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ORIGINAL ARTICLE

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Integration of solar PV in a Norwegian energy system, navigating the trade-offs between land use and solar power production

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Abstract. To achieve our climate goals, the energy sector is increasingly shifting towards zero-emission sources, mainly renewable energy sources (RES), with solar power playing a pivotal role on the global stage. Nevertheless, many forecasts for future energy systems concentrate mainly on techno-economic aspects, which may not sufficiently capture the complexities associated with the deployment of renewable energy technologies. In particular, the expansion of RES has in recent years sparked tensions related to land use for new energy infrastructure, as well as growing concerns for biodiversity and environmental degradation. This study investigates the land use implications of different renewable energy system configurations in Norway, highlighting key trade-offs between land use requirements, costs, and emissions. The research specifically investigates potential pathways for solar photovoltaic (PV) in the Norwegian energy system, aiming to assess its potential future role within the broader Nordic context. Our findings shows that achieving national climate targets could require land use ranging from 18.43 to 5149 km^2, depending on the selected scenario and land use metric. While onshore wind is initially favored due to high availability and a low physical footprint, including considerations such as spacing requirements and access roads significantly increase total land impact. Conversely, solar PV systems demand greater installed capacity, raising the physical footprint. Offshore wind and rooftop PV systems offer minimal direct land use but involve higher costs and technical constraints. The analysis underscores the importance of consistent land use metrics, integrated spatial planning, and the inclusion of socio-economic factors in energy system modeling. As the expansion of RES increases land demand, careful planning is essential to balance ecological preservation, public acceptance, and climate goals.

Keywords: Land use requirements / RES / solar PV / socio-economic

1 Introduction

One of the core strategies for achieving a climate-neutral economy is the promotion of renewable energy deployment [1]. The electricity and heat sectors currently contribute about 30% of total greenhouse gas (GHG) emissions. Combined with future expected electrification this share will increase [2], in which the integration of renewable energy sources (RES) has the potential to significantly reduce emissions [3]. Among these, solar power has experienced rapid growth in recent years, with projections indicating continued strong expansion in the near future [4].

Several studies have explored long-term planning for power systems [5–8]. However, most energy system optimization models primarily focus on techno-economic factors, which may be insufficient to fully understand the role of RES in future energy systems [5]. As the integration of RES increases, so does the demand for land. While some RES, such as solar and wind, are considered inexhaustible, land availability is finite. Therefore, an optimal solution generated by an energy system model may not be feasible in practice [5]. As greater power capacity will be required to ensure reliable electricity supply in the future, land-use constraints could conflict with proposed energy system modeling solutions [9–11].

The recent rapid RES development has increasingly led to conflicts, particularly due to concerns over land use requirements for new power generation infrastructure, as well as potential impacts on natural ecosystems [12]. Additionally, increased RES deployment may involve developing undisturbed natural areas, potentially affecting biodiversity [13]. Therefore, to balance ecological, recreational, and social interests, land use must be carefully considered in RES development.

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This paper investigates the potential role of solar photovoltaic (PV) in a Norwegian future energy system, focusing on the trade-offs between land use and increased RES integration. Norway is currently in the early stages of deploying utility-scale PV systems [14]. With a projected power deficit anticipated by 2027 and rising electricity demand driven by widespread electrification, the country needs to expand its power generation capacity [15]. Solar energy has the potential to play a pivotal role in addressing this growing demand. Consequently, it is important to evaluate the land use implications associated with scaling up PV infrastructure to ensure sustainable and efficient integration into the national energy system.

The primary contributions of this paper are as follows: An in-depth evaluation of the future Norwegian power system and potential decarbonization pathways, with a particular emphasis on land use considerations and the integration of solar PV technologies. The study further investigates the trade-offs between land use and RES deployment by analyzing various scenarios characterized by differing RES integration requirements. While the analysis is centered on Norway, the findings hold broader relevance beyond the national context. Lastly, the paper explores the trade-offs between land use and RES integration under varying CO_2 emission cap constraints.

The remaining of the paper is structured as follows: Section 2 reviews the current state of art research on land use requirements and socio-economic considerations in energy system modeling. Section 3 details the methodology, including key inputs and assumptions, and Section 4 presents our results. Lastly, Section 5 offers a discussion of the findings, whereas Section 6 concludes the paper with final remarks.

2 Literature review

A key challenge in addressing land use requirements is how to effectively quantify the value of land. Most existing studies primarily focus on techno-economic factors when assessing the landscape impact of RES [16,17]. However, some have attempted to incorporate socio-economic considerations into the evaluation of land use and RES placement [12,18,19]. Most of the research related to land-use conflicts and social acceptance of RES, has concentrated on challenges related to onshore wind power [11,20–23]. Given the anticipated substantial growth in solar power capacity [4], it is important to also examine the trade-offs between increased PV capacity and land use requirements to minimize future land-use conflicts [24].

2.1 Land use requirements in energy system modeling

Traditionally, landscape measurement lacks standard units and remains, to some extent, inherently subjective. As noted in [12], the subjectivity of landscape impact is closely tied to individual perception, which varies based on personal biases and experiences. In literature there is currently a large range of estimates and boundary levels for calculation of land use requirements, with land-use information collected either from official documentation, calculated using geometrical rules, or manual drawings [25]. As land use requirement plays a pivotal role in planning of a decarbonized energy system assessing land-sparing potential and investigated land limits necessitates more standardization [25].

Several studies estimate land use requirements based on individual installations or modeled electricity generation data [26]. However, as noted by Lovering et al. [26], such approaches may lead to over- or underestimation, since single installations do not necessarily reflect broader system-level realities. In contrast, their study compiles and calculates land-use intensities using real-world electricity generation data across all major energy sources. The findings reveal a wide range of land use requirements, highlighting that land availability could pose a significant constraint on deep decarbonization of the energy system.

Ref. [27] explores the impact of solar variability on land use, demonstrating that the need for overcapacity and energy storage can lead to significantly higher land occupation than typically reported in literature.

2.2 Methodologies for estimating land use requirements

While precise calculations of land use requirements are challenging, the literature has attempted to quantify these impacts using a combination of quantitative and qualitative metrics.

Quantitative metrics assess the physical extent of the impacted area. This may include only the direct impacted area, spacing requirements, buffer zones, or potentially the area impacted by noise and visibility [12]. In contrast, qualitative metrics measure public perceptions of these landscape changes, providing insight into the social and aesthetic dimensions of impact [12]. This distinction underscores the necessity of an integrated approach that merges quantitative assessments of land use and visibility with qualitative evaluations of public perception [12]. A common quantitative approach to assessing these requirements typically categorizes land use requirements into two main types, namely direct and total land use requirements [12].

Direct land use requirements denotes the physical area occupied by infrastructure, including additional access roads, panel or turbine spacing, and other installations necessary to mitigate operational impacts. On the other hand, total land use requirements, encompasses a broader array of considerations, such as visibility, noise impacts, in addition to the overall environmental footprint of the infrastructure. These additional factors contribute to significant variability in land use estimates within the literature, as perceptions of such impacts can vary across studies and regions [12].

For solar PV systems, direct and total land use requirements are generally comparable, with local insolation levels playing a significant role in determining overall land demand [28]. According to ref. [29], direct land use accounts for over 90% of the total, with the remainder attributed to panel spacing and buffer zones. Ref. [29] estimates land use at approximately 32 000 m^2/MW. In

contrast, ref. [30] reports a requirement of 23 255 m^2/MW, noting that this figure could decline with improvements in PV efficiency.

However, system design also affects land use. For instance, ref. [31] finds that fixed-tilt PV systems require 11 574 m^2/MW, while tracking systems demand 16 875 m^2/MW, underscoring the influence of system design on land use. In contrast, ref. [32] reports a broader range of total land use, between 22 472 and 65 359 m^2/MW, depending on geographic location.

Further variation is reported by ref. [33], which estimates direct land use between 4400 and 14 300 m^2/MW, and total land use ranging from 6250 to 111 111 m^2/MW. This wide range is attributed to the combined effects of latitude and system design parameters, such as tilt angle and shading criteria [33].

Comprehensive reviews from refs. [25] and [12] consolidate previous findings, indicating that direct land use spans from 722 to 23 255 m^2/MW, while total land use ranges from 1398 to 31 970 m^2/MW. These studies attribute the wide variability to the absence of standardized methodologies. Finally, ref. [34] reports total land use for solar PV systems between 29 137 and 31 970 m^2/MW.

In contrast to solar PV, wind energy exhibits a significant disparity between direct and total land use. The physical footprint of wind turbine foundations typically accounts for 10% of the total land area, with the remainder allocated to turbine spacing, access roads, and buffer zones for visibility and noise mitigation [35]. According to ref. [36], reported average direct land use requirement for onshore wind spans 3000 ± 3000 m^2/MW, while total land use can reach up to $340\,000 \pm 220\,000$ m^2/MW, reflecting substantial variability across studies. Similarly, [37] reports total land use requirements of 111 111 m^2/MW. This variation is further supported by [25], which documents direct land use values ranging from 193 to 2801 m^2/MW and total land use from 2336 to 111 111 m^2/MW, underscoring the wide range of estimates found in the literature.

In literature, land use requirements are most commonly reported using power-area or capacity-area ratios (measured in m^2/MW) [25]. However, as noted by ref. [38], this approach becomes problematic when accounting for the variability inherent in RES, particularly wind and solar. To partially address this issue, some studies incorporate capacity factors alongside installed capacity, thereby expressing land use in terms of energy-area ratios (e.g., m^2/GWh or km^2/TWh).

In Norway, total land use for onshore wind is based on the planning area of wind farms, with reported land use intensities around 35 km^2/TWh [39]. In contrast, other studies report significantly different values. Ref. [40] estimates total land use at 126 920 m^2/GWh, ref. [38] estimates 18 182 m^2/GWh, while [41] reports a much lower figure of just 1000 m^2/GWh.

For utility-scale PV systems, ref. [42] reports land use requirements of 13 759 m^2/GWh for total land use and 12 545 m^2/GWh for direct land use. A slightly lower estimate is provided by ref. [41], at 10 000 m^2/GWh for total land use. In comparison, [38] estimates total land use at 12 500 m^2/GWh.

Table 1. Direct and total land use requirements for different RES.

RES	Direct (m^2/MW)	Total (m^2/MW)
Onshore wind	3570	212 778
Utility-scale PV	11 045	30 682

As demonstrated above, the literature reveals a wide range of estimates, largely due to the absence of standardized methodologies for calculating land use requirements for RES. According to ref. [25], this variability is primarily driven by differences in how spacing areas are defined and calculated. Additional factors contributing to the spread include varying technical assumptions, differences in solar and wind resource availability, and the specific siting of wind turbines or PV panels. To address these inconsistencies, ref. [25] recommends using statistical aggregates derived from multiple studies to provide a more comprehensive understanding of land use requirements in a broader context.

In this study, we determine the land use requirement by calculating the mean value based on the land use requirements reported above. We restrict our focus to land use requirements for onshore wind and solar PV, due to the expected importance of these energy sources in future energy systems [43]. Land use requirements due to capacities in bio-energy would result in massive land use requirements, due to the massive area needed for bio-energy installations [44]. However, our model do not invest in any new bio-energy related capacity, due to its high investment costs. We therefore do not take these aspects into our considerations.

Further, as offshore wind is not located directly on land area, we set its corresponding land use requirements to zero. However, installing offshore wind turbines would in fact have impact on surrounding areas and ecosystems [44]. Similarly, we assume zero land use requirements for roof-mounted PV, as this technology utilizes existing buildings and already developed areas. The different land use requirements can be seen in Table 1.

In 2024, Norway's annual electricity consumption was approximately 136 TWh [45]. Assuming average annual capacity factors (CF) of 26% for onshore wind and 9.8% for solar PV [46], the estimated direct land use requirements, based on our estimates in Table 1, would account for 0.07% and 0.6% of Norway's total land area, respectively. This is equivalent to approximately 213 km^2 for onshore wind and 1743 km^2 for solar PV. When considering total land use requirements, which include spacing and auxiliary infrastructure, these figures increase to 4.21% (12 705 km^2) for onshore wind and 1.6% (4840 km^2) for solar PV. Land use requirements are calculated by multiplying the annual electricity consumption (in MWh) by the land use intensity values provided in Table 1. This product is then divided by the average annual full-load hours of the power plant, which are determined by multiplying the total number of hours in a year (8760 h) by the average annual CF.

Considering first solar PV, these estimates align reasonably well with previous findings. For instance, Midtgård et al. [47] estimated that meeting an annual electricity demand of 120 TWh would require approximately 0.7% of Norway's land area for solar PV, thereby supporting the plausibility of our solar land use estimate.

Our estimated land use requirements also fall within the range of average land use for Norwegian PV plants granted concession, equal to 18 190 m^2/MW [48]. However, the total land requirement for onshore wind appears comparatively high, likely due to extensive spacing assumptions adopted in some of the referenced literature. By contrast, applying the Norwegian planning area methodology for estimating total land use, as outlined in [39], yields a significantly lower figure, approximately 1.6% of the national land area, or 4795 km^2.

2.3 Solar energy and socio-economic aspects in energy system modeling

Solar power is projected to play a key role in future energy systems, with estimates suggesting it could contribute between 20% and 80.5% of the final energy mix, depending on the study consulted [43,49–52]. The study reported in [53] explores the role of PV technologies in the global energy transition under various scenarios, highlighting a rapid increase in PV installations and a significant rise in the share of solar energy in the overall energy mix. Similarly, [54] forecasts a six-fold acceleration in the growth of renewables by 2050 compared to business-as-usual trends, with solar PV and wind energy predicted to see the greatest expansion. A common limitation in these studies is the reliance on techno-economic assumptions only, which may lead to scenarios that are not practically feasible when implemented.

In regional and global assessments of decarbonization pathways, land-use change, biodiversity threats, and the land footprint of energy sources is often overlooked, with exception for land-intensive options like bio-energy in some cases [26]. However, some researchers have attempted to integrate socio-economic dimensions to gain a better understanding of the impacts associated with a higher share of RES. For instance, ref. [24] estimates the potential land use requirements and the resulting land-use changes for solar energy across various countries. This study employs an integrated assessment model (IAM) that links socio-economics, energy, land use, and climate systems, enabling a comprehensive estimation of land cover impacts and land-use change emissions for different decarbonization scenarios.

In contrast, ref. [5] adopts a different methodology using Modeling to Generate Alternatives (MGA) to identify near-optimal solutions that reduce pressure on land-use requirements.

The importance of spatial planning is underscored in ref. [55], which argues that achieving a 100% renewable energy system will require significant expansion in solar and wind capacity. This study emphasizes the need for careful spatial planning to protect biodiversity and safeguard agricultural lands. By comparing the spatial needs for a fully renewable energy system with available land, the study concludes that 2.2% of the EU's total land area would be required to decarbonize its energy system, excluding agricultural and protected areas. Despite the relatively small land footprint, the study stresses that effective spatial planning is essential to minimize public opposition, and ensure the feasibility of the energy transition.

The development of RES has accelerated significantly in recent years. However, this rapid expansion has been met with increasing public resistance to the transition away from traditional energy sources [56]. According to ref. [56], public opposition is often linked to concerns about landscape changes and disruptions to established ways of life. The study suggests that shifting from a purely technical focus to more inclusive planning processes, could help mitigate social resistance. It emphasizes that if social barriers are not adequately addressed, they have the potential to delay, discourage, or even halt RES projects [56].

Research by ref. [57] revealed public opposition in over 35% of all proposed wind farms in the western United States. Similarly, ref. [58] documents increasing land-use conflicts and heightened public opposition to landscape impacts in Spain, due to the rapid development of onshore wind energy.

Currently the debate regarding landscape impacts of PV installations has been less prominent, and most research concerning RES and landscape impacts has centered on wind power [59]. Nevertheless, some studies do focus on solar energy [60–63], which is crucial for understanding public attitudes towards the deployment of large-scale PV projects [64,65]. These studies contribute to a more nuanced understanding of how the expansion of solar energy is perceived and highlight the need for more research in this area to address potential social and environmental concerns.

A potential solution explored to mitigate land use conflicts is the co-utilization of land, such as through agrivoltaics or the co-location of onshore wind and ground-mounted PV systems. According to the European Climate Law, such co-use of land can help alleviate land competition while also supporting agricultural productivity and food security [66].

Ref. [67] conducted simulations to assess how combining PV systems with shade-tolerant crops affected overall productivity. The study reported a 30% increase in farm value for those implementing agrivoltaic systems compared to conventional farms, although outcomes varied depending on the crop type [67]. Similar findings were reported in [68]. Ref. [69] highlighted additional benefits of combining PV and agriculture, including reduced water requirements, lower soil erosion, and decreased pesticide use, attributed to the protective structure of the PV installations. Ref. [70] examined the integration of livestock with PV systems, concluding that shading from solar panels could reduce heat stress in animals, thereby lowering water consumption and promoting greater weight gain.

Other studies have investigated land co-use through the hybridization of wind farms and PV systems. Ref. [71] evaluated the hybridization of an existing grid-connected

wind farm by co-locating PV installations, demonstrating that this approach significantly enhanced the utilization of existing grid infrastructure. Similarly, ref. [72] analyzed the integration of solar, wind, and battery energy storage systems (BESS), showing that coupling of the considered energy sources enabled more efficient use of interconnection capacity and reduced overall system costs.

2.4 Energy system modeling and the role of PV in a Norwegian context

Socio-economic dimensions are also considered in several of the energy transition pathways proposed for Norway. Ref. [73] explores a national energy pathway towards 2050, emphasizing the need for significant capacity expansion to meet the country's growing electricity demand. Wind power was projected to play a central role, accounting for 42% of total installed capacity. Although onshore wind is more cost-effective and technologically mature, its development is currently constrained by public opposition, effectively halting new projects [73]. Consequently, ref. [73] estimates that 54% of the total wind capacity will originate from offshore installations. The report also projects a substantial increase in PV capacity, expected to constitute 20% of total installed capacity by 2050.

Public opposition is further examined in ref. [74], which investigates public preferences for various power generation technologies in Norway and incorporates the preferences into an energy system model for 2040. Initially, the model prioritizes investments in onshore wind. However, when public preferences are considered, investment shifts towards nuclear, hydropower, offshore wind, and both ground-mounted and rooftop PV [74]. This shift necessitates a larger installed capacity due to the lower availability of solar energy compared to wind, ultimately increasing system costs and price variability [74].

Ref. [75] presents an interdisciplinary approach to Norway's energy transition, linking socio-technical transition theory with energy system modeling. The study explores four scenarios with varying degrees of disruption to existing socio-technical regimes. The study concludes that scenarios marked by limited socio-institutional change result in increased electricity trade and substantial investment in power generation, fully exploiting the Norwegian potential of onshore wind and driving further development of offshore wind capacity [75]. In contrast, scenarios with significant socio-institutional transformation result in only modest increases in power generation capacity, with new production primarily derived from building-integrated PV, accounting for 11% of the supply mix by 2050 [75].

Although wind power emerges as the most cost-efficient solution in several decarbonization pathways, recent studies have increasingly examined the potential role of solar PV in Norway's future energy system. Ref. [76] assesses the technical potential of solar PV using existing buildings and grey areas such as parking lots and gravel pits, estimating a total technical potential of 231 GWp, equivalent to 199 TWh/year. For comparison, Norway's hydropower production averages 137.6 TWh annually [45].

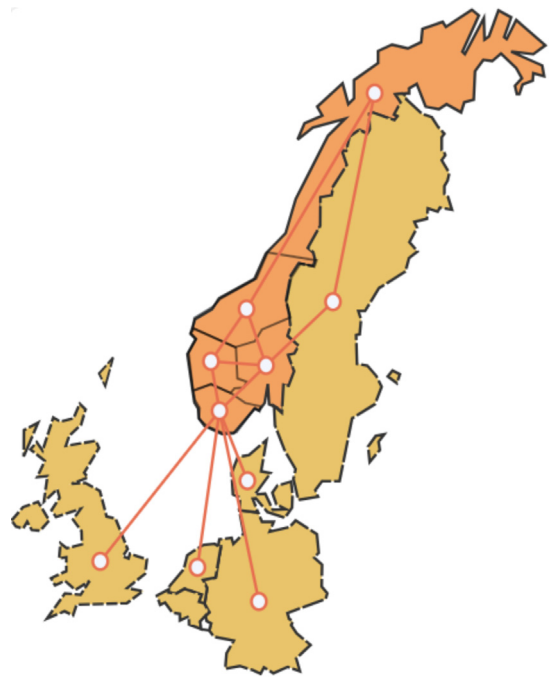


Fig. 1. Simplified North European power system.

The technical potential of solar PV is also discussed in ref. [77], which estimates 65.6 TWh/year from existing building surfaces. However, the study highlights that the seasonal variability of solar production in Norway, particularly the reduced output during winter months, necessitates robust energy management strategies [77].

Ref. [78] investigates the cost-competitiveness of roof-mounted PV under various energy transition scenarios, utilizing the socio-technical frameworks developed in ref. [75]. The findings suggest that in scenarios with restricted wind power investments and high socio-institutional change, PV could contribute up to 10% of total electricity generation [78]. Conversely, in scenarios with low socio-technical development and unrestricted onshore wind investments, rooftop PV plays a minor role in the energy mix [78]. Nevertheless, the study highlights that reducing investment costs and barriers to flexibility and energy storage could further enhance PV deployment [78].

3 Material and methods

3.1 Model design

To explore the trade-offs between land use and RES integration, a case study of the North European energy system is conducted. The system consists of six interconnected areas, as depicted in Figure 1. Areas 1 through 5 represent the Norwegian power system, divided into distinct price zones (NO1–NO5). Area 6 models a simplified North European power system, integrating data from Denmark, the United Kingdom, Germany, Belgium, the Netherlands, and Sweden. This zone is included to account for power imports and exports between Norway and the broader North European region, and is hereafter

referred to as the Continent. The energy system modeling is based on previous work from [79], and is modified to fit with our study.

The analysis uses the GenX modeling framework, an open-source model that optimizes investments in electricity generation, storage, transmission, and demand-side resources to meet a future electricity demand [80]. To determine investment portfolios and operational strategies, the model uses constrained linear or mixed-integer linear optimization techniques.

GenX is implemented using the Julia programming language and the JuMP optimization framework. It employs a least-cost planning methodology to determine the optimal set of investments required for future energy systems. This approach incorporates a range of considerations, including operational constraints, limitations on resource availability, and broader factors such as market structures, environmental regulations, and policy mandates [80]. The model operates deterministically and typically addresses capacity expansion planning for a specified future year, guided by the following optimization formulation.

$$\begin{aligned}
&\min \sum_{z\in Z}\sum_{g\in G}\left(C_{g,z}^{\mathrm{Inv}}\cdot A_{g,z}\cdot\delta_{g,z}^{\mathrm{Inv}} + C_{g,z}^{\mathrm{FixOM}}\cdot\Delta_{g,z}\right)\\
&+\sum_{z\in Z}\sum_{t\in T}\sum_{g\in G}\left(G_{g,z}^{\mathrm{VarOM}} + G_{g,z}^{\mathrm{Fuel}}\right)\cdot\varphi_{g,t,z}\\
&+\sum_{z\in Z}\sum_{t\in T}\left(C_{s}^{\mathrm{VarOM}}\cdot\varphi_{g,t,z} + C_{s}^{\mathrm{VarOM}}\cdot\varphi_{s,t,z}\right)\\
&+\sum_{z\in Z}\sum_{t\in T}\left(C^{\mathrm{curt}}\cdot\gamma_{t,z}^{e} + C^{R}\cdot\gamma_{t,z}^{r}\right)\\
&+\sum_{z\in Z}\sum_{t\in T}\sum_{g\in G}\left(\Pi_{g,z}^{\mathrm{START}} + \varepsilon_{g,t,}\right)\\
&+\sum_{l\in L}\pi_{l}^{\mathrm{TCAP}}\cdot\Delta\varphi_{l}^{\max}
\end{aligned} \tag{1}$$

The objective function in the GenX model is composed of several cost components that reflect the economic trade-offs in power system planning. The first component accounts for fixed annual costs, including both capital investment and fixed operation and maintenance (O&M) expenses. Specifically, the term $C_{g,z}^{\mathrm{Inv}}\cdot A_{g,z}\cdot\delta_{g,z}^{\mathrm{Inv}}$ represents the annualized investment cost for generation technology g in zone z, where $C_{g,z}^{\mathrm{Inv}}$ is the capital cost per MW, $A_{g,z}$ is the annuity factor, and $\delta_{g,z}^{\mathrm{Inv}}$ is the newly installed capacity. In parallel, the fixed O&M cost is captured by $C_{g,z}^{\mathrm{FixOM}}\cdot\Delta_{g,z}$, where $\Delta_{g,z}$ denotes the total installed capacity.

The second and third components of the objective function represent variable costs associated with generation and fuel consumption. These include $G_{g,z}^{\mathrm{VarOM}}$ and $G_{g,z}^{\mathrm{Fuel}}$, which are the variable O&M and fuel costs, respectively, and are multiplied by $\varphi_{g,t,z}$, the energy output from generator g at time t. For storage technologies, the variable cost is given by C_{s}^{VarOM}, applied to the charged or discharged energy $\varphi_{s,t,z}$.

The fourth cost component addresses penalties for demand curtailment and reserve shortfalls. Here, C^{curt} and C^{R} represent the penalty costs for curtailed energy and unmet reserve requirements, while $\gamma_{t,z}^{e}$ and $\gamma_{t,z}^{r}$ quantify the respective shortfalls in MWh.

The fifth term captures startup costs for technologies that require unit commitment modeling, calculated as the product of the startup cost $\Pi_{g,z}^{\mathrm{START}}$ and the number of startup events $\varepsilon_{g,t}$ for each generator cluster at each time step.

Finally, the model includes costs associated with transmission infrastructure expansion, represented by $\pi_{l}^{\mathrm{TCAP}}\cdot\Delta\varphi_{l}^{\max}$, where π_{l}^{TCAP} is the cost of constructing or reinforcing transmission line l, and $\Delta\varphi_{l}^{\max}$ is the additional capacity added.

In addition to these cost terms, GenX enforces a set of constraints to ensure realistic system behavior. These include technology-specific constraints such as capacity limits, operational bounds, and resource availability, as well as systemwide constraints like reserve requirements, hourly energy balance, and compliance with CO_2 emissions caps. The model also incorporates unit commitment constraints, startup and shutdown dynamics, and storage cycling behavior.

The study builds upon an existing modeling framework to determine the optimal operational strategy for the North European energy system. To solve the underlying optimization problem, a detailed representation of the power system is required. This includes assumptions regarding generation technologies, demand profiles, and energy storage options, all of which are defined by the authors. Further details on the model setup can be found in [81].

During initial testing, the hydropower module produced unrealistic reservoir depletion patterns. To address this issue and ensure more realistic hydropower behavior, equation (2) was incorporated into the model.

$$\Gamma_{y,z,t} \geq \alpha\Gamma_{y,z}^{MAX}\forall y\in Y, z\in Z, t\in T. \tag{2}$$

Equation (2) ensures that the reservoir level, $\Gamma_{y,z,t}$, does not fall below a predefined threshold, α, representing a fraction of the total reservoir volume, $\Gamma_{y,z}^{\mathrm{MAX}}$. In this study, α is set to 0.25, based on historical reservoir level data from [82].

The following section outlines the data inputs and modeling assumptions used in setting up the system.

3.2 Input data and assumptions

Simulations are based on cost projections and assumptions for the year 2040. A brownfield optimization approach is applied, leveraging existing generation capacities as reported in [83]. No capacity expansions are permitted for hydropower or run-of-river technologies. In alignment with the anticipated coal phase-out, new investments in coalfired generation are also excluded [84]. Hydrogen production is not considered in this study.

Hydropower operations are optimized over a one-year horizon, incorporating historical inflow data, power-to-energy ratios, reservoir constraints, and minimum storage levels. Inflow data for Norway are sourced from [82], while data for the Continent is taken from [85]. For the purposes of this analysis, run-of-river hydropower is assumed to have inflow values identical to those of reservoir-based hydropower, due to the lack of data on hourly inflow variations. Given that run-of-river generation accounts for only a

small part of the total energy production, this assumption is not anticipated to substantially affect the overall results. Investment costs for hydropower are drawn from [86] and detailed in Appendix Table A1.

To capture the variability of RES, hourly capacity factors are obtained from [46]. In this study, we use a single reference year to simulate the different cases. However, the choice of reference year may influence the results. One way to address this limitation is to optimize over multiple weather years, as explored in [86]. Their findings show that the selected weather year can significantly impact the optimal solution, particularly in scenarios with high RES penetration. They recommend conducting capacity expansion optimization using multiple years of weather and load data to enhance robustness. Alternatively, a robust approach could involve using a worst-case scenario, also discussed in [86]. In such cases, a year with lower RES availability may lead to higher installed capacity and increased land use requirements. Conversely, for battery investments, relying on worst-case scenarios may result in greater dependence on battery capacity, although the associated land use impacts may be less pronounced. Based on an analysis of weather data from 2007 to 2019, the year 2013 was identified as representative and is used as the reference year. Scheduled maintenance for nuclear power is modeled as a flexible source, using hourly availability data from [85]. Other generation technologies are assumed to operate with constant capacity factors.

Fuel prices and associated CO_2 emissions are sourced from [87] and [88], with full details provided in Appendix Table A2. Bio-energy is assumed to be carbon-neutral, following the assumptions in [89]. Technology-specific parameters for all generation types are taken from [90] and summarized in Table A3. Investment, fixed, and O&M costs are based on the EU Reference Scenario 2020 [90], with annuities calculated using a 5% discount rate (see Tab. A1).To enhance computational efficiency, power plants are aggregated into clusters with homogeneous characteristics.

Transmission capacities between zones are compiled from ENTSOG and ENTSO-E Ten-Year Network Development Plans (TYNDPs) and presented in Appendix Table A4. The study does not allow for any network expansion.

The Norwegian energy system represents a unique case globally, as Norway is already highly electrified [91]. This trend is expected to intensify as electrification expands into sectors traditionally reliant on fossil fuels, such as transportation and parts of industry [2,92]. Accordingly, we assume that the Norwegian energy system will be predominantly electricity-based by 2040. As a result, this analysis focuses exclusively on electricity demand when assessing the future structure of Norway's energy system. Hourly load profiles are derived from historical data [83] and scaled upward using projections from [93] and [87] to account for anticipated increases in electrification. These projections include a 20% increase in electricity demand by 2030 relative to current levels [93], followed by a further 25% increase by 2040 compared to 2030 levels [87].

Table 2. RES investment options for the different cases.

Case	Onshore wind	Offshore wind	Solar PV Utility	Solar PV Roof
1	X	X	X	X
2		X	X	X
3			X	X
4		X		X

No cases allow for investments in emitting thermal power capacity. Abbreviations: Solar PV Utility: Utility-scale ground-mounted PV, Solar PV Roof.: Roof-mounted PV.

For Norway, the projected annual electricity demand reaches approximately 199 TWh, while the total aggregated demand across Northern Europe amounts to 1708 TWh. Inter-annual demand variability is represented using an average hourly demand profile constructed from historical data spanning the years 2015 to 2021. The value of lost load is set at 10 000 \$/MWh.

The analysis includes two energy storage technologies: lithium-ion batteries with a 4 h duration and pumped hydro storage (PHS) for seasonal balancing. This allows for an assessment of how different storage options influence land use requirements. Battery cost assumptions are based on [94], while PHS costs are taken from [95], with full details in Table A1.

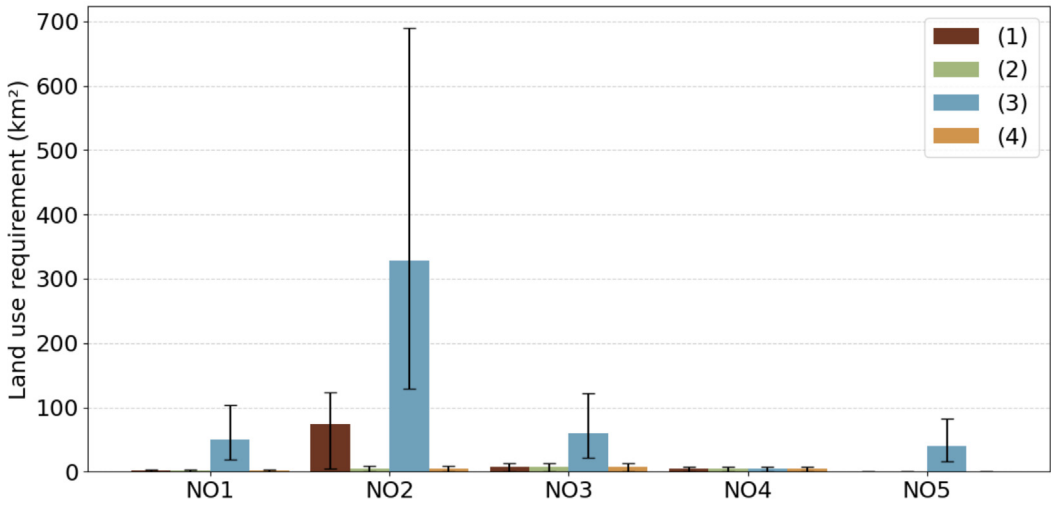
3.3 Description of cases

To quantify the role of solar power in Norway's future energy system and examine the trade-offs between land use and increased RES development, four different cases are investigated. The cases are categorized as the following. Case 1: No additional investments allowed in emitting thermal power generation, case 2: No additional investments allowed in emitting thermal and onshore wind power generation, case 3: No additional investments allowed in emitting thermal, onshore, and offshore wind power generation, and case 4: No additional investments allowed in emitting thermal, onshore, and ground-mounted PV power generation.

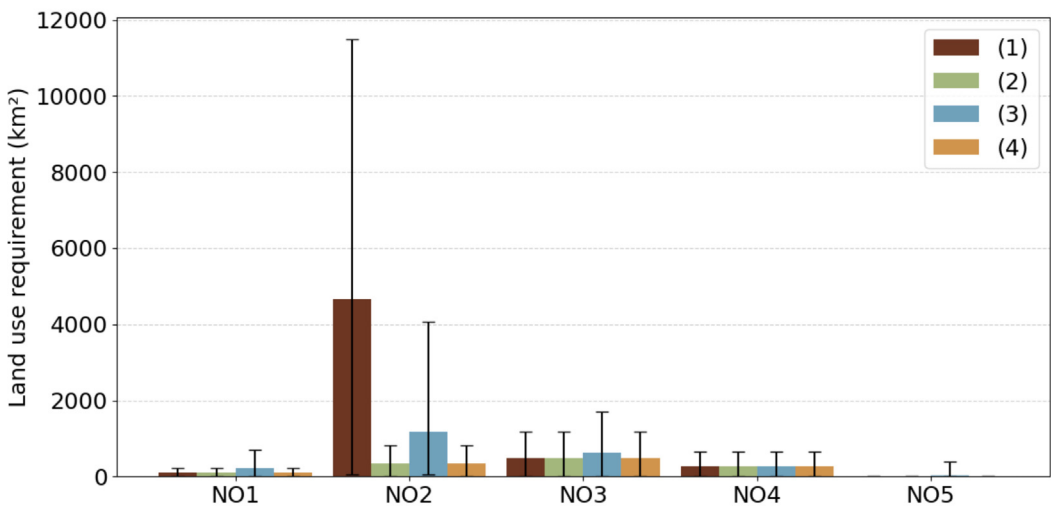
In case 1, we simply want to meet the electricity demand with increased RES, nuclear and carbon capture and storage (CCS) capacity. In case 2, we set restrictions on onshore wind investments, to meet the current Norwegian public opposition against wind build-out in later years [96,97]. Case 3, represents a scenario where Norway invests solely in solar power, to investigate how only increasing PV capacity influences the corresponding land use requirements and system operation. Lastly, case 4 equals a strict scenario in which we do not allow for any RES development using land area. The different cases are displayed in Table 2.

Investments are allowed in both the Norwegian and Northern European energy systems, subject to the same investment constraints in each region.

Each case is initially run with a CO_2 cap at 90% of 1990 emission levels, in alignment with the objectives of the European Union [98]. The CO_2 cap are based on production, meaning that emissions are allocated the area



(a) Direct land use requirements.



(b) Total land use requirements.

Fig. 2. Land use requirements for the different cases in Norway, divided into each price zone. In the figure, (1)–(4) corresponds to case 1–4.

in which power is produced. The cases are subsequently re-run with varying CO_2 caps, allowing for battery and PHS investments, to investigate different trade-offs between land use and RES development.

4 Results

In the following section, we examine the trade-offs associated with land use requirements under varying restrictions on the deployment of RES, with a particular emphasis on the role of solar PV in shaping Norway's future energy system. We begin by analyzing land use implications across the different cases, highlighting the balance between minimizing land footprint and enabling RES expansion. Subsequently, we evaluate the effect of allowing battery storage investments on overall land use requirements. Finally, we investigate how different CO_2 emission cap constraints influence both land use and the optimal configuration and operation of the energy system.

4.1 Land use requirements

Figure 2 illustrates the considerable variation in both direct and total land use requirements across the modeled cases. In terms of direct land use, case 3 stands out with the highest land demand. This is primarily due to largescale investments in ground-mounted PV systems, which dominate the energy mix in the absence of wind capacity.

These PV investments are heavily concentrated in NO2, where solar irradiance is comparatively higher. In contrast, NO4 sees no PV deployment, due to the long periods of low solar availability in winter. Although NO4

Table 3. Overview of land use in Norway by price zone and land area classification [100].

Land Area	NO_1 (km^2)	NO_2 (km^2)	NO_3 (km^2)	NO_4 (km^2)	NO_5 (km^2)
Built-up area	2656	1019	907	763	576
Agricultural	4620	1728	2375	1264	1016
Forest	42 131	19 503	21 359	30 811	9212
Open land	17 108	12 418	20 628	52 241	14 090
Open bog	3916	1286	5188	5876	644
Bare rock, gravel areas	3140	1353	2628	14 677	5216
Glaciers	73	0	72	995	1118
Freshwater	5657	3827	3331	6408	1998
Sum area available for RES build-out	66 295	34 561	49 803	103 605	29 163

benefits from extended daylight during the summer months (i.e., the midnight sun), this seasonal production peak misaligns with the Norwegian electricity demand, which peaks during winter [99]. As a result, there is a clear temporal mismatch between solar energy availability and consumption needs.

In comparison, the cases allowing for wind energy investments generally require significantly less direct land use. This is mainly due to the higher capacity factor of wind power and the relatively small physical footprint of wind turbines themselves. However, evaluating wind power's land impact solely on turbine foundations may underestimates its broader spatial implications. The need for sufficient spacing between turbines, along with necessary grid infrastructure, affects the total land area impacted and further influences the surrounding environment [12]. This is clearly seen in Figure 2b. Accounting for total land use requirements, the overall land footprint increases substantially, particularly in the onshore wind cases.

As seen in Figure 2b, case 1 now exhibits the highest overall land use requirements. Using total land use requirements, land use demands have increased by up to 4599 km^2, depending on the specific case analyzed. Despite the lower installed capacities in case 1, increased spacing between turbines and the associated infrastructure significantly amplify land use requirements. Consequently, onshore wind scenarios demand more total land compared to case 3. As in previous observations, the majority of investments are concentrated in NO2, attributed to the superior wind availability in this region.

The error bars in Figure 2 also show the substantial uncertainty mentioned in Section 2, especially in total land use estimates. This reflects methodological challenges in quantifying land use, which is sensitive to assumptions about spacing, technology configurations, and environmental definitions of land use. These factors complicate comparisons across studies and emphasize the importance of transparency in land use modeling.

Table 3 provides an overview of existing land areas in Norway, categorized by land type. As illustrated in Figure 2, the majority of RES development is concentrated in NO2, which is also the price zone with the second lowest amount of available land in the country. Consequently, RES expansion in this region may appear more intensive compared to other zones with greater land availability, potentially increasing the risk of public opposition. In NO2, total land use requirements for RES deployment range from 1% to 14% of the available area across the different cases. However, it is important to emphasize that not all available land is suitable for every technology.

Onshore wind turbines are typically installed on open land or bare rock areas. Based on this assumption, total land use requirements in case 1 would account for approximately 23% of the suitable area in NO2. However, this estimate is likely conservative, as it does not account for additional constraints such as wind resource availability, proximity to built-up areas, and potential impacts on biodiversity.

In contrast, ground-mounted PV systems offer greater locational flexibility and can be deployed in forests, open land, bogs, bare rock and gravel areas, or agricultural land through agrivoltaics. Under these assumptions, total land use requirements in case 3 would constitute only 3% of the available area, despite the substantial PV capacities required to meet demand. This percentage, however, may vary depending on site-specific conditions. Ground-mounted PV systems can also be installed in already developed, or grey areas [76], potentially expanding the usable land base. On the other hand, development of bogs can lead to significant greenhouse gas emissions, which have resulted in requests for regulatory restrictions on their use [101]. As with onshore wind, further environmental and regulatory considerations may impose additional constraints on land availability.

Figure 3 presents the total installed capacity across all evaluated cases. All cases involve substantial RES buildout, driven by projected declines in technology costs by 2040. Case 3, which excludes wind investments, exhibits the highest installed capacity, with ground-mounted PV systems accounting for 89% of the total. This massive investment in solar PV stems from its low capital cost, but it also reflects a need to compensate for solar's lower capacity factor and seasonal variability, compared to wind. Consequently, despite its high installed capacity, case 3 yields the lowest overall renewable electricity generation due to poorer capacity utilization. Across all cases, no new investments are made in nuclear capacity, primarily due to the assumption of high capital costs associated with such projects.

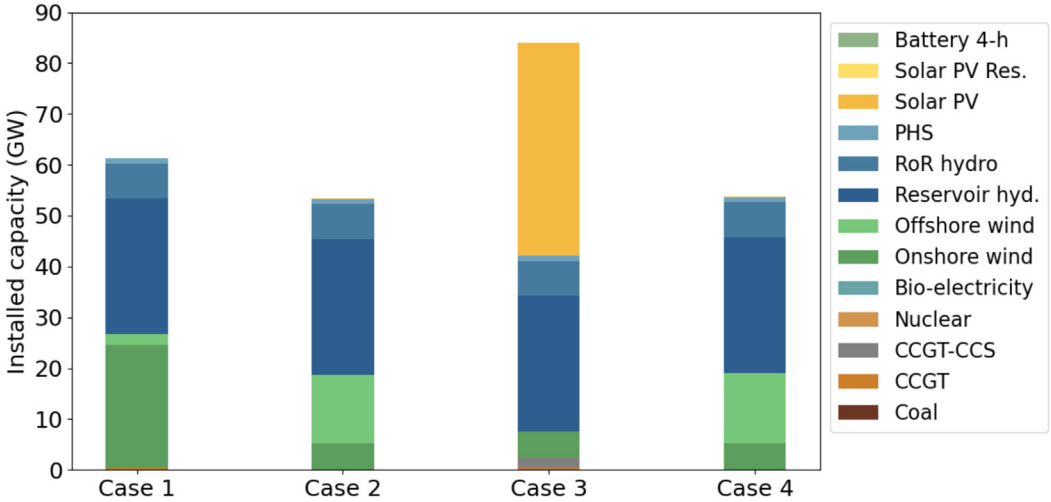


Fig. 3. Total installed capacity in Norway for the different cases (in GW). "Solar PV" refers to ground-mounted photovoltaic systems, while "Solar PV Res." denotes residential roof-mounted photovoltaic systems.

The model initially favors onshore wind, benefiting from favorable wind conditions and relatively low investment costs. Not allowing for onshore wind investments (cases 2-4), the system compensates by shifting toward more costly offshore wind technologies or by expanding PV capacity. As illustrated in Figure 4, this transition results in increased total system costs and higher average energy costs. The annual average energy cost is determined by dividing the total system cost by the total energy demand.

In cases 2 and 4, excluding onshore wind investments forces a shift towards more expensive offshore wind technologies. Whereas in case 3, system costs rise, due to the lower availability of solar PV requiring additional PV capacity. Additionally, due to the diurnal variation in PV generation, this case also necessitates additional investments in CCS capacity and increased reliance on natural gas production to ensure system reliability and flexibility. Gas production is mainly concentrated during winter months, which also correlates with lower solar availability. These requirements substantially increase both costs and emissions.

Across all cases, power generation in Norway exhibits distinct seasonal variation. During the winter months, Norway primarily imports electricity from the Continent with the imported power mainly originating from thermal sources. At the same time, thermal power production increases, both domestically and on the Continent. This pattern reflects the seasonal fluctuation in the Norwegian electricity demand, which peaks in winter due to widespread use of electric heating [102]. In case 3, this trend is further reinforced by reduced solar availability during winter [103]. As a result, Norway becomes more reliant on dispatchable thermal generation to ensure secure energy access, alongside increased imports from the Continent. Conversely, wind energy production in Norway typically peaks during the winter months [99], aligning more closely with seasonal demand and making it a more suitable renewable energy source for the Norwegian climate. However, even in scenarios that include wind investments, imports from the Continent remain necessary to meet overall demand.

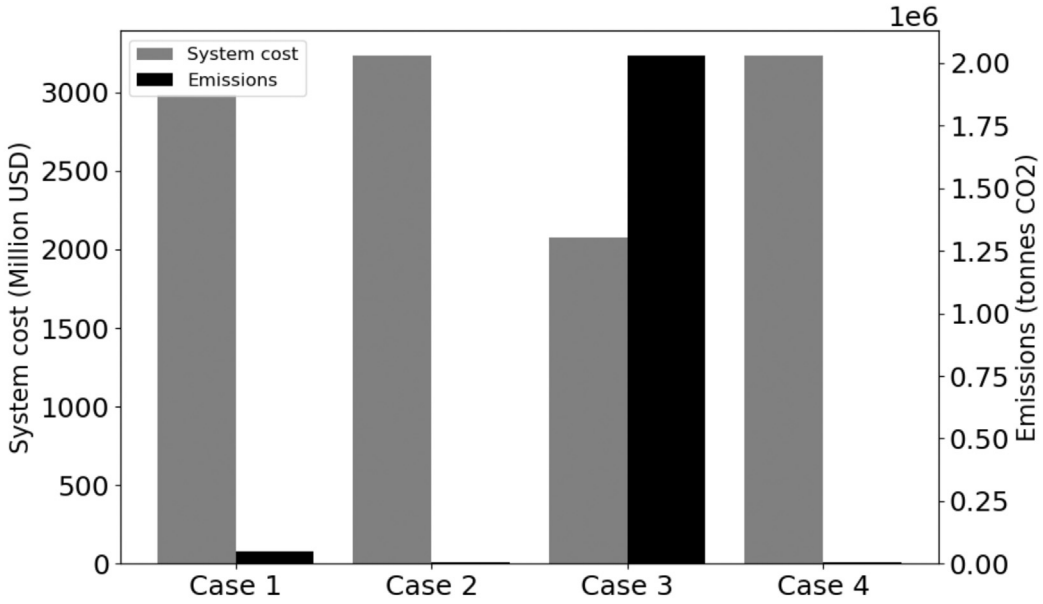
As illustrated in Figure 3, case 4 does not include any investments in roof-mounted PV. This outcome is driven by the relatively high costs and lower availability of rooftop solar compared to offshore wind, rendering it a less attractive option within the model's optimization framework.

Expanding the analysis to the entire North European energy system reveals considerably higher land use requirements compared to the Norway-only case, as shown in Figure 5. This increase is primarily driven by the extensive build-out of renewable energy infrastructure necessary to meet the aggregated energy demand across the region.

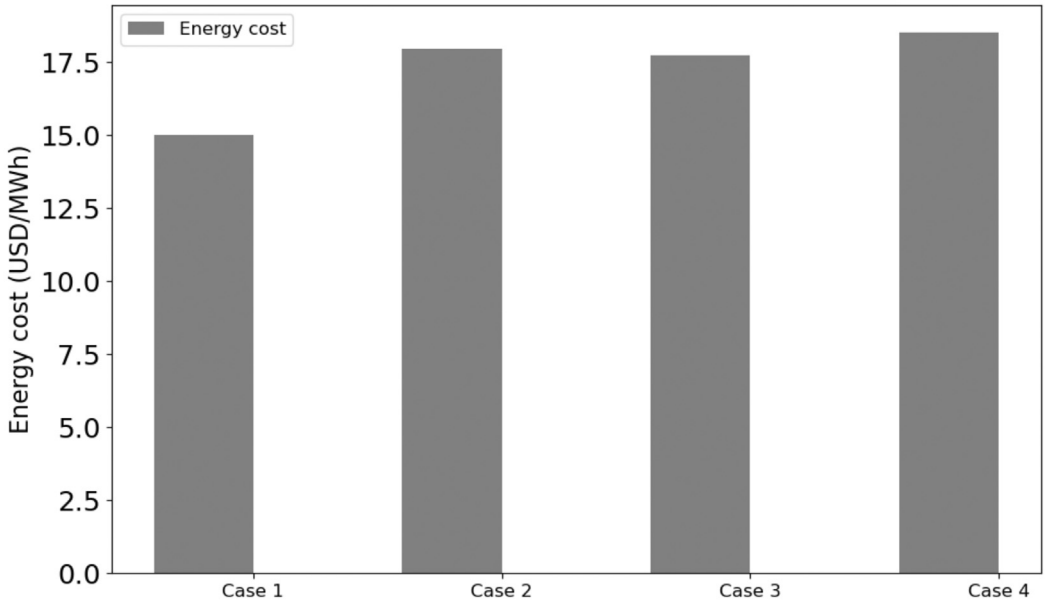
In terms of direct land use, the difference between cases 1 and 3 is less pronounced than in Norway. This is because of massive investments in onshore wind capacity across the Continent, which dominates land use across all cases. Notably, case 1 results in the highest total installed capacity, reflecting a strong preference for cost-effective onshore wind, as illustrated in Figure 6.

We further observe that although average solar availability is relatively similar between Norway and the Continent, case 4 now includes investments in roof-mounted PV on the Continent, in contrast to the Norwegian case. Additionally, we see more PV deployment on the Continent, compared to Norway. This is explained by Norway's superior wind resources and its already low emissions profile, largely supported by existing hydropower capacity. As a result, fewer additional RES investments are needed in Norway to meet emissions targets, whereas the Continent must rely more heavily on solar and wind expansions to decarbonize.

Based on our results, direct land use requirements across the modeled cases range from 0.006% to 0.16% of Norway's total land area and from 0.04% to 0.12% of Europe's total area [55,104]. When accounting for total land use, these estimates rise substantially, reaching 0.4%–1.69% for Norway and 0.65%–2.8% for Europe. Notably, these figures do not exclude areas unsuitable for development, such as mountain terrain or ice-covered regions,



(a) Total system costs (left axis, in Million USD) and total emissions (right axis, in tonnes CO_2), for Norway.



(b) Average energy cost per MWh, for Norway.

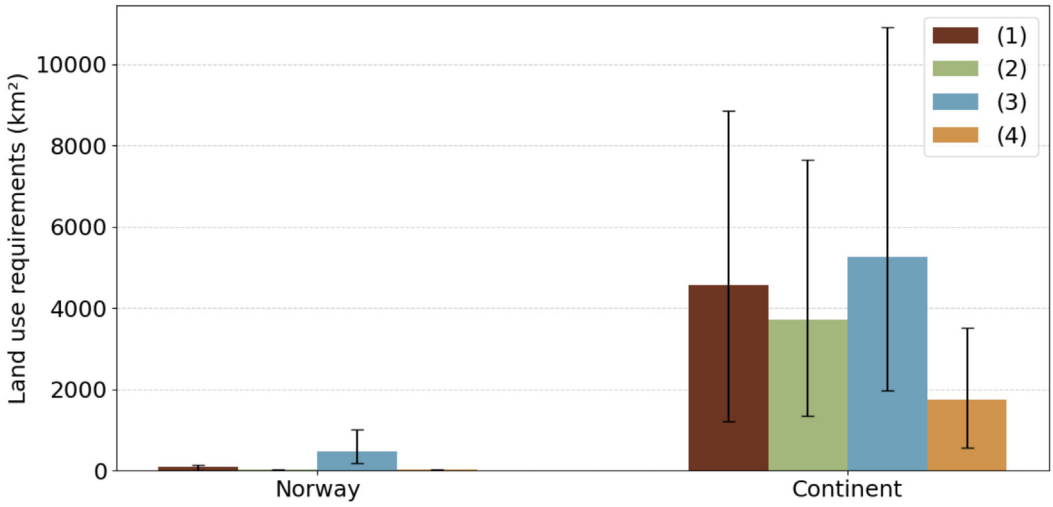
Fig. 4. Total system costs, energy costs and total emissions for Norway.

suggesting that actual land impacts may be even higher. Moreover, the anticipated increase in electrification across all energy sectors is expected to further intensify land use requirements [2].

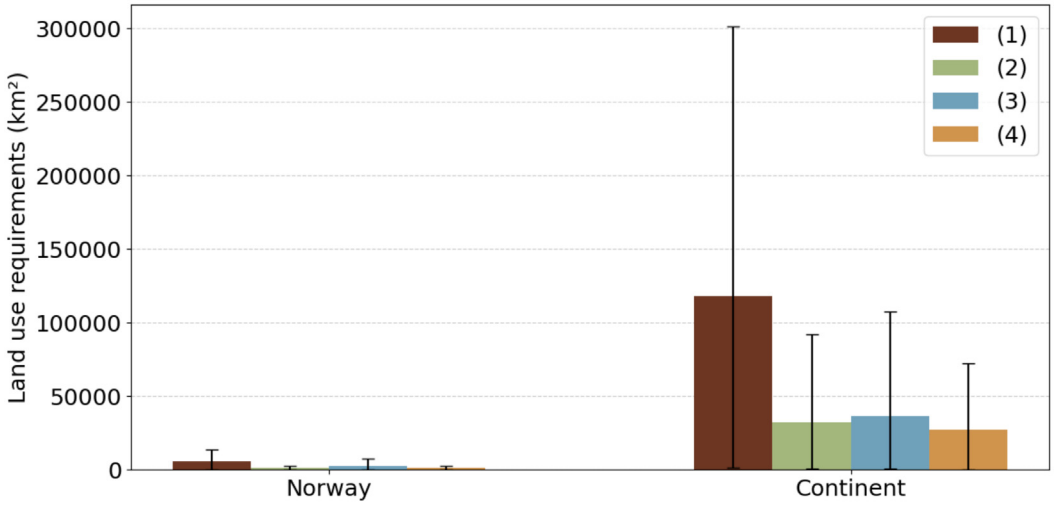
The above findings highlight the wide variation in land use outcomes depending on the chosen renewable deployment strategy and underscore the spatial footprint associated with a transition to a 90% renewable power system. However, due to the considerable uncertainty and variation in current land use methodologies these percentages could vary, depending on the specific assumptions and calculation methods applied.

4.2 Battery installations

The integration of long-duration energy storage has been shown to significantly reduce power system costs in scenarios with a high share of variable renewable energy



(a) Direct land use requirements.



(b) Total land use requirements.

Fig. 5. Land use requirements for the different cases, divided between the Continent and Norway. In the figure, (1)–(4) corresponds to case 1–4.

sources (VRES) [86,105]. To further investigate this effect, the model is re-run with the option to invest in battery storage technologies, specifically lithium-ion batteries and PHS. This section analyzes the impact of battery capacity on land use requirements across the different scenarios. Given that the Continent is represented as a highly aggregated and simplified region, primarily intended to model imports and exports, its results are excluded from this analysis.

All modeled cases include substantial investments in PHS, with case 3 exhibiting the highest installed capacity. In contrast, no lithium-ion battery systems are deployed due to their comparatively high capital costs, which render them economically unfeasible under current assumptions.

The effect of battery storage on land use differs markedly depending on the dominant generation technology, as shown in Figure 7. In case 3, where solar PV plays a central role, the increased availability of PHS enables a significant expansion of PV capacity. This results in a 134% increase in direct land use requirements. Conversely, in case 1, where onshore wind is more prominent, the additional storage capacity enables better temporal utilization of wind generation, allowing for a modest reduction in wind capacity. As a result, total land use requirements decrease slightly compared to the baseline. This trend is further reflected in annual power exports, which decrease slightly compared to the scenario without battery investments. In the cases allowing for wind investments, surplus electricity is increasingly used to

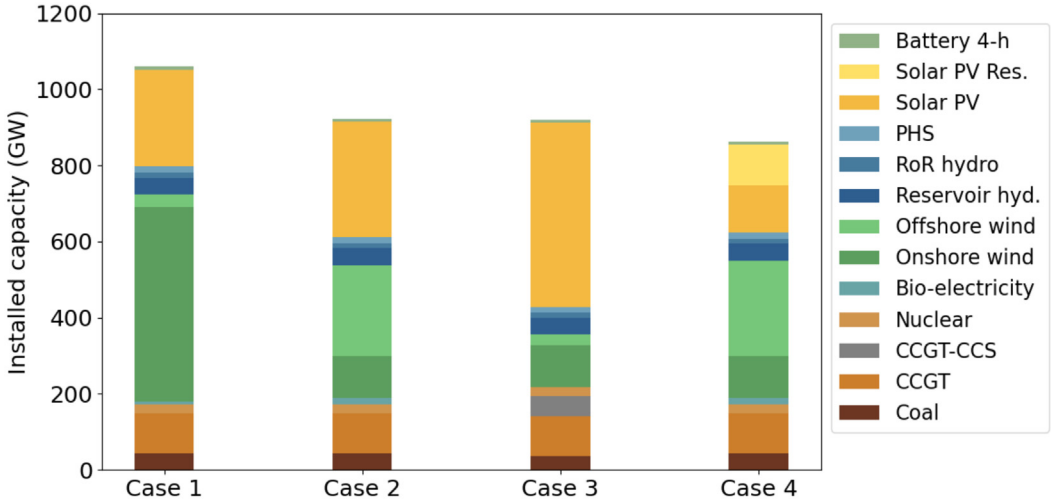
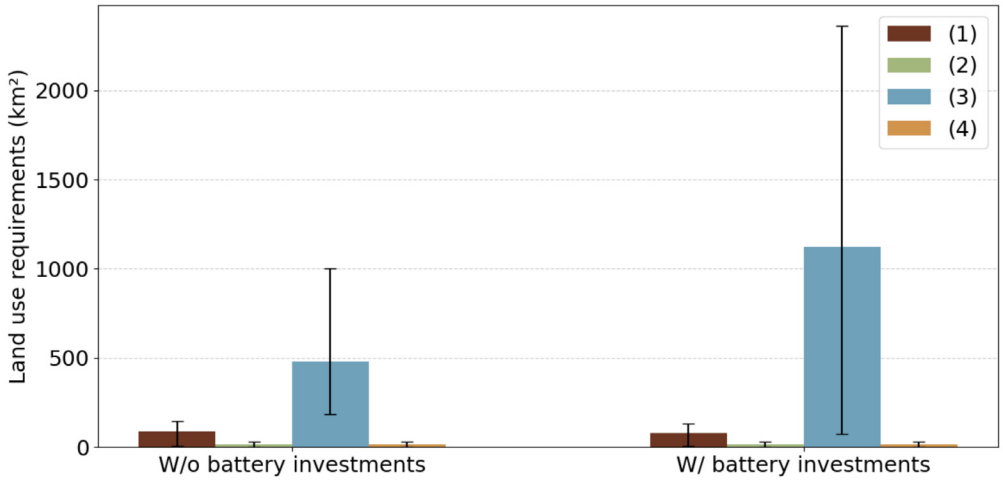
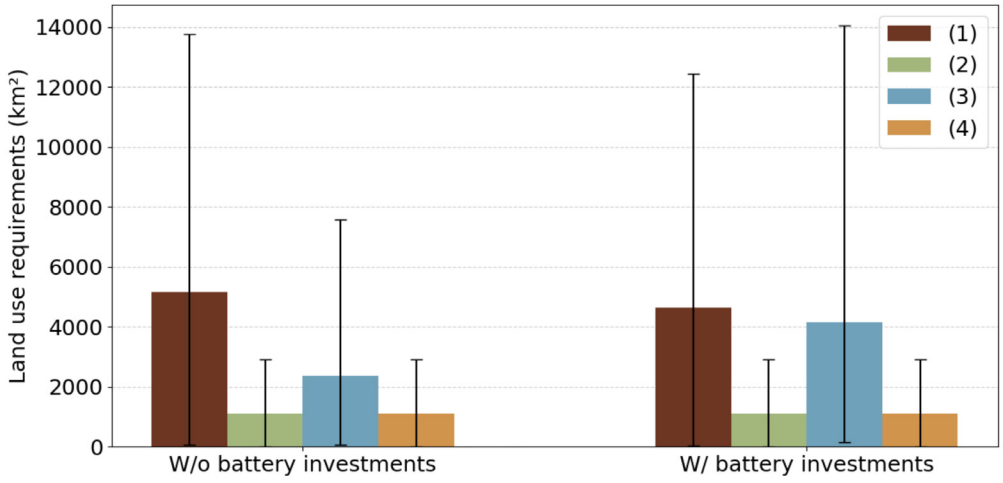


Fig. 6. Total installed capacity for the different cases (in GW). "Solar PV" refers to ground-mounted photovoltaic systems, while "Solar PV Res." denotes residential roof-mounted photovoltaic systems.

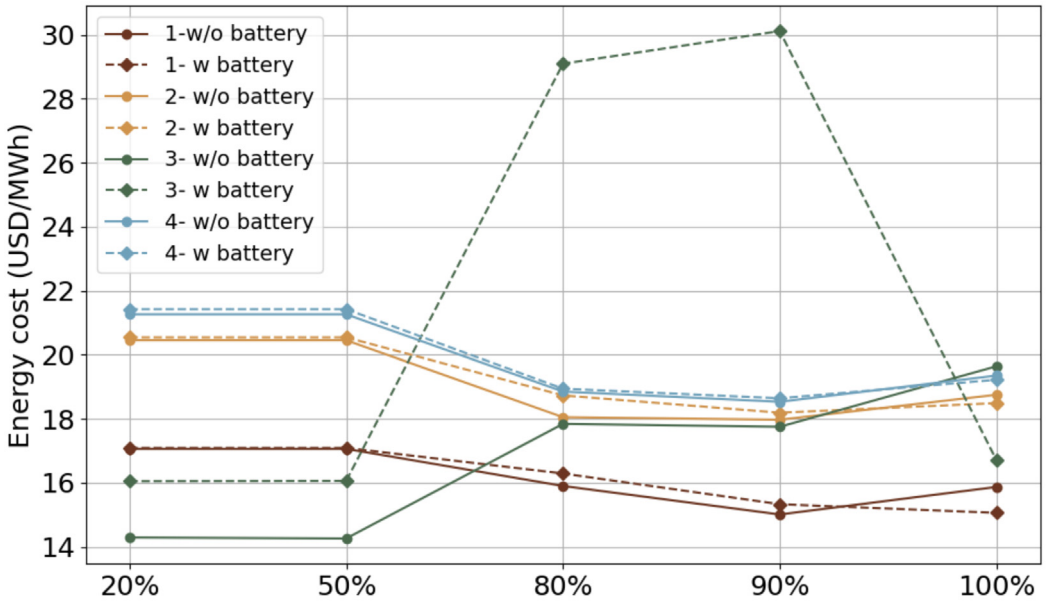


(a) Direct land use requirements.

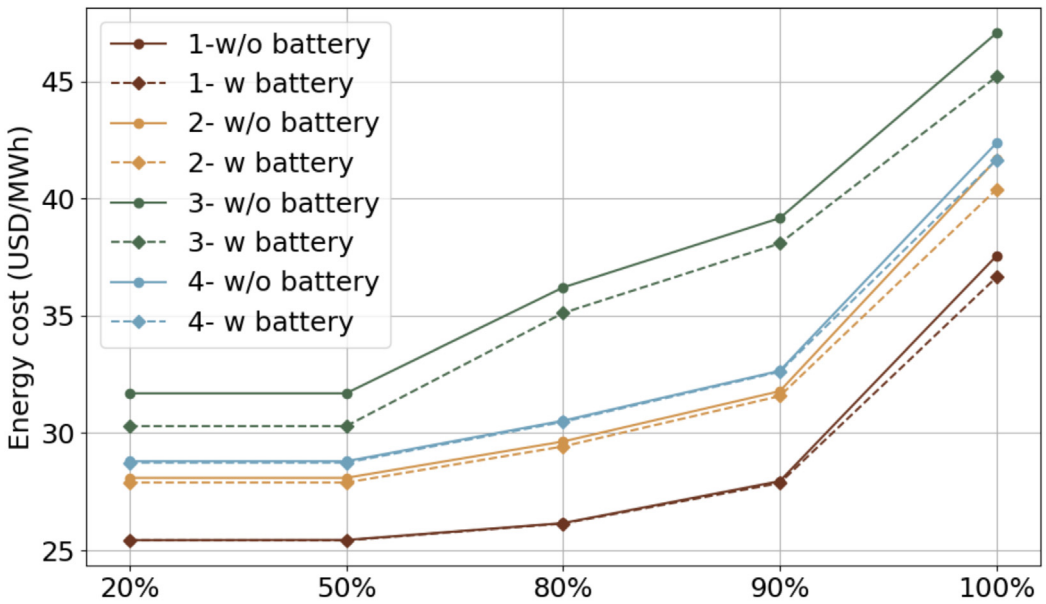


(b) Total land use requirements.

Fig. 7. Land use requirements for the different cases in Norway with (W/) and without (W/o) allowing for battery investments, using direct and total land use requirements. In the figure, (1)–(4) corresponds to case 1–4.



(a) Norwegian average energy costs.



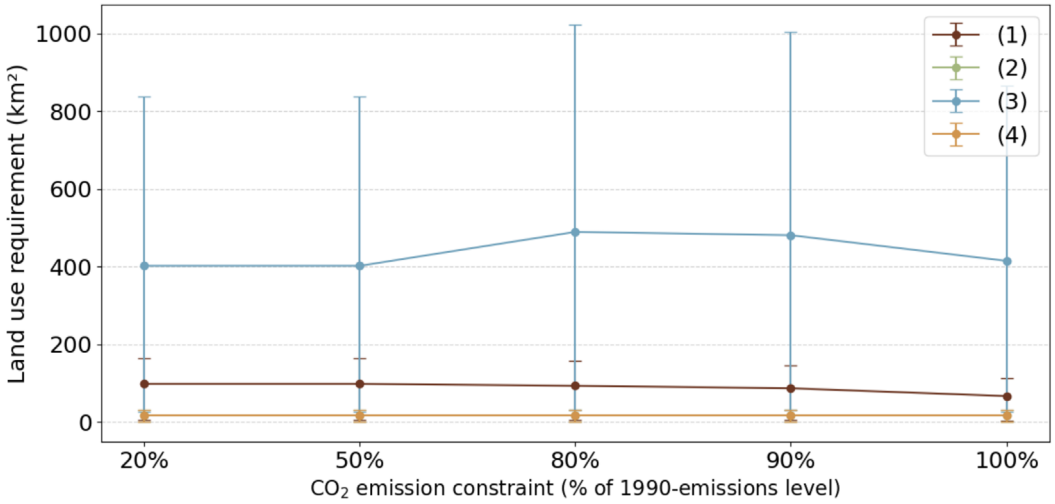
(b) Total average energy costs.

Fig. 8. Average energy costs for the four cases using different CO_2 emission constraint, with (w) and without (w/o) allowing for battery investments.

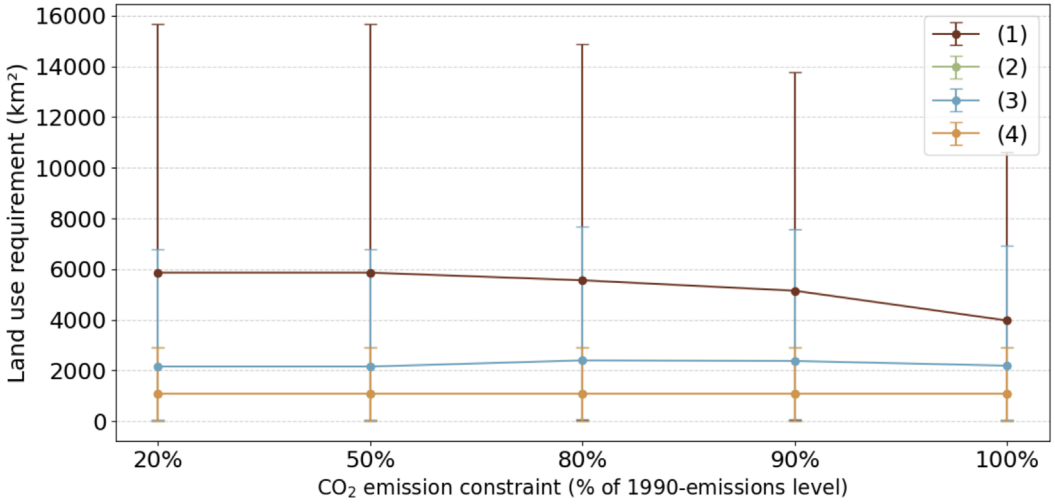
replenish reservoir levels, particularly during the summer months when demand is lower. In contrast, case 3 shows a substantial increase in Norwegian power exports, driven by the additional PV capacity. The significant PV investments result in large volumes of excess electricity during summer, leading to increased exports to the Continent.

4.3 Different CO_2 emission constraints

As a general trend, stricter CO_2 emission limits lead to higher average energy costs, as illustrated in Figure 8b. This increase is primarily driven by the phase-out of thermal generation and the need for expanded investments in renewable energy. Among the scenarios, case 3 incurs the



(a) Direct land use requirements.



(b) Total land use requirements.

Fig. 9. Land use requirements for the different cases in Norway.

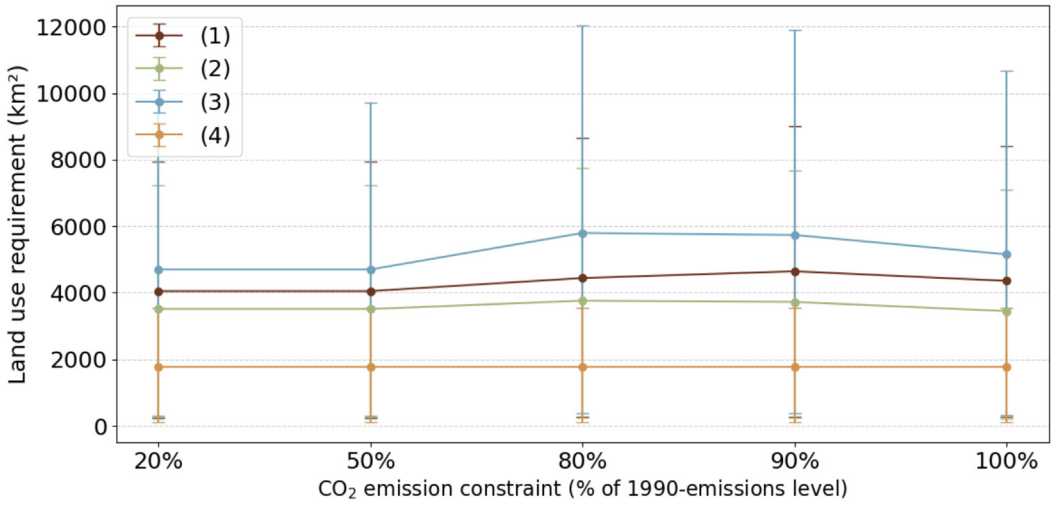
highest costs due to its massive investments in PV capacity. This necessitates stable backup capacity, provided either by fossil-based generation or CCS, depending on the stringency of the emission constraints.

The introduction of battery storage helps mitigate these costs, particularly in case 3, where storage reduces dependence on thermal generation and the associated fuel and CCS expenditures. In contrast, the impact of PHS in cases 1, 2, and 4 is relatively modest. However, under the 100% CO_2 reduction scenario, battery investments reduce average energy costs by 1.5–4.7%, primarily by lowering the need for CCS deployment.

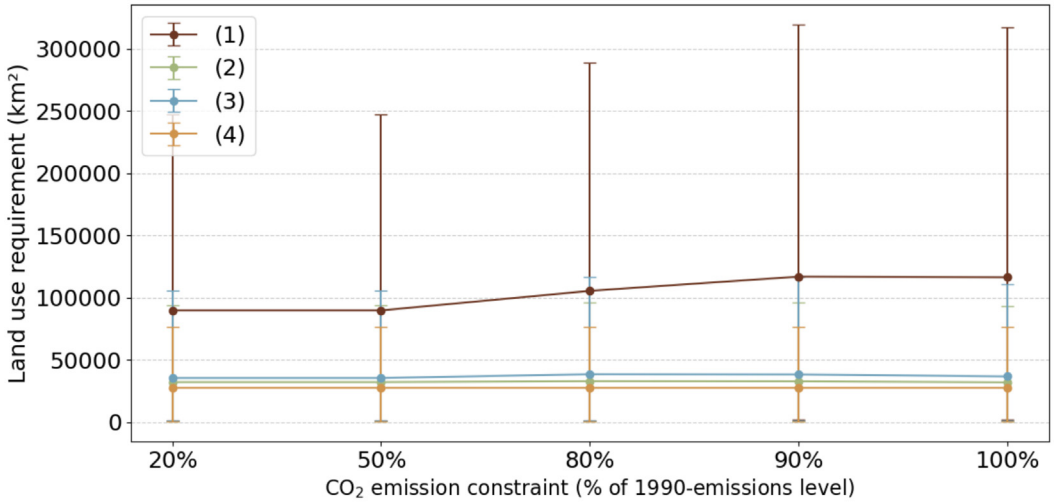
In the Norwegian system (Fig. 8a), average energy costs generally decline as CO_2 constraints tighten in cases 1, 2, and 4, with a slight increase observed under full decarbonization. Notably, stricter constraints reduce domestic RES deployment, increasing reliance on electricity imports from the Continent. This also affects the electricity price in Norway, as increased reliance on renewable energy imports from the Continent tends to lower domestic electricity prices. At the same time, the Norwegian energy system is less influenced by fluctuations in natural gas prices, due to stricter CO_2 regulations on the Continent that reduce gas dependency. In contrast, case 3 follows the total system trend, with rising average energy costs under tighter CO_2 constraints. This reflects the growing expansion of PV combined with CCS, to manage periods of low solar output.

Interestingly, allowing for battery investments in Norway tend to increase average energy costs across all scenarios, except under the 100% CO_2 reduction case. This effect is most pronounced in case 3, where storage facilitates significant PV expansion, thereby increasing associated land use and costs.

The cost dynamics are further reflected in the associated land use outcomes (Fig. 9). In case 3, direct land use rises with tighter CO_2 constraints due to increased



(a) Direct land use requirements.



(b) Total land use requirements.

Fig. 10. Land use requirements for the different cases, considering the whole system.

PV deployment. However, under the 100% reduction target, direct land use requirements drop sharply as the system shifts from PV expansion to CCS investments to meet the emission goals. In contrast, case 1 shows declining direct land use requirements with stricter constraints, driven by reduced onshore wind development in Norway and increased reliance on imports. This shift reflects large-scale wind expansion on the Continent, which leads to overcapacity and curtailment, reducing the need for domestic generation. The total land use requirements follows similar trends, but with greater magnitude (Fig. 9b).

When considering the entire system (Fig. 10), land use requirements generally increase as CO_2 constraints become more stringent, reflecting the expansion of renewable energy sources. However, under the 100% CO_2 reduction scenario, land use declines as the system shifts from further additional RES capacity towards greater reliance on CCS. While this transition reduces spatial impacts, it comes at the expense of higher system costs, highlighting a key trade-off between land efficiency and economic performance.

5 Discussion

The above results highlight significant differences in land use requirements depending on the chosen energy system configuration. In the Norwegian context, the model initially favors onshore wind due to its higher availability, aligning with findings from previous studies [73–75,78]. However, our results assign greater value to onshore wind and impose fewer restrictions on its development, leading to higher onshore wind capacities and reduced investments in offshore wind compared to for instance [73] and [75]. This discrepancy can be attributed to endogenous factors within the respective energy system models, as well as differences in modeling assumptions. Another contributing factor may

be the level of detail in the energy system representation. Our model represents a simplified representation of the North-European energy system, and adding more granularity could significantly influence the final outcomes.

The initial high dependence on onshore wind capacity results in relatively low direct land use but substantially higher total land impacts. This discrepancy stems from the large spacing requirements between wind turbines necessary to maintain optimal performance [106], which expands the overall land area impacted. In contrast, a system limited to solar PV requires greater installed capacity due to lower solar availability, leading to increased direct land use and higher overall system costs. Additionally, this solar-dominated scenario sees elevated emissions because of increased reliance on thermal generation to address solar power's diurnal variability.

However, only considering the physical footprint of an energy source may not fully capture the total impacts of a wind farm, or PV plant, as the spacing between wind farms, rotor movements, or glaring effects of PV panels may impact the surrounding ecosystems and social interests. In this case, using the total land use requirements can give a better representation and understanding of the societal and ecological consequences of increased RES development.

When total land use is prioritized over direct land use, the PV-dominated scenario exhibits a lower overall land impact compared to the onshore wind case. This underscores the importance of selecting appropriate metrics when assessing the land use implications of renewable energy systems.

The analysis also exposes substantial variability in land use estimates across the literature, reflecting inconsistencies in definitions and methodological approaches. This variability introduces uncertainty in projecting land use impacts of future energy systems, complicating efforts to assess the true consequences of transitioning to low-emission systems. Furthermore, it underscores the challenge of integrating subjective factors into land use assessments, as stakeholder perceptions of wind and solar farms can differ significantly.

In our study, land use requirements in cases 2 and 4 are minimal, based on the assumption that offshore wind and rooftop-mounted PV systems do not require additional land. However, the deployment of offshore wind infrastructure can still lead to indirect land use changes [44]. Furthermore, although offshore wind typically benefits from stronger and more consistent wind conditions, such projects are generally more expensive. As a result, concerns about the economic viability of offshore wind have emerged, with some projects even being decommissioned due to financial challenges [107].

Roof-mounted PV systems offer the advantage of utilizing existing buildings, thereby avoiding the need for new land development. However, this approach often entails higher costs compared to ground-mounted PV systems, due to more complex installation procedures and structural limitations [108]. Furthermore, as a large share of roof-mounted PV systems are installed on private residences [109], this may present challenges for investment. Additionally, not all rooftops are suitable or accessible for PV installations, which restricts the total available area. Rooftop PV may also require the deployment of greater total capacity, as buildings are not necessarily situated in locations with optimal solar exposure. Moreover, the limited rooftop area may be insufficient to meet energy demand, potentially necessitating additional land use changes.

An alternative strategy involves situating renewable energy infrastructure within already developed areas, such as gravel pits, roadside verges, or parking lots [110]. While this approach reduces pressure on undeveloped land, these sites often present suboptimal conditions that may reduce energy yield or increase production costs. Thus, the trade-off between preserving natural land and maintaining economic efficiency must be carefully evaluated.

In this study, we have exclusively focused on land use requirements associated with the installation of energy technologies, and have not considered land use related to mining, material consumption, or water use for production and cooling. However, these factors can significantly influence the overall land use impact of different technologies. Including land use for mining and resource extraction would increase the total land requirements for certain PV technologies, whereas gas and nuclear power generally exhibit lower land use demands [111]. Furthermore, incorporating additional dimensions such as impacts on human health or climate change could alter which technology is considered most impactful, as illustrated in ref. [112].

Another limitation of the current paper lies in its predominantly quantitative focus, which solely considers land use requirements to assess the impact of increased RES development. However, several other critical dimensions, such as energy efficiency and security [113], cultural factors, and the knowledge held by local communities and indigenous people, also play a significant role in shaping investment decisions and public perception [114]. Since many of these aspects cannot be adequately captured through quantitative methods alone, complementary approaches, such as impact assessments and tools from social science, are essential to fully understand the environmental implications of RES integration.

Lastly, our simulations are based on optimization using a single representative weather year. As such, the results may vary if a different meteorological year is selected. Optimizing across multiple weather years or incorporating a worst-case scenario, rather than relying on an average year, could lead to a more robust and resilient system design [86]. Exploring these effects in more detail could provide valuable insights into the resilience and scalability of the system.

As our results indicate, meeting the climate target of reducing emissions to 90% of 1990 levels by 2040 will necessitate significant investments in renewable energy capacity, consequently leading to increased land use demands. A strategy focused solely on economic optimization leads to a significant expansion of onshore wind, resulting in land use requirements of 86.50 km^2 for direct land use and 5149 km^2 when accounting for total land use requirements. These figures correspond to approximately 0.03% and 1.69% of Norway's total land area, respectively. Given the current public opposition to wind turbine installations, this approach may face considerable social and political challenges.

Alternatively, restricting all capacity expansions based on land use constraints results in significantly lower land occupation, 18.43 km^2 (0.006%) for direct land use and 1092 km^2 (0.4%) for total land use. While this approach may reduce public resistance, it comes at the expense of nearly a 20% increase in overall system costs. Moreover, the offshore wind cost assumptions used in our analysis are based on offshore wind in shallow waters, suggesting that the actual cost increase could be even higher in less favorable conditions. Additionally, our land use estimates assume zero land requirements for rooftop PV and offshore wind. In reality, offshore wind involves indirect land use, which ultimately increases the total land use requirements. For instance, offshore wind farms necessitate extensive grid infrastructure to transmit electricity from sea to land [44]. Moreover, additional factors, such as conflicts with the fishing industry, impacts on marine biodiversity, and potential environmental degradation, can lead to public opposition and must be carefully considered. Furthermore, when offshore wind farms are situated in shallow coastal waters, they may cause visual disturbances and trigger social resistance, including the Not In My Backyard (NIMBY) phenomenon, which further complicates their development [44].

As previously discussed, not all areas in Norway are suitable for RES deployment, which imposes constraints on land availability. In addition, 17.7% of Norway's land area is protected and designated as national parks [115], further limiting the space available for development. Additional restrictions, such as construction limitations and regulatory frameworks under the Norwegian Planning and Building Act, also contribute to reducing the areas viable for RES deployment.

Furthermore. due to more favorable conditions in NO2, we find that the majority of investments are concentrated in this region. Notably, NO2 also has the second lowest amount of available land area among the price zones considered, which may make RES expansion appear more intensive compared to development in areas with greater land availability. In addition, NO2 has a relatively high population density by Norwegian standards, potentially increasing the likelihood of public opposition to new projects. On the other hand, restricting investments in NO2, would likely result in higher overall system costs, as projects would need to be relocated to less optimal regions, potentially requiring additional capacity to meet demand. Such trade-offs are important to consider when planning the future structure of the Norwegian energy system.

Ultimately, several renewable energy deployment strategies can help minimize land use impacts, though they often involve trade-offs in terms of cost, efficiency, and technical feasibility. Prioritizing development within built environments can reduce the need to convert undeveloped land. Nevertheless, expanding renewable energy capacity will inevitably require land, with consequences for biodiversity and ecosystems. To avoid delays or cancellations due to public opposition or competing land-use interests, effective and inclusive spatial planning is essential. Moreover, it is crucial to recognize that inaction carries its own risks, potentially resulting in even greater land degradation through biodiversity loss and environmental damage driven by climate change.

6 Conclusion

This study examines the potential contribution of solar power to Norway's future energy system, with a particular focus on the trade-offs between land use requirements and the deployment of RES. Our analysis shows that achieving national climate targets could require land use ranging from 18.43 to 5149 km^2, depending on the selected scenario and land use metric. This corresponds to approximately 0.006–1.69% of Norway's total land area. Moreover, we find that efforts to minimize land use often lead to increased system costs and/or higher emissions. These findings underscore the limitations of relying solely on economic metrics, as doing so overlooks the broader environmental and societal implications of the energy transition.

Inevitably, achieving a low-emission energy system will require significant land use. While several RES development pathways can help mitigate these spatial demands, they often come with trade-offs in the form of higher system costs or increased emissions. Therefore, to avoid public opposition that may hinder or delay progress, integrated spatial planning at the system level is essential. Such planning can help balance spatial efficiency with economic performance and ensure more sustainable decision-making. Nonetheless, it is important to acknowledge that any RES deployment will entail some degree of environmental impact. These impacts must be thoroughly assessed and minimized to safeguard natural ecosystems.

Future research should focus on developing a more detailed understanding of land use requirements within specific local contexts. This includes exploring co-optimization strategies across multiple weather years and quantifying the land use impacts of offshore wind to enable consistent comparisons with solar PV and onshore wind. Additionally, integrating socio-economic dimensions into energy system modeling will be essential for capturing the broader societal implications of transitioning to a low-emission energy future.

Glossary

Term	Definition
BESS	Battery Energy Storage System
CCS	Carbon capture and storage
GHG	Greenhouse gas
IAM	Integrated assessment model
MGA	Modeling to Generate Alternatives
NIMBY	Not In My Backyard
PHS	Pumped Hydro Storage
PV	Photovoltaic
RES	Renewable energy sources
TYNDPs	Ten-Year Network Development Plans
VRES	Variable renewable energy sources

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Conflicts of interest

The authors declare that they have no financial conflicts of interest related to this article.

Data availability statement

The data supporting this study are available in [81].

Author contribution statement

Petry Kristine Nøttum Haaland: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Investigation, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization.
Magnus Korpås: Validation, Writing – Review & Editing.
Ole-Morten Midtgård: Conceptualization, Validation, Writing – Review & Editing, Supervision, Project Administration.

AI declaration

In preparing this work, we used Copilot to assist with language refinement and to generate initial code for figure plotting. All content produced with the help of this tool was carefully reviewed and revised by us, and we take full responsibility for the final version of the publication.

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Appendix A: Additional Information

This section summarize the key assumptions used in this study. It is structured in four parts: Investment and fixed and O&M costs (Tab. A1, [82,86,90,96]), fuel price and CO_2 content (Tab. A2, [87,88]), properties for each generating unit (Tab. A3, [90]), and transmission capacities between each zone (Tab. A4, [87]).

Table A1. Cost assumptions for different generation technologies.

Generation Technology	Investment ($/MW-year)	Fixed O&M ($/MW-year)	Variable O&M ($/MWh)	Technical Lifetime (years)
STHC	112140.36	1979.86	2.62	40
STLC	131474.90	2513.49	3.27	40
CCGT	41221.25	1546.76	2.52	30
CCGT CCS	116007.27	2706.84	3.14	40
Bio-energy	255602.68	4872.31	6.34	40
Nuclear	464029.07	8352.52	8.28	60
Wind onshore	73471.27	928.06	0.20	30
Wind offshore	140755.48	2242.81	0.43	30
Solar PV Utility	28692.46	734.71	0.00	30
Solar PV Residential	40370.53	858.45	0.00	30
Run-of-River	190933.06	9480.00	0.00	60
Hydropower	249043.13	29840.00	0.37	60
PHS	70952.46	1809	0.47	60
Battery: 4-h	88229.00	27491.00	0.00	15

Abbreviations: STHC: Steam Turbine Hard Coal; STLC: Steam Turbine Lignite Coal; CCGT: Combined Cycle Gas Turbine; CCS: Carbon Capture and Storage; Conv: Conventional; PHS: Pumped Hydro Storage.

Table A2. Fuel price and CO_2 content.

Fuel	Price ($/MMBtu)	CO_2 content (tons/MMBtu)
Hard Coal	3.24	0.24
Lignite	3.20	0.28
Natural Gas	8.40	0.10
Nuclear	3.89	0.00
Bio-fuel	48.91	0.00

Table A3. Technologies.

Unit	Type	Efficiency	Fuel
STHC	Thermal	0.43	Coal
STLC	Thermal	0.38	Coal
CCGT	Thermal	0.59	Gas
CCGT CCS	Thermal	0.48	Gas
Bio-energy	Thermal	0.32	Bio-fuel
Nuclear	Thermal	0.38	–
Wind onshore	VRE	NA	–
Wind offshore	VRE	NA	–
Solar PV	VRE	NA	–
Run-of-River	VRE	NA	–
Conventional hydro	Hydro	NA	–
Pumped hydro storage	Storage	0.87	–
Battery: 4-h	Storage	0.92	–

Table A4. Transmission capacities.

Line from	Line to	Capacity (MW)
Area 1	Area 2	3500
Area 2	Area 1	2200
Area 1	Area 3	500
Area 3	Area 4	1200
Area 4	Area 3	400
Area 5	Area 3	500
Area 3	Area 5	800
Area 5	Area 2	500
Area 5	Area 1	3900
Area 2	Area 5	600
Area 4	Area 6	900
Area 3	Area 6	1000
Area 1	Area 6	2100
Area 2	Area 6	5248