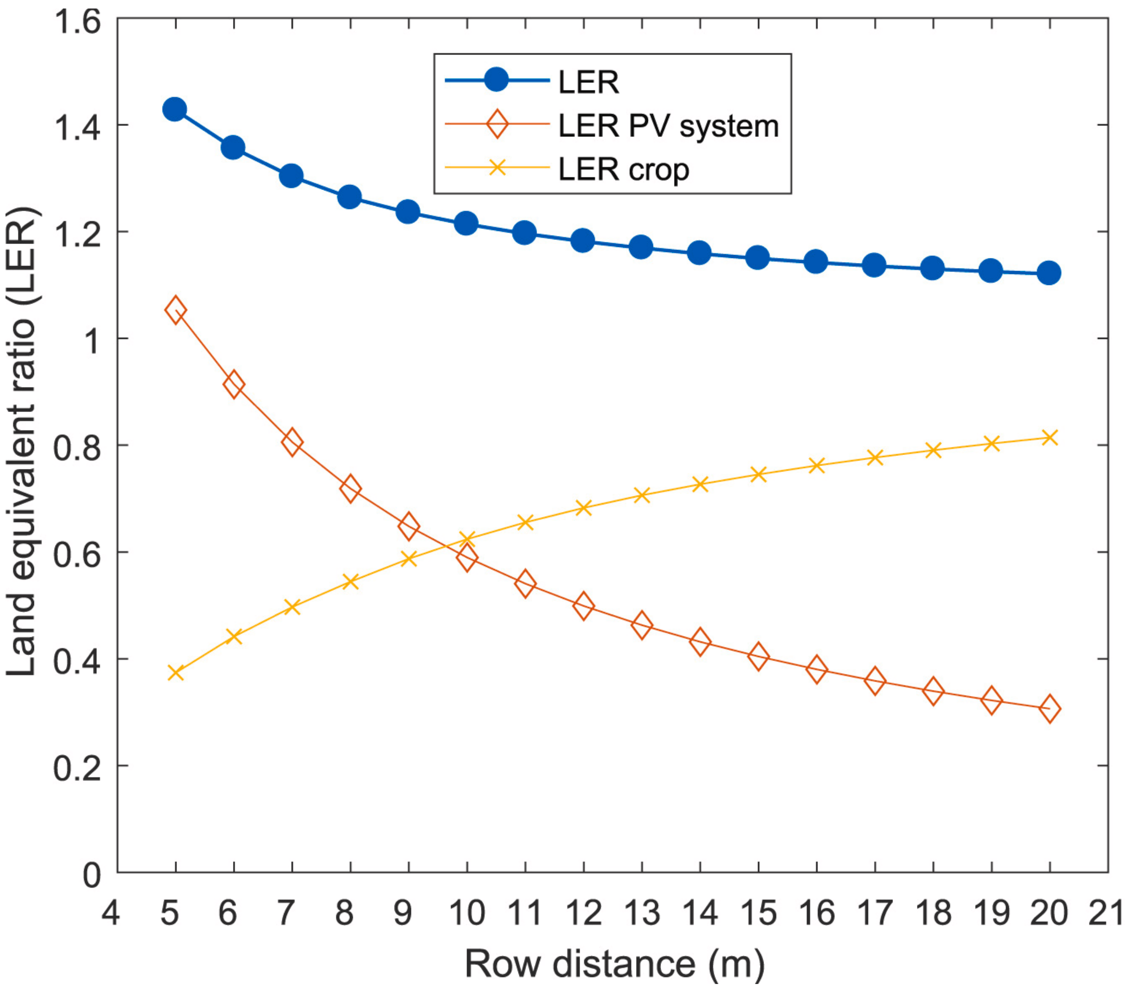

Figure 13. Campana et al (2021). LER for agricultural and solar-energy yield of oats in Sweden, and combined LER. *Optimisation of vertically mounted agrivolatic systems.* Journal of Cleaner Production, 325, p.18 s. https://doi.org/10.1016/j.jclepro.2021.12909

A meta-analysis by Laub et al. (2022) investigated studies based on temperate and sub-tropical regions. While there is no guarantee that the outcomes in temperate regions are applicable to Norway, they can still provide an indication of which crop species have been grown under agrivoltaic system conditions. . The study found that C3 cereals – rice, wheat and barley – initially showed less than proportional yield loss under reduced solar radiation, while corn experienced strong yield losses even at low shade levels. The study estimated that C3 cereals could maintain a yield of 90% compared to unshaded conditions at a reduction in solar radiation (RSR) of up to 50%. In contrast, corn, a C4 plant, was found to be the most susceptible to shading among all crop types studied.

This somehow contradicts what was found in a study in Japan by Sekiyama and Nagashima (2019). When investigating the performance of agrivoltaic systems for corn, a typical shade-intolerant crop, they found corn production increased under the agrivoltaic system. The corn yield of the low-density PV panel configuration was higher, not only than that of the high-density configuration, but also than that of the no-module control configuration. The biomass of corn stover grown under PV module arrays spaced at 1.67 meter intervals was even greater than that of corn without PV modules by a magnitude of 4.9%. The study concluded that it could be possible to grow corn, a typical shade-intolerant crop, even under the shade of agrivoltaic PV panel, and an increase in the overall productivity of land could be achieved, even with crops that require plenty of sunlight.

4.2.5 Vegetable production

Trommsdorff et al. (2021) also investigated potato and celeriac production in an agrivoltaics setting in Germany. In 2017, celeriac and potato yield were reduced by 18% compared to the reference field. In 2018 however, harvestable yields were 11% and 12% higher than the reference field, for potato and celeriac, respectively. Again, it was attributed to the dry and hot summer conditions, suggesting that agrivoltaics can provide benefits for vegetable production, particularly during periods of climate stress. The LERs can be seen in Figure 12 (Trommsdorff et al., 2021), where the electrical yield essentially stays the same for both years, but where the agricultural yield varies greatly.

This is quite similar results to Campana et al. (2021), which used crop model simulations to investigate potato growth in Sweden, based on different row spacings, as shown in Figure 14 (Campana et al., 2021) below. They found that if the target of a guarantee is 70% crop yield, the row spacing would be 11 meters.

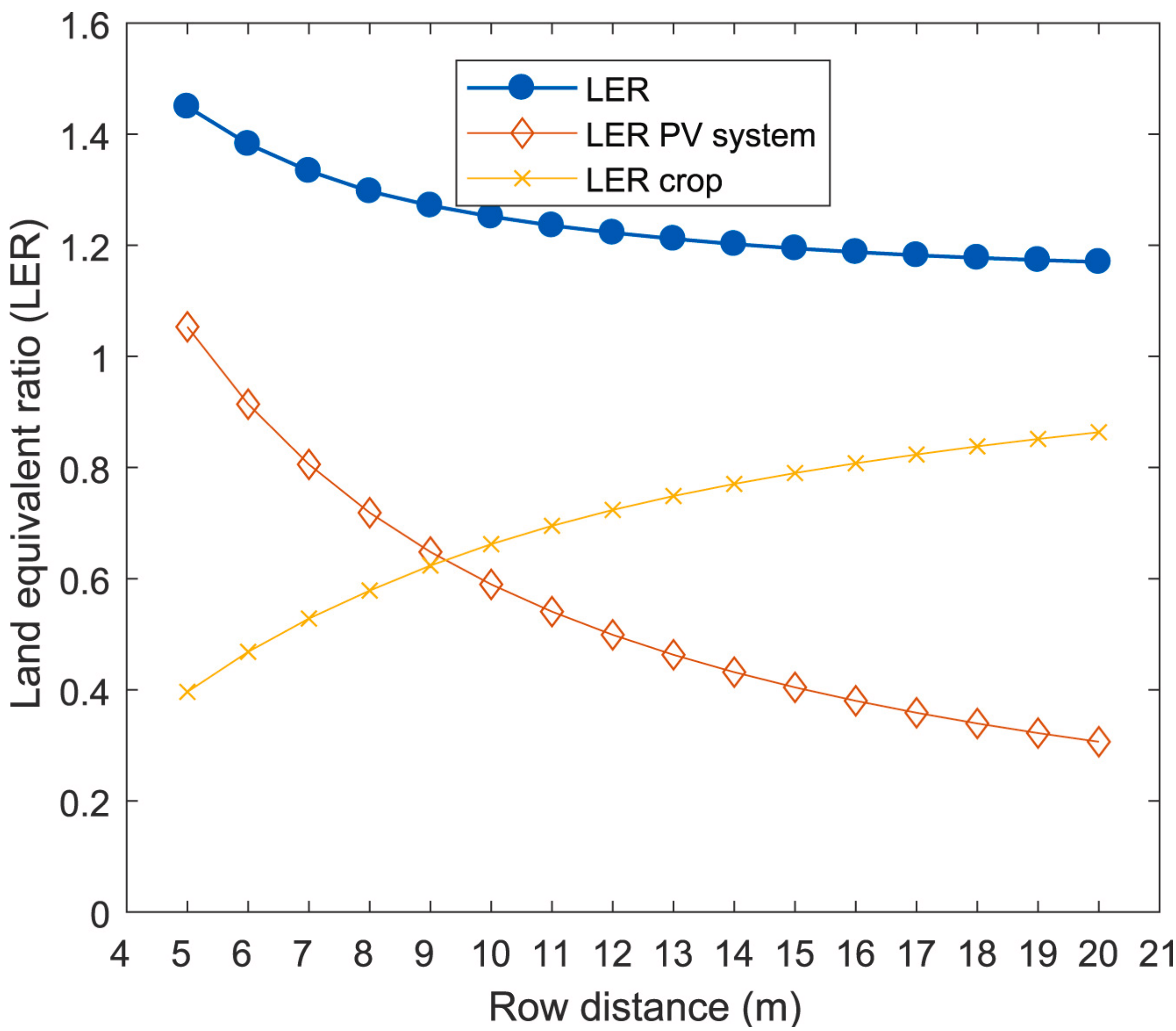

Figure 14. Campana et al (2021). LER for agricultural and solar-energy yield of potatoes in Sweden, and combined LER. *Optimisation of vertically mounted agrivolatic systems*. Journal of Cleaner Production, 325, p.18 s. https://doi.org/10.1016/j.jclepro.2021.12909

Another vegetable species with great potential for production in agrivoltaics is broccoli (Chae et al., 2022). It was studied in South Korea over three cultivation periods, in Naju, Jeollanam Province. Although the climate is somewhat different to Norway and Europe in that summers tend to be very hot, it provides useful insights for another crop species grown under agrivoltaic conditions. and warrants further reserach.

The results showed that broccoli grown under agrivoltaic systems had comparable yield, antioxidant capacity, and levels of health-promoting compounds (glucosinolates and their hydrolysis products) to those grown in open-field conditions. Interestingly, the addition of shading treatments within the agrivoltaic system produced broccoli with a greener appearance, which was preferred by consumers. Although the average weight of broccoli heads under agrivoltaic systems was slightly lower (5-13%) than the open-field control, this difference was not statistically significant, and seasonal variations had a greater influence on yield.

4.2.6 Fruit and berry production

A recent meta-analysis by Hermelink et al. (2024) examined the shade tolerance of individual berry crops and their suitability for agrivoltaic systems. The study developed yield response curves for strawberries, blueberries, blackberries, and black currants under increasing shade levels, considering both low and high radiation intensity environments. The results showed that blueberry could benefit from up to 50% shade under high radiation intensity conditions. Other berry types were also classified as shade tolerant, enduring up to around 35% shade without yield loss.

Similar results were found in the research conducted by Laub et al. (2022) which investigated the yield responses of different crop types to varying levels of shading. The study analyzed data from both intercropping and artificial shading experiments in temperate and subtropical regions. It was found that the relationship between reduction in solar radiation (RSR) and crop yield is non-linear for all crop types, with significant differences in yield responses among crop types. It classified crop responses into three phases: shade benefit, where yield increases due to shading; shade tolerance, with less than proportional yield losses; and shade susceptibility, with disproportionately large yield decline. Morpho-physiological changes in plants, such as increased leaf area and photosynthetic efficiency, may explain the shade tolerance of some crop types. The study is useful because it offers preliminary metrics to evaluate the compatibility of various crops for agrivoltaic systems or other forms of dual land use, introducing detailed yield response curves as essential instruments for maximizing the production of annual crops within these frameworks. The authors emphasize the need for more data and further experiments on new agrivoltaic designs to improve yield predictions and adapt dynamic crop growth models for these systems.

It was found that in temperate and subtropical regions, berries and fruits may benefit from a reduction in solar radiation (RSR) of up to 40%. The study estimated that under both 20% and 40% RSR, berries could maintain a yield of 114% compared to unshaded conditions, while fruits could achieve yields of 114% at 20% RSR and 113% at 40% RSR.

In a related study conducted in Belgium, researchers Willockx et al. (2024) investigated the use of semi-transparent solar panels in a pear orchard. Although the yield decreased by 16% with 25% shading, the panels provided significant protection against heat waves, drought, heavy rain and hail events, highlighting an important benefit of such systems.

These findings, summarized in Figure 17 (Laub et al., 2022) below and in Table 2, indicate that fruit and berry production could be viably integrated into agrivoltaic systems in temperate climates such as those found in Norway and Europe. This potential is underscored by the need for further research, especially as the data currently available is primarily from regions with higher solar radiation

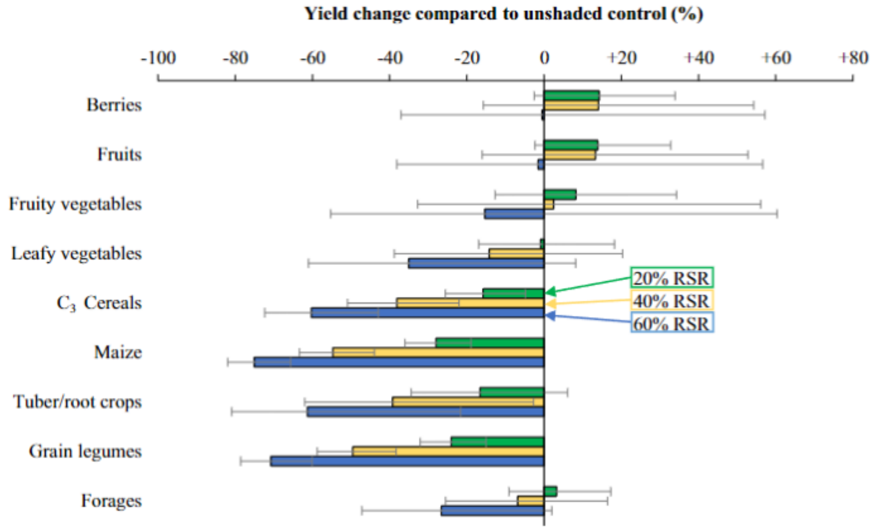

Figure 15. Laub et al. (2022). Yield change for various crops under different levels of reduction in solar radiation (RSR). *Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis*. Agronomy for Sustainable Development, 42, 51. https://doi.org/10.1007/s13593-022-00783-7

4.2.7 Summary and Recommendations

Crop/agricultural produce	**Effect of Shading (Reduction in Yield)**	**Effect in a Dry Year**	**Location of Study**
Grass/Pasture	3-29% reduction with 10-50% shading	Shading could mitigate yield loss due to reduced evaporation	Norway (modelling study)
Grass/Pasture Lamb growth	Lower yield in fully shaded areas, but higher forage quality	Less heat stress on animals	Oregon, USA
Clover Grass	5% reduction in 2017, 8% reduction in 2018 (dry year)	No advantage in dry year	Germany
Winter Wheat	19% reduction in 2017, 3% increase in 2018 (dry year)	Increased yield in dry year due to reduced water stress	Germany
Oats	For 70% yield target, row spacing of 9 meters needed (30% loss)	-	Sweden (modelling study)
Corn	Increased yield with low-density PV panel configuration compared to control	-	Japan
Potatoes	18% reduction in 2017, 11% increase in 2018 (dry year)	Increased yield in dry year	Germany
Potatoes	For 70% yield target, row spacing of 11 meters needed (30% loss)	-	Sweden (modelling study)

Celeriac	18% reduction in 2017, 12% increase in 2018 (dry year)	Increased yield in dry year	Germany
Broccoli	5-13% reduction, but not statistically significant	-	South Korea
Berries	Up to 35% shade tolerance without yield loss	Could benefit from up to 40% shade in temperate regions	Meta-analysis
Fruits	Up to 35% shade tolerance without yield loss	Could benefit from up to 40% shade in temperate regions	Meta-analysis
Pears	15% reduction in yield with 25% shading.	-	Belgium

Table 2. Summary of impact of shading and agrivoltaic systems on agricultural production.

In general, raised panels on stilts take up the lowest proportion of areas, and can be implemented for typically used for agricultural production (Trommsdorff et al., 2021).

Likewise for the vertical bifacial, which have the second lowest proportion of area use, and have the added benefit of having a small vegetation strip under and next to the panels that could potentially be a refuge for wildflower species and pollinators, which could increase agricultural production (Campana et al., 2021).

If the area will be used as a low or no maintenance pasture grazing area for sheep, a relatively narrow row spacing of less than 6 meters can be used. In Norway and temperate regions, low maintenance pasture sites with low row spacing provide potential sites to establish agrivoltaics. Such an approach would also have the added benefit of increased animal welfare, providing them with a shaded area for hot summer days (Andrew et al., 2021).

If the area is planned to be used as a high herbage yield area with regular maintenance activities such as fertilization and chalking, then the row spacing must be large enough to accommodate the largest equipment used (NIBIO, 2024). There will therefore be need for sufficient area for reversing, turning, and manoeuvring the equipment. The costs associated with such an approach may be prohibitive, as additional cabling will also have to be dug to a sufficient depth to not interfere with operations.

Production of certain vegetables also appear to be quite suitable for agrivoltaics system, especially in dry areas (Trommsdorff et al., 2021). Indeed, the findings outlined in this section suggest that agrivoltaics systems can increase the production of these crops compared to non-shaded areas, due to less evaporation that leads to more water availability (NIBIO, 2024; Campana et al., 2021). Similar trends are found for oats and winter wheat, which suffered losses of yield in a normal year, but increases in yield in dry year.

For practical purposes and travel between the vegetables beds, fixed tilt, tracked or panels on stilts might make the best choice for vegetable production, or vertical bifacial panels raised sufficiently so it is possible to go under the panels. For grain production, vertical bifacial system or raised on stilts would likely be the best choice, as they provide the largest possible area to grow on.

Fruit and berries demonstrate substantial potential for agrivoltaic systems, both due to their tolerance for shade and their added protection against heat waves, drought, heavy rain, and hail (Laub et al., 2022; Willockx et al., 2024). Despite the limited research on these crop species, the prevalence of fruit and berry production in Norway suggests that further investigation into their cultivation under agrivoltaic conditions is warranted.

4.3 Power production

For large scale agrivoltaics and PV power stations, there are many important and deciding factors for where to locate the projects. Among them are grid connection, the proximity and capacity of the grid, distance to other infrastructure, and power prices. A discussion of these factors is outside of the scope of this thesis and will therefore not be discussed in any detail.

The orientation and tilt angle of solar panels play a crucial role in maximizing their energy efficiency. In general, in the northern hemisphere, solar PV panels are best oriented to the south, while in the southern hemisphere, they are best oriented to the north (Abdallah et al., Manjunath et al., 2021). The optimal tilt angle of the solar panel varies depending on the latitude and the time of year.

Conventional fixed-tilt panels have been the most common configuration in solar farms due to their simplicity, reliability, and cost-effectiveness (Salih, 2023). However, fixed-tilt panels have limitations in terms of energy yield, as they cannot adapt to the changing position of the sun throughout the day and year (Ramli et al., 2021). In the context of agrivoltaics, fixed-tilt panels may not be the most optimal configuration, as they can create significant shading and limit the available land for agricultural activities, except for sheep grazing.

Tracking panels, such as single-axis or dual-axis tracking systems, have gained popularity due to their ability to follow the sun's movement and increase energy yield compared to fixed-tilt panels. Studies have shown that tracking systems can increase energy production by 8-40% compared to fixed-tilt panels (Lazaroiu et al., 2015; Sumathi et al., 2017). However, the added complexity and maintenance requirements of tracking systems can increase costs and potentially impact profitability (Ramli et al., 2021). In agrivoltaic systems, tracking panels may provide more flexibility in terms of optimizing solar energy production while minimizing the impact on agricultural land use.

Vertical panels, also known as bifacial panels, have emerged as a promising configuration for agrivoltaic systems. These panels are installed vertically, allowing for the capture of direct and reflected sunlight on both sides of the panel (Guerrero-Lemus et al., 2016). This configuration has been shown to potentially increase energy yield, in regions with high levels of diffuse sunlight or snowfall (Chudinzow et al., 2019). Vertical panels have reached maturation in terms of profitability, with several studies demonstrating their economic viability (Joge et al., 2019; Shoukry et al., 2016). In agrivoltaic systems, vertical panels can provide increased energy production while minimizing the shading impact on crops, making them an attractive option for dual-use solar farm projects. They can also be used for fencing, making it easy to manage small-sized pastures and frequent moving of animals. (Next2Sun, 2024).

Panels on stilts, also known as elevated or raised solar panels, are an emerging configuration that aim to maximize land use efficiency by allowing for agricultural activities beneath the panels (Dinesh & Pearce, 2016). This configuration has the potential to mitigate the land scarcity dilemma characterized by competition between solar energy production and agriculture (Dupraz et al., 2011). By raising the solar panels, more sunlight can reach the crops below, enabling a more efficient use of land resources. However, the profitability of panels on stilts is still being established. The additional costs associated with the supporting structures and installation processes may prove to impact the economic viability of this configuration (Weselek et al., 2019). As research and development continue, it is expected that the cost-effectiveness of panels on stilts will improve, making them a more attractive option for agrivoltaic systems.

In conclusion, when considering the optimal solar panel configuration for agrivoltaic systems, it is essential to balance energy production, land use efficiency, and economic viability. However, further research is needed to optimize the design and implementation of these configurations in agrivoltaic systems, considering site-specific conditions and crop requirements.

5 DESIGN

As seen in the previous chapter, it is challenging to address several considerations simultaneously, and is illustrated with Venn-diagram in Figure 16.

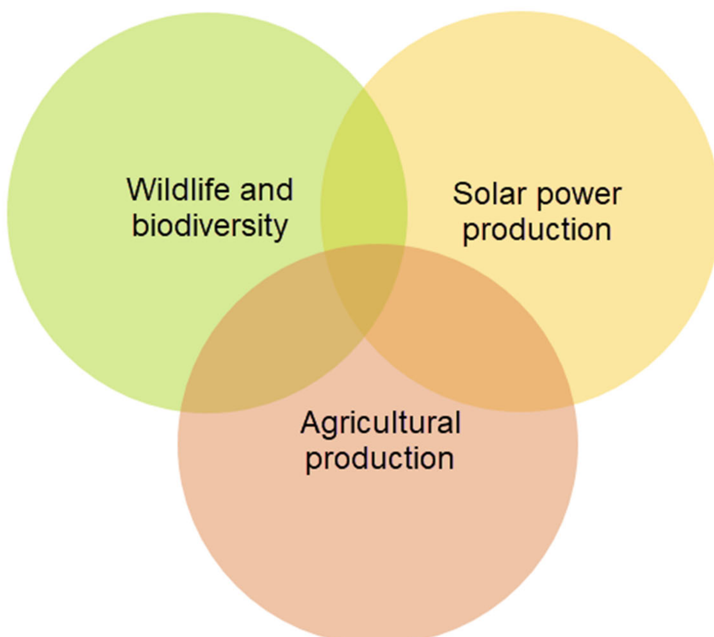

Figure 16: Venn-diagram illustrating the challenge of considerations when designing an agrivoltaic system.

Giving up sun or area for solar panels or native plants, will usually reduce the agricultural yield (NIBIO, 2024). However, there are exceptions, as discussed in previous chapter. Dry conditions where shading is ideal, or the potential of wildflowers to enhance pollination.

The design principles and ideas presented in this chapter aim to integrate the various considerations discussed in the previous chapters, including the impact on wildlife, agricultural production, and power generation. By carefully balancing these factors, agrivoltaic systems can be designed to maximize their benefits while minimizing potential negative impacts.

Prioritize site selection to minimize impacts on wildlife and biodiversity:

- Avoid areas of high native biodiversity and protected habitats, such as meadows and mires.
- Focus on agricultural areas with low biodiversity, such as pastures with few species or monocultures.
- Consider the potential for habitat fragmentation and maintain wildlife corridors.site selection to minimize impacts on wildlife and biodiversity

Incorporate wildlife-friendly features at the micro-level:

- Integrate native vegetation and pollinator-friendly plants to provide valuable foraging and nesting resources.
- Use wildlife-permeable fencing to allow for animal movement while ensuring the safety of the solar infrastructure.
- Create microhabitats and refuges, such as bird boxes or artificial nesting structures, in areas that do not interfere with solar panel functioning or agricultural activities.

Select appropriate solar panel configurations based on the specific agricultural requirements:

- Use raised panels on stilts for crop production to maximize the available area for cultivation while minimizing shading.
- Consider vertical bifacial panels for grazing or grass production to create small vegetation strips that can serve as refuges for wildflower species and pollinators.
- Employ fixed-tilt or tracking on stilts above fruit and berry production to protect crops from extreme weather events.

Adapt row spacing and panel height to accommodate agricultural machinery and practices:

- Ensure sufficient row spacing for the use of large agricultural equipment, such as plows and fertilizer spreaders.
- Adjust panel height to allow for the passage of machinery and to optimize shading for specific crops.

Prioritize the selection of shade-tolerant and drought-resistant crops:

- Choose crop varieties that have demonstrated good performance under partial shading conditions, such as certain vegetables, fruits, and berries.
- Consider the potential benefits of shading for reducing water stress and improving crop resilience, particularly in regions prone to drought or under future climate change scenarios.

Implement long-term monitoring and evaluation of agrivoltaic systems:

- Establish protocols for monitoring crop performance, including yield, quality, and resource use efficiency.
- Assess the effectiveness of wildlife mitigation measures through regular surveys of flora and fauna within and around the agrivoltaic system.
- Use the monitoring data to inform adaptive management strategies and to refine agrivoltaic system designs over time.
- Disseminate research findings and best practices:

These design principles are also summarised in Figure 17.

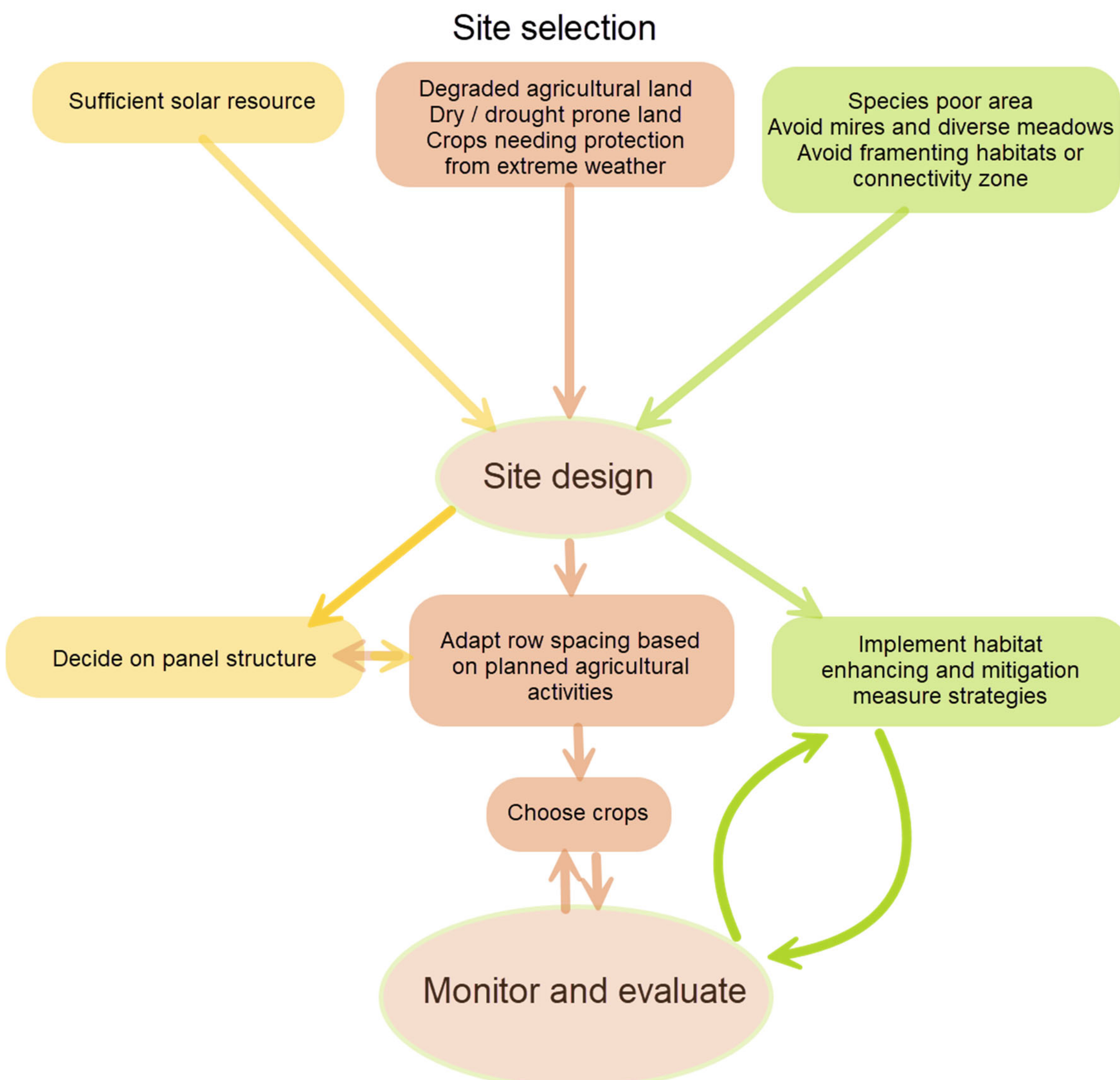

Figure 17:High-level flow chart for taking into various considerations.

5.1 Design ideas

Several selected design ideas were developed to illustrate different principles from the design consideration analysis. The original photos, which have been used for editing, are displayed and cited below to facilitate easy comparison with the modified versions.

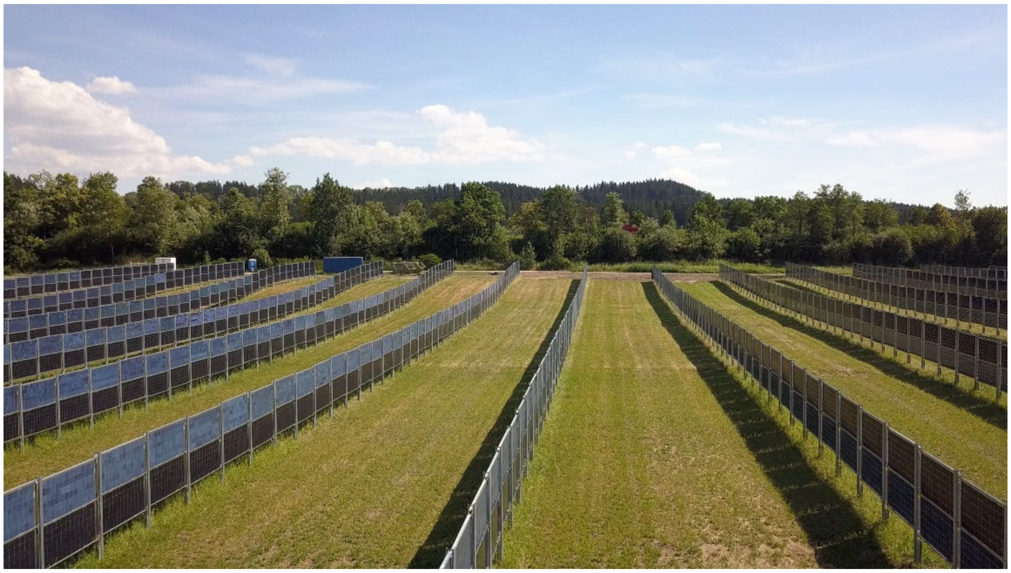

Figure 18. Keller T. (2020). Original photo used for editing. A*asen agrivoltaics solar plant with walls of vertical bifacial modules near Donaueschingen Germany*. Creative Commons Licence https://creativecommons.org/licenses/by-sa/4.0/deed.en Available at: https://en.m.wikipedia.org/wiki/File:Aasen_agrivoltaics_solar_plant_with_walls_of_vertical_bifacial_modules_near_Donaueschingen_Germany_3.jpg (accessed 05.05.2024)

Figure 19. KU Leuven. Original photo used for editing. Bierbeek agrivoltaics pear orchard. Available at: https://iiw.kuleuven.be/apps/agrivoltaics/pictures/Bierbeek_omslag.jpeg (accessed: 10.05.2024).

Below in Figure 20, you can see the various considerations in vertical bifacial agrivoltaic system. The green boxes indicate wildlife consideration, the brown are agriculture, and yellow is power production.

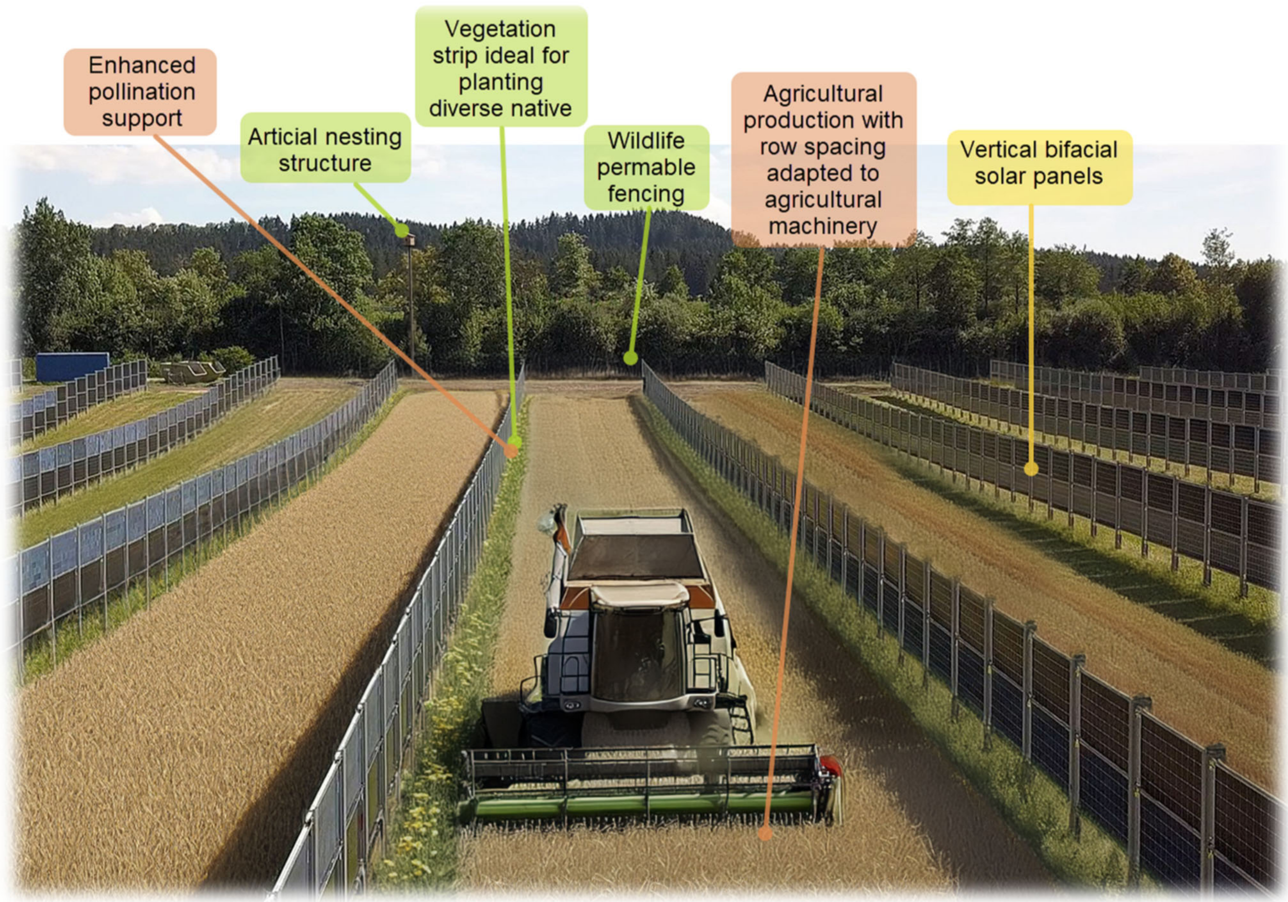

Figure 20: Design proposal for grain or vegetable production with vertical bifacial solar panels.

- Arrange vertical bifacial panels in rows with sufficient spacing to accommodate agricultural machinery.
- Include native vegetation strips along the panel rows to provide habitat for pollinators and other beneficial insects.
- Incorporate bird boxes and perches on the panel structures to support local bird populations.

Similarly, in Figure 22 and 23, various design considerations have been illustrated, for grazing and grass production, using fixed tilt or tracking solar panels, or vertical bifacial panels.

- Use vertical bifacial panels with a lower panel height to allow for the passage of livestock.
- Create a diverse mix of shade-tolerant grass species and wildflowers in the alleys between panel rows.
- Install wildlife-permeable fencing to control livestock movement while allowing for the passage of smaller animals.

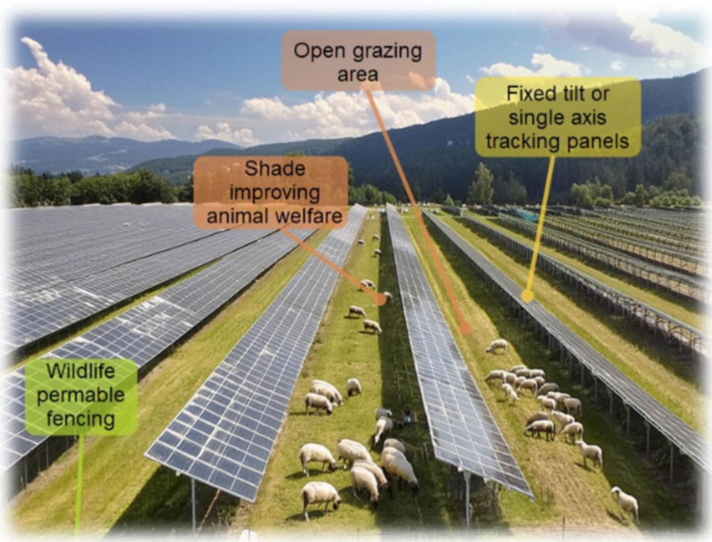

Figure 22: Design proposal for grazing with fixed tilt or tracked solar panels.

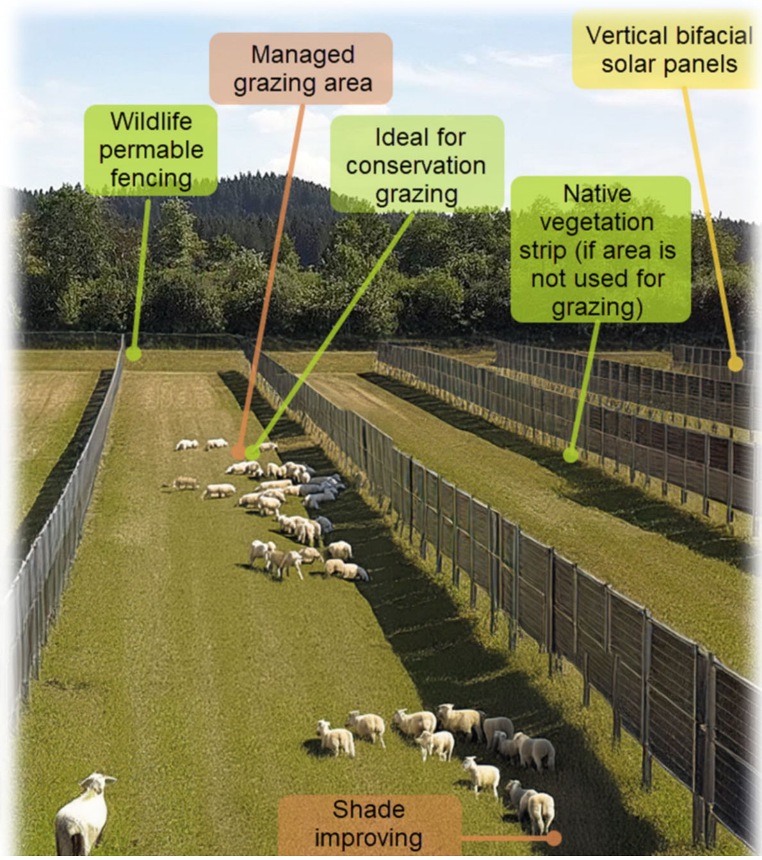

Figure 21. Design proposal for grazing or grass production with vertical bifacial solar panels.

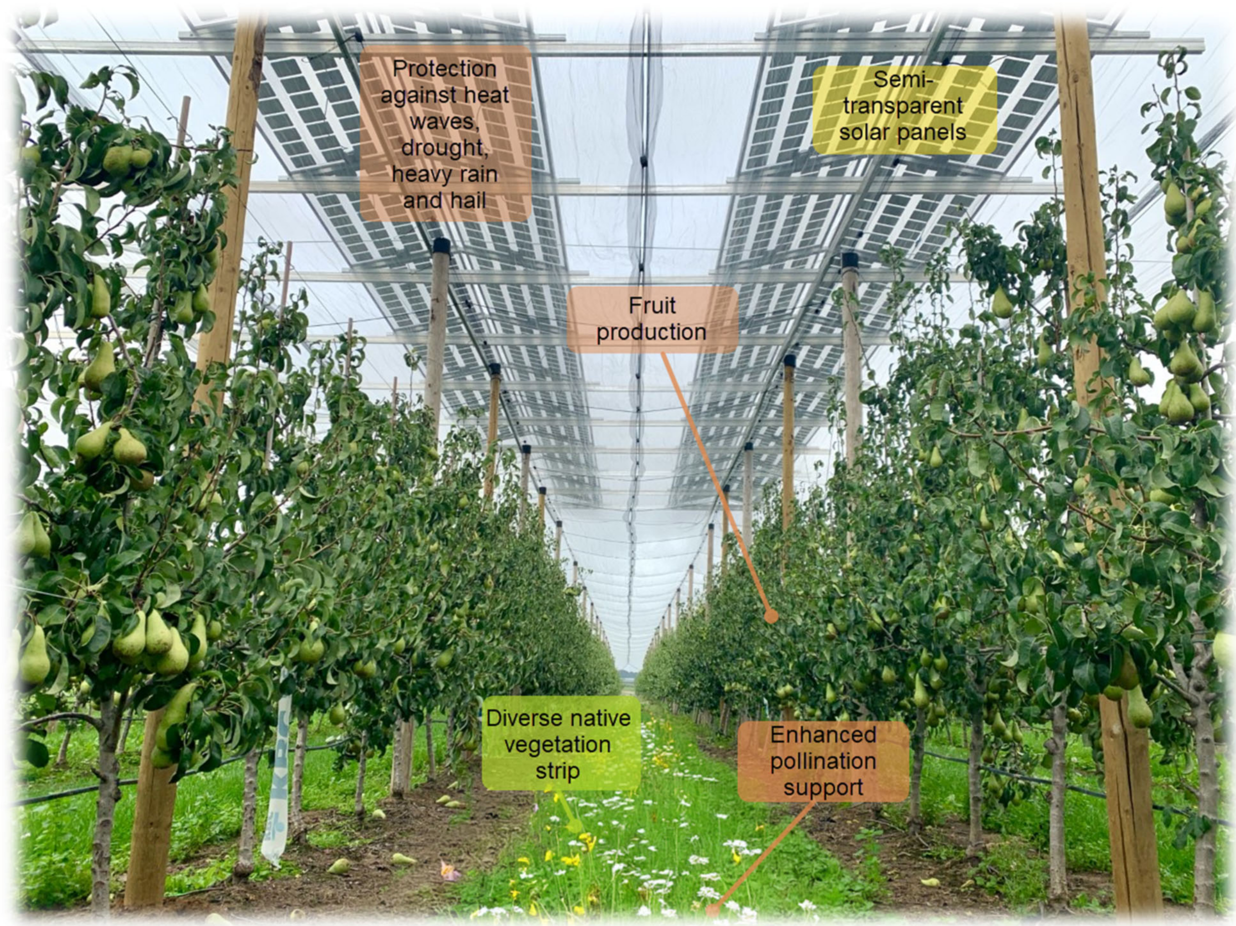

Figure 23: Design proposal for fruit orchard.

Lastly, a design proposal for a fruit orchard is presented in Figure 23, using the principles found in the analysis of the various considerations.

- Arrange solar panels in a grid pattern above the fruit trees, with a panel height and spacing that optimizes shading and allows for the passage of orchard machinery.
- Select fruit tree varieties that are well-suited to the local climate and can benefit from the microclimate created by the solar panels (e.g., protection from hail or frost).
- Incorporate flowering understory plants to support pollinators and improve overall biodiversity within the orchard.

6 Discussions

The field of agrivoltaics, particularly in the context of Norway and temperate regions, is still in its early stages, with a limited body of research available. This lack of comprehensive studies and empirical data presents challenges in understanding the full potential and limitations of agrivoltaic systems in these specific geographical and climatic contexts (Weselek et al., 2019). It does, however, give an indication as to what can work in terms of agricultural production, panel structures, and impact on wildlife, and can serve as a guide to where further research should be prioritised.

As climate change continues to alter weather patterns and environmental conditions, the uncertainties surrounding the future climate add another layer of complexity to the planning and implementation of agrivoltaic projects (Hernandez et al., 2014). Climate change-induced shifts in temperature, precipitation, and extreme weather events can have significant consequences for agricultural production (Zhao et al., 2017). These changes may necessitate adaptations in crop selection, farming practices, and infrastructure, including agrivoltaic systems. The design and management of agrivoltaic projects must take into account the potential impacts of climate change on both the agricultural and energy production components to ensure long-term sustainability and resilience (Dupraz et al., 2011). The climate in the future might become dryer and more drought-prone, where agrivoltaics could provide a safety net for farmers. As presented earlier, agrivoltaics can outperform regular agriculture in situations where water is scarce, and could also serve as a source of additional income for farmers.

While the integration of solar energy production with agriculture may require the utilization of some agricultural land, the additional income generated from agrivoltaic systems can provide a financial incentive for farmers to adopt these technologies (Dinesh & Pearce, 2016). This extra revenue stream can support the sustainability and resilience of farming operations, particularly in the face of climate change-related challenges. Furthermore, the income from agrivoltaic projects can be invested in conservation efforts and the protection of valuable ecological areas (Hernandez et al., 2019).

To address these knowledge gaps and uncertainties, further research is crucial. While the design principles and ideas presented in this thesis provide a useful starting point, field trials and pilot projects that put these ideas to practice in Norway and other temperate regions can provide valuable insights into the performance, challenges, and opportunities of agrivoltaic systems under specific local conditions (Schindele et al., 2020).

If conducted, these studies must investigate various aspects, such as crop suitability, solar panel configurations, microclimate effects, and economic viability. Additionally, long-term monitoring and evaluation of established agrivoltaic systems are necessary to assess their sustainability, identify areas for improvement, and develop best practices tailored to the regional context (Trommsdorff et al., 2021). The impact on wildlife also should be closely monitored and evaluated, to ensure the mitigation measures work as intended, and ensure future projects can learn from the mistakes and success of earlier projects.

The strategic placement of agrivoltaic systems near protected areas or within buffer zones can create opportunities to support and expand wildlife conservation initiatives. These systems can serve as transitional habitats or ecological corridors, facilitating the movement of wildlife between core habitat patches (Drechsler et al., 2011). By engaging farmers and local communities in the management of agrivoltaic systems, a sense of stewardship and appreciation for wildlife conservation can be fostered (Pascaris et al., 2021). This collaborative approach can help align agricultural practices with conservation goals, promoting a more holistic and sustainable land-use strategy.

While there are significant knowledge gaps and uncertainties surrounding agrivoltaics in Norway and temperate regions, the potential benefits of these systems warrant further research and exploration. By investing in field trials, long-term monitoring, and interdisciplinary collaborations, we can develop a deeper understanding of how agrivoltaic systems can be optimized to support sustainable agriculture, renewable energy production, and wildlife conservation in the face of a changing climate.

7 Conclusion

This thesis explores the design considerations for agrivoltaic systems, focusing on their impact on wildlife, agricultural production, and electricity generation. The findings highlight the importance of an integrated approach to agrivoltaic system design that balances the needs of wildlife conservation, sustainable agriculture, and renewable energy production.

The discussion on the impact of agrivoltaics on wildlife emphasizes the significance of both macro-level landscape considerations and micro-level site-specific factors. Strategies such as avoiding natural habitats, maintaining wildlife corridors, and prioritizing development on degraded agricultural land can minimize negative impacts on wildlife. At the site level, the integration of native vegetation, wildlife-permeable fencing, protection of water resources, and erosion control measures can create wildlife-friendly environments within the agrivoltaic system.

The analysis of various solar panel configurations and their suitability for different agricultural practices reveals the potential of agrivoltaics to enhance crop production, particularly in dry conditions. Raised panels on stilts and vertical bifacial panels emerge as promising options for various crops, including vegetables, grains, fruits, and berries. The additional shading provided by agrivoltaic systems can also improve animal welfare in pasture grazing areas. Various design proposals have been illustrated, giving inspiration to further studies.

The lack of comprehensive studies and empirical data specific to Norway and temperate regions presents challenges in fully understanding the potential and limitations of agrivoltaic systems in these contexts, however. The uncertainties surrounding the future climate further complicate the planning and implementation of agrivoltaic projects. To address these knowledge gaps, further research, field trials, and long-term monitoring are crucial to assess the performance, challenges, and opportunities of agrivoltaic systems under local conditions.

The potential benefits of agrivoltaics extend beyond sustainable agriculture and renewable energy production. Strategically placing agrivoltaic systems near protected areas or within buffer zones can support wildlife conservation initiatives by creating transitional habitats and ecological corridors. Engaging farmers and local communities in the management of these systems can foster a sense of stewardship and appreciation for wildlife conservation.

In conclusion, agrivoltaic systems offer a promising approach to reconciling the competing demands of energy production, food security, and wildlife conservation. By carefully considering the design elements that impact wildlife, agricultural production, and electricity generation, we can work towards developing agrivoltaic systems that are optimized for the specific needs and conditions of Norway and temperate regions. Further research and exploration in this field are essential to unlock the full potential of agrivoltaics and contribute to a more sustainable and resilient future.

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