

Potential impacts of Ground-mounted photovoltaic panels on land cover and carbon storage in Norway – a scenario analysis

Keywords: *Solar power, Land use change, Carbon storage, Biodiversity, Norway*

Scenario analysis, Renewable energy transitions

Trond Simensen¹, Jonathan Rizzi², Anne Catriona Mehlhoop¹, Matthew Grainger¹, Erlend Hustad Honningdalsnes³, Heine Nygard Riise³

¹ Division for Land and Biodiversity, Norwegian institute for nature research (NINA), P.O. Box 5685 Torgarden, 7485 Trondheim, Norway

² Department of Geomatics, Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway

³ Department of Solar Power Systems, Institute for Energy Technology (IFE), P.O. Box 40, 2027 Kjeller, Norway

Abstract

In cool-temperate and boreal regions, ground-mounted photovoltaic (PV) is rapidly emerging as a new land use, but planning-relevant evidence on land requirements, siting options, and land-system impacts remains limited. Based on an analysis of built and planned ground-mounted PV projects in Norway ($n = 77$), we quantify size, capacity density, land-cover composition and net greenhouse gas effects, and model land use requirements to 2050 under contrasting siting strategies. Current and proposed projects are largely concentrated in forest and woodlands (96.4% of mapped project area), with median capacity density and energy yield density clustering around ~ 80 MWp/km² and ~ 84 GWh/km²/year. For the assessed siting pattern, combined land-use-related and PV life-cycle emissions were approximately 5,000 t CO₂e per km² per year, annualised over 30 years. This estimate implies net emissions reductions if PV displaces electricity with the emission intensity of the EU-27 mix but increases relative to the current Norwegian mix. Achieving about 1, 4, or 21 GWp by 2050 would require approximately 15, 56, and 268 km² of land, respectively. Shifting development towards agricultural and heavily modified land slightly increases overall land demand by ca. 25 % under our scenario assumptions but can reduce expansion into (semi-)natural ecosystems, reduce greenhouse gas emissions from land cover changes, while offering opportunities for co-use and biodiversity mitigation. The results support a diverse siting strategy, with greater use of previously modified land and agricultural co-use, guided by site-specific assessment and monitoring of land-use and ecosystem impacts.

1. Introduction

Scaling up renewable electricity is a key part of climate mitigation, but the land footprint of new projects can conflict with biodiversity objectives and other land uses (Johnson et al., 2021; Palmer-Wilson et al., 2019). Many countries, including Norway, now pursue two goals at once: scaling up renewable energy while reducing the rate of conversion from nature and cropland to artificial surfaces to limiting impacts on biodiversity and ecosystem services (Ministry of Climate and Environment, 2024; NOU 2023:3, 2023). In Norway, this tension is sharpened by high land take per capita (Venter et al., 2026), increasing the need for land-efficient deployment and careful allocation of land-demanding infrastructure.

Ground-mounted photovoltaic (PV) technology is rapidly emerging as a new component of the Norwegian energy transition (Norges vassdrags- og energidirektorat, 2025). As of January 2026, only 9 (>500 kWp) facilities are operative but many more are in planning, while national guidance on allocation, siting priorities, and mitigating negative effects for biodiversity expectations remain limited. Licensing and permitting have also been slow, increasing uncertainty for municipalities, developers, and land managers. Ground-mounted PV is therefore not only an energy question but a land-use policy question: which land-cover types should carry the footprint, and what forms of co-use and mitigation are realistic at scale (Diffendorfer et al., 2024; Hernandez et al., 2015; Wu et al., 2023).

Ground-mounted solar PV affects land systems mainly through where it is placed and how sites are designed and managed. Direct impacts include land-cover change and habitat alteration from vegetation clearing, ground levelling, installation of foundations (such as concrete footings, ballast blocks, or driven piles/ground screws), access roads, and cabling, as well as long-term occupation that can increase fragmentation and edge effects (Borgelt et al., 2026; Hernandez et al., 2014; Lafitte et al., 2023). These effects are typically more severe when projects are sited in semi-natural or natural areas rather than already modified land. Indirect effects can extend beyond habitat loss through shading and changes in microclimate (light, temperature, moisture) and water flows (runoff and local hydrology), with potential consequences for ecological processes such as plant growth, soil functioning, erosion, and pollination (Lafitte et al., 2023; Schwarz & Ziv, 2025). Species responses are context- and species-specific, ranging from habitat loss and barrier effects to potential creation of habitat where vegetation structure and connectivity are maintained through management (Schwarz & Ziv, 2025). Importantly, impacts also depend on PV design and operation such as panel height and spacing, orientation, and whether land use is single-purpose or dual-use.

Ground-mounted PV is often framed as a driver of ‘land take’ when it converts (semi-)natural or agricultural land to infrastructure (Turney & Fthenakis, 2011). However, conflicts may be reduced through co-location with other land uses (‘co-use’), including deployment on already modified sites such as industrial areas, parking lots, rooftops, landfills, and in some cases within existing energy

landscapes. We use the term ‘grey areas’ for previously developed or heavily modified land where current use falls below its potential, including brownfields, obsolete infrastructure and underused urban areas (Jacek et al., 2022). Despite growing policy interest, greyfields remain weakly integrated into energy system planning and the capacity of grey areas to accommodate renewable energy production remains largely unquantified. Agrivoltaic systems (Agri-PV) combine food production and solar energy conversion on the same land, while ‘ecovoltaic’ approaches aim to maintain or restore vegetation, soils, and habitat features through low-disturbance construction and active site management (Schwarz & Ziv, 2025; Zainali et al., 2025). Figure 1 summarises four stylised PV siting and design options that motivate our scenario comparison of current planning practice versus strategies that prioritise agriculture and already modified land. The extent to which these approaches reduce net ecological impacts remains largely uncertain, particularly in northern, high-latitude environments where evidence is limited (Lafitte et al., 2023).

Land-use choices directly interact with climate objectives through carbon emissions from land use and land cover changes. Protection of carbon sequestration and storage in natural and semi-natural ecosystems can contribute substantially to climate mitigation, and energy planning has been criticised when it overlooks emissions risks from loss of natural carbon stocks and other impacts of nature loss associated with infrastructure development (Van De Ven et al., 2021). Siting projects in carbon-rich ecosystems can create an up-front carbon loss and reduce future net CO₂ uptake, potentially delaying or diminishing the net climate benefits of renewable electricity. Taken together, the key land-use policy question is not only whether PV expands, but how much land it requires, what characteristic has that land, how carbon-rich is that land and how much of that carbon can be lost, and how alternative siting and co-use strategies shift risks across ecosystems and landscapes.

Here, we combine a national snapshot of current PV planning in Norway with scenario modelling to 2050 to quantify future land demand and how the land-cover burden shifts under contrasting siting assumptions. By reporting both total land requirements and plausible alternatives for distribution across land-cover types, the study provides a planning-relevant basis for discussing allocation strategies, feasible co-use options, and priorities for more detailed assessment of direct conversion and indirect effects.

The aim of this study is to inform land-use policy for ground-mounted solar PV in Norway by quantifying how siting choices translate into land demand and land-cover exposure. Specifically, we (i) describe current planning practice based on proposed projects ($n = 77$), (ii) develop planning-relevant density metrics for ground mounted solar PV, and (iii) develop explorative national scenarios to 2050 to estimate total land requirements and how the land-cover burden shifts under contrasting allocation strategies. We discuss findings in relation to current land use and future land use and energy policies.

102 a)



b)



103

104 c)



d)



105

106 e)



f)



107

108 *Figure 1. Six siting and design options for ground-mounted PV in Norway, with different land*
109 *requirements and potential for co-use. a) PV in heavily modified land (grey areas), co-use with car*
110 *parking. b) PV on heavily modified land on top of a former landfill site. c) PV on grasslands. d) Agri-*
111 *PV on farmland: combines energy with farming/grazing. e) PV with full land conversion from forest to*
112 *heavily modified land (i.e., 'land take'). f) PV in a logged forest ecosystem with a light footprint,*
113 *keeping the ground relatively intact ('ecovoltaics').*

2. Material and methods

2.1 Data collection

To get a snapshot of current trends in PV planning, we collected data from existing or proposed solar facilities downloaded from The Norwegian Water Resources and Energy Directorate (NVE), January 2026. For planned projects (not yet built or licensed/permited), we included only cases taken into processing by NVE to reduce bias from submissions that are screened out and unlikely to be realised. For these projects, we collected data from applications documents, downloaded, extracted or digitized polygons representing the perimeter of the PV area (Figure S1). We extracted key information for each planned PV park, including administrative information (applicant, stage in the planning process), technical information (planned capacity installation (MWp), as planned land use and management regime (e.g., multifunctional land use such as agriculture or grazing). Current ecosystem type was extracted from the National base map for ecosystem accounting, following the typology (level 2) from Eurostat (2026). For five newly developed projects we conducted area-covering land cover type mapping in the field, including a buffer zone of minimum around the perimeter of the PV production area. (minimum 500 m), providing a validation and input to the interpretation of GIS-based land cover data, and impact from PV installations.

To estimate carbon stock changes and greenhouse-gas (GHG) flux implications of land-cover change related to ground-mounted PV, we used NIBIO's nationwide, map-based carbon calculator (Mathiesen et al., 2026). The calculator follows IPCC Guidelines (IPCC, 2006, 2019) while utilising detailed Norwegian spatial datasets, measurements and modelling to develop its emission factors. Because only a subset of a project's perimeter is typically occupied by physical infrastructure, we represented the share of land remaining vegetated using a 'green fraction', defined as the proportion of the PV area not covered by technical installations and roads. Technical installations include both PV panels and transformer (trafo) stations. Based on the concession applications, we assumed a green fraction of 90% within panel areas, with vegetation retained beneath and between arrays and limited ground sealing. For areas occupied by transformer stations, we applied a green fraction of 25%, consistent with standard assumptions for infrastructure; this value may vary across facilities depending on design. Emission factors were selected according to soil type, distinguishing organic from mineral soils. We assumed that areas with organic soils within the developed footprint are, or will become, drained, and therefore applied emission factors for drained organic soils. While drainage effects under PV may differ from those of conventional agricultural drainage (e.g., for cultivation), we did not have sufficient evidence to parameterise alternative drainage intensities. For forested sites, we accounted for both immediate losses of on-site carbon stocks (e.g., in trees, dead wood, and other biomass) due to vegetation removal and ground levelling, and the foregone future carbon sequestration (net CO₂

uptake) that would have occurred through continued forest growth. Both components were included in our estimates of area-based emissions and removals associated with PV establishment.

The CO₂e emissions from producing electricity from PV, which is separate and adds to emissions from land cover change, was estimated to 35.8 g CO₂e/kWh using the Life Cycle Assessment (LCA) of monocrystalline Si panels prepared by the International Energy Agency (Stucki et al., 2024). The LCA evaluates emissions related to manufacturing, transport, installation, use, maintenance, and end of life practices, and its scope includes PV panels, cabling, mounting structure, inverter and system installation. PV electricity emissions were treated as assumptions and were not assigned uncertainty. The combined CO₂e emissions from a PV project were treated as the sum of the emissions from land cover change and the emissions estimated from the LCA of PV electricity (Table 3). The combined emissions of a PV project can be compared to the emissions of other sources of energy to evaluate the total carbon footprint of the project. To complement the detailed land-cover carbon accounting, we used a simplified calculation to compare the estimated emissions under planned land cover, combined with PV life-cycle emissions, against emissions from displaced electricity (Supplementary material Table S2). We evaluated two scenarios where we assumed that PV displaced a mix of existing energy sources: 1) that PV displaced electricity with the same emission intensity as the Norwegian energy mix in 2024 with 11.9 g CO₂e/kWh, and 2) that PV displaced electricity with the same emission intensity as the European energy mix in 2024 with 187.1 g CO₂e/kWh (European Environment, 2025; Norwegian Water Resources and Energy Directorate, 2026). The emission factors per kWh were converted to emission factors per km² by multiplying with the project energy yield density (Table 2). The difference between the combined emissions of a PV project and the emissions of the displaced electricity mix provided a net carbon budget per km² for the PV project.

2.2 Scenario modelling

To simulate plausible future land use change for different energy production trajectories, we modelled future land requirements for solar PV in Norway to 2050 using a Monte Carlo simulation framework that converts installed capacity (MWp) to land area (km²) and allocates land area to land-cover groups. To contrast different policy options, we developed a scenario framework combining three alternative energy production trajectories with two spatial placement strategies, resulting in six distinct energy deployment and land use policy scenarios (Table 1).

Table 1. Scenario framework for solar PV deployment in Norway (2026–2050). Combination of three installed-capacity pathways and two spatial allocation strategies, resulting in six scenarios (e.g. 1a–3c).

		Spatial allocation	
		a) Business as usual	c) Agri-PV and grey areas
		Size and placement patterns based on snapshot from current concession applications. Capacity density: sampled from the empirical distribution of proposed projects (median 80.2 MWp/km ² ; IQR 36.3; range 36.2–173.7.6; n = 77).	Equal allocation of installed capacity between agricultural land and grey areas; adjusted area demand for agri-PV (1.5). Capacity density: sampled from the same empirical distribution as BAU (n = 77). Agri-PV land demand adjusted by a co-use factor (1.5).
Installed capacity	1) Low growth	1a – Low energy growth and current placement patterns	1c Low growth within agri-PV and grey areas
	0% annual growth in capacity additions $\approx$ 1 GWp in 2050.		
	2) Intermediate growth	2a – Medium energy growth and current placement patterns	2c – Medium growth within agri-PV and grey areas
	10% annual growth in capacity additions $\approx$ 4 GWp in 2050.		
	3) High growth	3a – High energy growth and current placement patterns	3c – High growth within agri-PV and grey areas
	20% annual growth in capacity additions $\approx$ 21 GWp in 2050.		

We used three cumulative installed-capacity pathways (MWp by year): (1) Low growth (0% annual growth in new additions), (2) Intermediate growth (10% annual growth in new additions), and (3) High growth (20% annual growth in new additions). All pathways started from a cumulative installed capacity of 77 MWp in 2026. The baseline annual capacity addition was 44 MWp, corresponding to the increase between 2025 and 2026. From 2027 onwards, annual additions remained constant under low growth or increased by 10% and 20% per year under intermediate and high growth, respectively. To account for expected technology developments that will lead to higher efficiency PV modules, and consequently higher capacity densities for future projects, we have assumed efficiency improvements as projected by the International Technology Roadmap for Photovoltaics (VDMA, 2026). A shift from PERC technology (21.7% efficient modules in 2025) to TOPCon technology (23.2% efficient modules in 2025) is assumed to occur in 2026. TOPCon efficiency improvements are assumed to start at 23.2% in 2026 and end up at 24.7% efficient modules in 2035. We linearly interpolate module efficiency in the years 2027-2034, and do not assume new technology development after 2035. Similarly, we have also assumed a bifaciality factor improvement from 80% in 2025 to 85% in 2035. These technology improvements are combined into an annual technology factor that is multiplied with the capacity densities in the scenarios. Thus, the technology improvements lead to a gradually higher capacity density up to 2035, after which the density stays

constant. The median capacity density in 2035 and beyond is estimated to be 93.7 MWp/km². Scenario MWp values were treated as assumptions and were not assigned uncertainty.

For each scenario year, we converted cumulative installed capacity (MWp) to total land requirement (km²) by dividing capacity by an assumed capacity density (MWp per km²). Capacity density (MWp per km²) was treated as uncertain and, in each Monte Carlo iteration, was sampled with replacement (bootstrap sampling) from the empirical distribution observed in the NVE planning snapshot of proposed projects ($n = 77$ density estimates; median 80.2 MWp/km², IQR 36.3; range 36.3–173.7). This non-parametric approach preserves the observed variability without assuming a particular parametric distribution.

Under the business-as-usual (BAU) strategy, total land requirement was allocated across land-cover classes in proportion to the mean land-cover composition observed within current planning polygons; uncertainty in land-cover composition was represented using a Dirichlet distribution centered on the observed mean proportions. The Dirichlet parameters were $\alpha_i = 500p_i$, where p_i is the observed mean proportion of land-cover class i and 500 is a fixed, assumed concentration parameter. One land-cover composition was sampled per iteration and applied across all years and capacity pathways. Under the Agri-PV + grey area strategy, total land requirement was allocated between agricultural land and grey areas using three fixed sensitivity values (30/70, 50/50, and 70/30), with 50/50 used for the main comparison. The agricultural component was multiplied by a fixed co-use factor (1.5) to reflect higher land demand per MWp under Agri-PV designs. We did not cap the availability of grey areas in the model; instead, the model outputs the grey-area requirement, which can be compared with mapped grey-area potential in a subsequent GIS step.

We ran 5,000 Monte Carlo iterations per scenario to propagate uncertainty in capacity density and land-cover composition. Results are reported as medians and 90% intervals (5th–95th percentiles) for total land demand over time and land-cover group requirements in 2050.

2.3 Analysis of suitable land

Grey area resources > 10 were identified by filtering the Norwegian Mapping Authority's grey area dataset (Geonorge, 2025) to exclude areas ≤ 1 ha, and areas in active use, based on land-use classes, mineral concession data and a building share threshold of 25% (Supplementary material, Figure S2).

3. Results

3.1 Current planning practice

Planned project size and output varied widely and were right skewed. Median planned capacity was 24.5 MWp (IQR 38.8) and median estimated annual production was 26.0 GWh (IQR 42.1), with means consistently higher than medians, indicating a small number of very large projects (Table 2). In contrast, area-normalised metrics were more consistent across projects: median capacity density was 80.6 MWp/km² (IQR 25.4) and median energy yield density was 85.1 GWh/km² (IQR 33.1). Density metrics were available for 77 proposed projects. Agri-PV projects had slightly lower capacity density than non-Agri-PV projects: mean 67.5 MW/km² (median 63.2; SD 24.6; $n = 18$) versus 72.4 MW/km² (median 71.8; SD 20.5; $n = 30$).

Table 2. Descriptive statistics for project area, capacity, electricity production, and area-normalised metrics for planned solar facilities ($n = 77$). Values are reported as mean (SD), median (IQR), and minimum–maximum.

Variable	Unit	Mean (SD)	Median (IQR)	Min	Max
Area	Km ²	0.6 (0.8)	0.3 (0.6)	0.01	3.4
Installed capacity (DC)	MWp	44.0 (51.8)	24.5 (38.8)	1.1	264.6
Installed capacity (AC)	MW	39.7 (48.9)	21.0 (38.0)	1.8	264.6
Annual production	GWh	49.5 (60.8)	26.0 (42.11)	1.8	311.3
Capacity density	MWp/km ²	80.6 (25.4)	80.2 (36.3)	36.2	173.7
Energy yield density	GWh/km ² /year	85.1 (23.5)	84.1 (33.1)	33.2	148.4

Total area for planned PV projects was 49.2 km² ($n = 77$). Projects areas ranged from 0.01 to 3.4 km², with a median project size of 0.3 km (IQR 0.6). Across all projects, forest and woodlands dominated the mapped project footprint, accounting for 96.4% of the total area (49.2 km²). Land-cover composition varied markedly between projects: the average site was 88.0% forest (SD 24.8), suggesting that many proposals are almost entirely in forest areas while a subset occupy more mixed land-cover mosaics (Table 3).

Using land-cover-specific emission factors, the mapped project footprint corresponds to substantial differences in cumulative net CO₂e balance across land-cover groups over a 30-year horizon (Table 3). Under current land cover, forests and woodlands dominate the carbon signal because they account for nearly all mapped area; the estimated 30-year net balance for forests and woodlands is approximately –642,000 t CO₂e (net uptake), while other land-cover groups contribute comparatively little in absolute terms (Table 3). When expressing the same footprint as a conversion to built land, the 30-year balance shifts strongly towards net emissions and is dominated by current forest areas that become

artificial surfaces, with an estimated balance across land cover types at ~2,879,000 t CO₂e over 30 years. Across the full mapped footprint, the implied difference between the ‘current’ and ‘planned’ carbon trajectories over 30 years is approximately 3,518,000 t CO₂e.

Table 3. Land-cover composition and estimated CO₂e-balance within proposed solar project polygons (*n* = 77). Mean (SD) shows the average percentage cover of each land cover type across projects. Total (km²) and Share of total (%) represent the summed area and percentage of the total mapped project footprint across all projects. Negative CO₂e-values indicate net uptake, while positive values indicate net emissions.

Land cover types	Land cover composition				CO ₂ e 30-years balance	
	Mean (%)	SD (%)	Total (km ²)	Share of total (%)	Current CO ₂ e balance (tons)	Projected 30-years CO ₂ e balance (tons)
Forest and woodlands	87.0	26.4	47.4	96.4	-641,604	2,859,134
Settlements and other artificial areas	7.7	23.0	0.8	1.7	1,741	-1,054
Inland wetlands	0.5	1.5	0.4	0.8	792	20,435
Heathland and shrub	2.5	7.9	0.3	0.6	0	-408
Cropland	0.6	2.8	0.1	0.2	151	-158
Sparsely vegetated ecosystems	0.8	6.5	0.1	0.1	0	0
Grassland	0.5	3.0	0.1	0.1	-14	963
Lakes and reservoirs, rivers and canals	0.4	3.3	0.0	0.1	-0	48
Sum	100	NA	49.2	100	-638,934	2,878,960

3.2 Net greenhouse gas effects

When emissions from land-use change were combined with life-cycle emissions from PV components, installation, operation and decommissioning, the estimated carbon footprint was approximately 4,997 t CO₂e km⁻² yr⁻¹, or 149,913 t CO₂e km⁻² over an assumed 30-year project lifetime (Table S2). The resulting net carbon balance depended strongly on the electricity source assumed to be displaced. Relative to the EU-27 electricity mix, PV reduced emissions over its lifetime, whereas relative to the low-carbon Norwegian electricity mix, the combined emissions from land-use change and the PV system exceeded the avoided electricity-sector emissions. These estimates should be interpreted as contrasting displacement scenarios rather than predictions of the realised carbon balance of individual projects.

Planned multifunctionality (i.e., several co-existing land-uses within the PV area) was common but inconsistently specified. Among projects with available information (*n* = 70), 34 (48.6%) proposed sheep grazing within the PV area. Agri-PV classification was recorded for fewer projects; among those

with available coding, 18 (38.3%) were classified as Agri-PV and 29 (61.7%) as conventional PV, although the descriptions in project applications were often ambiguous. Projects located largely in already heavily modified ecosystems were uncommon, reported for 10 of 76 projects with available data (13.2%).

3.3 Scenario modelling (2024–2050)

Projected land demand increased strongly with the capacity trajectory and was sensitive to the assumed placement strategy (Figure 2; Table S3). Under business-as-usual (BAU) allocation based on observed land use allocation from 2026, median total PV area demand in 2030 was 3.3 km² (90%: 2.2–6.0) under low growth, 3.9 km² (2.7–7.1) under medium growth, and 4.7 km² (3.2–8.5) under high growth. By 2050, median total area increased to 14.6 km² (10.0–26.7), 56.3 km² (38.6–102.7), and 268.4 km² (184.2–489.2) for low, medium, and high growth, respectively. Uncertainty intervals widened over time because land demand scales directly with capacity density (MWp per km²), which was treated as uncertain.

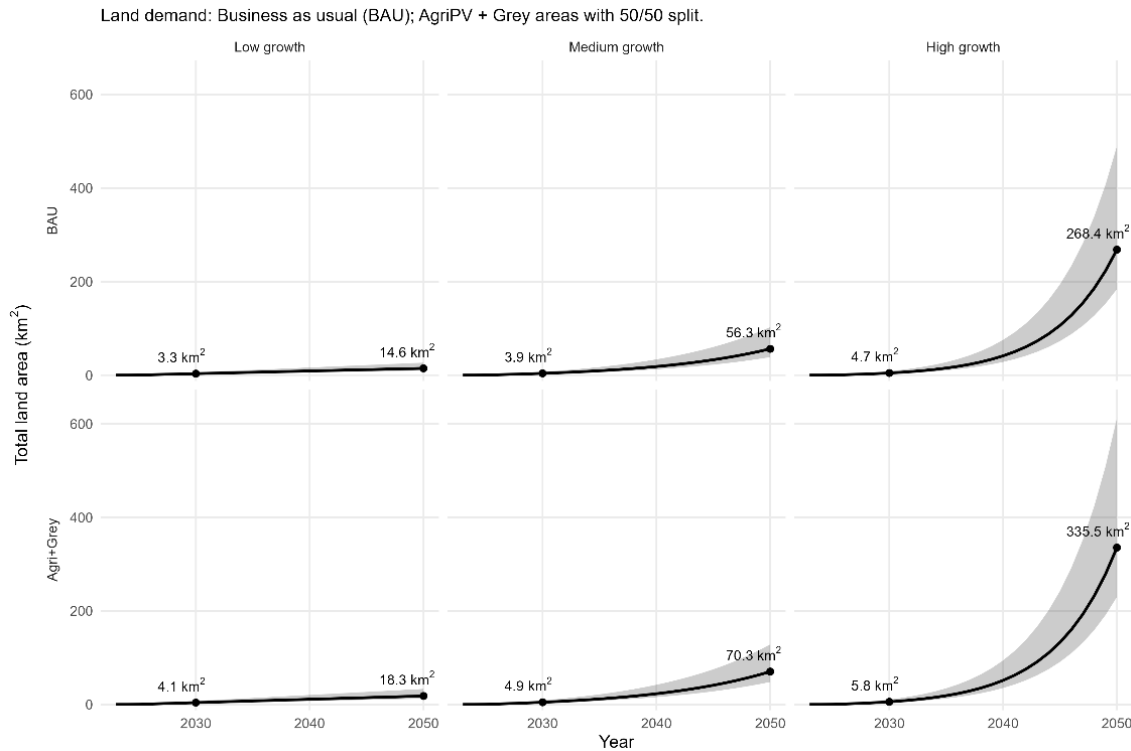
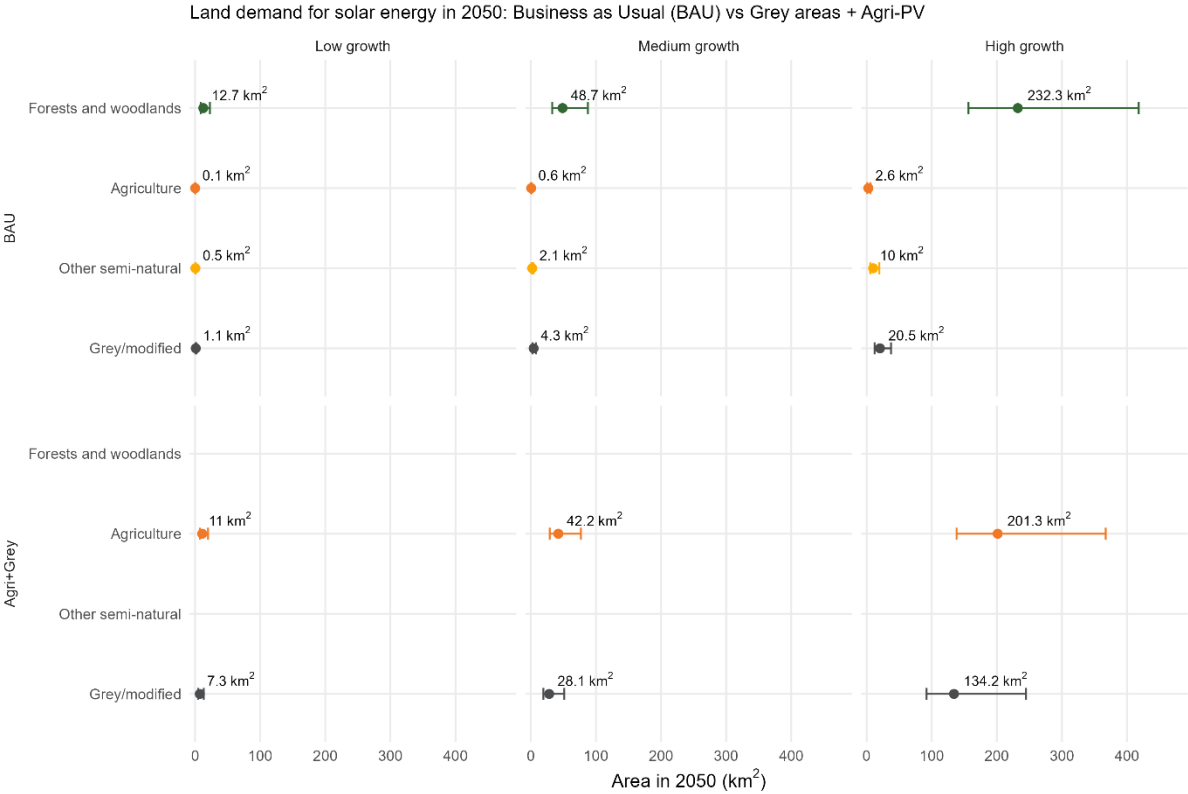


Figure 2: Projected total land demand for ground-mounted solar PV (2024–2050) under three capacity trajectories and two allocation strategies. Lines show the median total land area required (km²) across 5,000 Monte Carlo iterations; shaded ribbons show the 90% interval (5th–95th percentiles) reflecting uncertainty in capacity density (MWp/km²). The BAU strategy allocates land demand according to the observed land-cover composition of current concession applications. The Agri-PV + grey strategy assumes a 50/50 split between agriculture and grey areas and applies a fixed land-demand multiplier of 1.5 for Agri-PV.

The two policy-dependent allocation strategies produced contrasting land-cover requirements (Figure 3). Under the BAU strategy, most projected land demand occurred in forests and woodlands, reflecting the observed land-cover composition of current concession applications. In 2050, the median forest area required was 12.7 km² (8.5–22.8) under Low growth, 48.7 km² (32.8–87.6) under Medium growth, and 232.3 km² (156.6–418.1) under High growth, while other land-cover groups contributed comparatively little.

Under the Agri-PV + grey area strategy (50/50 split), land demand was instead allocated to agricultural land (cropland and grassland) and grey areas (settlements and other artificial areas) by construction, with no allocation to forests. By 2050, the median agricultural area required was 11.0 km² (7.5–20.0) under Low growth, 42.2 km² (29.0–77.0) under Medium growth, and 201.3 km² (138.1–367.3) under High growth (Table S3). The corresponding median grey-area requirements were 7.3 km² (5.0–13.3), 28.1 km² (19.3–51.3), and 134.2 km² (92.1–244.9).

Because Agri-PV was assumed to require more land per unit of installed capacity (co-use factor 1.5), the total land requirement under the Agri+Grey strategy (50/50 split) was consistently higher than under BAU for the same capacity pathway (approximately 25% higher total area).



317

318

319

320

321

322

323

324

325

326

327

328

329

330

331

332

333

334

335

Figure 3. Land-cover group requirements in 2050 under BAU and Agri-PV + grey allocation strategies. Points show the median land area (km²) allocated to each land-cover group in 2050; horizontal bars show the 90% interval (5th–95th percentiles) across 5,000 Monte Carlo iterations. Under BAU, land demand follows the land-cover composition of current concession applications. Under Agri-PV + grey (50/50 split), land demand is allocated to agriculture (cropland + grassland) and grey areas (settlements and other artificial areas), with no allocation to forests. In BAU, rare classes in the 2026 footprint (wetlands, heathland, water) contribute little and are not shown separately in the table. Note that land demand refer to areas within the perimeter of the PV plant; direct physical conversion will vary across facilities.

If future solar development is redirected away from forests and towards agricultural and grey areas, the required area can be quantified from the scenario results. Under the main scenario (50/50 Agri–Grey), median total land demand ranged from 18.3–335.5 km² in 2050 across growth pathways. Of this, 11.0–201.3 km² in 2050 would occur on agricultural land, and 7.3–134.2 km² in 2050 on grey areas (Table S3). Because Agri-PV was assumed to require more land per unit of installed capacity (co-use factor 1.5), the total land requirement under the Agri+Grey strategy (50/50 split) was consistently higher than under BAU for the same capacity pathway (approximately 25% higher total area).

3.4 Grey area analysis

We allocated 318 km² of grey area resources larger than 1 ha with transformation or densification potential in Norway, of which 264 km² were located in Mid- and Southern Norway, where solar energy is most relevant (numbers in parentheses hereafter). Mean and median size of grey area resources in Mid- and South Norway were 3.5 and 1.9 ha respectively. Of these grey area resources, 42% were located in industrial areas, 21% were areas for mineral extraction, 19% were ‘unclassified built-up areas’, while the remaining 18 % were distributed across eleven built-up land use types.

4. Discussion

4.1 Land requirements from ground mounted PV in future Norwegian energy and land systems

Ground-mounted photovoltaic development is emerging as a distinct land use in cool-temperate and boreal land systems. Norway provides a useful case for quantifying this footprint because ground-mounted PV is at an early stage of deployment, while substantial expansion is being considered. In this study we estimate key measures of land-use efficiency based on 77 current and pipeline projects, and project national land requirements to 2050 under contrasting deployment scenarios. The projects have a median capacity density of approximately 80 MWp/km² and an energy yield density of 84 GWh/km²/year, slightly above previously published early Norwegian estimates based on a small sample ($n = 7$; 80.1 GWh/km²/year; Kenawi et al., 2025). Our energy density estimates are in the upper range of, or above, previously published international density estimates (87 GWh/km²/year; Nøland et al., 2022; 35–79 GWh/km²/year; Smil, 2015; 51 GWh/km²/year; van Zalk & Behrens, 2018). Since the benchmarks from our study are based primarily on planned rather than operational projects, they should therefore be continuously validated against realised projects as measurements are carried out. Regardless of the uncertainty, the estimates provide practical benchmarks for early-stage land-use and energy planning. As a rule of thumb, current project designs require approximately:

- 0.0125 km² (12.5 decares) per MWp installed capacity
- 0.0119 km² (11.9 decares) per GWh of annual electricity production, equivalent to approximately 11.9 km² per TWh

For Agri-PV, the area units may be multiplied by the assumed co-use factor of 1.5, to allow wider spacing for continued agricultural use. Reduced shading at wider spacing may slightly increase electricity yield per unit of installed capacity, but this effect is not included given the approximate nature of these estimates.

Our scenarios represent different roles of ground-mounted PV in the national energy system, ranging from approximately 1 to 21 GWp of ground-mounted PV by 2050. They should be interpreted as

contrasting land-demand pathways rather than projections of Norway's national solar target, which includes building-mounted systems. For context, the national ambition of 8 TWh solar energy (~10 GW installed capacity) by 2030 is substantially larger than our scenarios at that date (NVE, 2024). Across these pathways, the relative importance of PV as a driver of land-use change varies considerably. At the national scale, the land required for ground-mounted PV would remain relatively limited under low and medium growth scenarios but could become a substantial part of annual land-use change under high growth scenarios. In our scenarios, median cumulative PV area reaches a total of ~15 km² (low), ~56 km² (medium), and ~268 km² (high) by 2050. Maximum cumulative PV area in 2050 is equal to ~0.1% of Norway's total land area. Norway's annual land take, the conversion of non-built land to artificial surfaces, has been estimated at 35 km² per year in the period between 2017 and 2023 (Venter et al., 2026). Annualised over the years 2024–2050, our scenarios imply PV land demands equivalent to approximately 2%, 6%, and 30% of Norway's annual land take under low, medium, and high growth scenarios, respectively. Ground-mounted PV would therefore remain a relatively minor component of national land take under low and medium growth scenarios but could become a substantial additional driver under high growth. For comparison, solar PV has been projected to occupy roughly 0.5–2.8% of EU territory and 0.7–1.5% of global land area (Saxena et al., 2024; van de Ven et al., 2021). Yet, impacts on ecosystems and land systems will depend on location, as it is a well-established fact from land system science that some land uses with a small spatial extent can have large widespread impacts far larger than their own relatively small land footprint (Meyfroidt et al., 2022). Ground-mounted PV may account for only a small share of total land-cover change, but may still create substantial pressures in specific areas or land-cover types (Diffendorfer et al., 2024). Moreover, land requirement estimates should be interpreted cautiously, since PV development may or may not be counted as 'land take' depending on siting in natural or heavily modified land cover types as well as degree of ground levelling and soil sealing in PV areas, co-use with other land uses and mitigation measures applied to improve biodiversity.

4.2 Siting strategies and co-use determines ecosystem and carbon emission impacts

Despite PV being a flexible and scalable technology, current siting strategies show limited diversity as 97 % of the current and proposed project area lies in forest and woodlands. Net emissions from solar PV in forest areas reflect both carbon released by land-use change and lost potential uptake. Since productive forests have the highest annual net CO₂ uptake across Norwegian ecosystems (de Wit et al., 2015), continuing the current siting strategy will reduce the potential of solar PV as a low-carbon energy source relative to alternative land use policies for solar PV. The net climate impacts from PV-projects during their lifetime, will depend on 1) carbon dynamics from land use and land cover changes, 2) PV life cycle emissions related to production, operation, maintenance and

decommissioning of the PV facilities; and 3) emissions from displaced energy. Whether solar PV in Norway will contribute to a net increase or reduction of emissions will depend on the electricity it replaces. Our results indicate that, under current siting strategies, ground-mounted solar energy in Norway will become a net source of greenhouse-gas emissions when land-use and land-cover changes are accounted for, if PV displaces electricity with the same emission intensity as the current Norwegian, largely renewable energy mix. If PV displaces electricity with the same emission intensity as the European energy mix, the results will be a net reduction in greenhouse gas emissions, even when land use and land cover change is included in the calculations. In forests, lower-impact designs that retain soil and ground vegetation (ecovoltaics) may reduce this net emission effect, but their contribution remains uncertain and needs further investigation.

Redirecting ground-mounted PV from forests to agricultural and heavily modified land can reduce emissions and increase the opportunities for mitigation measures for biodiversity. Under high growth, the required areas correspond to less than 2 % of Norway's agricultural land and less than 3 % of the developed area (Statistics Norway, 2026). However, these aggregate figures do not indicate how much land is locally available or technically suitable, particularly when project economy, grid access and competing land uses are considered.

Agri-PV generally requires larger areas and can compete with food production but also allows continued agricultural use. The feasibility of Agri-PV is dependent on crop choice, PV design choice, and climate. In Norway, the solar resource is limited, and PV designs should allow sufficient light to the ground while the choice of crops should prioritize shade-tolerant plants. If both aspects are considered, the crop yield can even increase (Honningdalsnes et al., 2025). Honningdalsnes et al. modelled the impact of vertically mounted PV on the yield of timothy (*Phleum pratense* L.), Norway's most important cultivated forage grass for livestock production. They found that beneficial wind sheltering can counteract detrimental PV panel shading indicating that sustained agricultural activity is possible inside ground-mounted PV in Norway. Consequently, vertical Agri-PV can fulfil the capacity requirements under the high growth scenario by utilizing 7% of the current land where timothy is grown (area estimates based on Sturite et al., 2024). Abandoned or underused agricultural land may provide additional opportunities, but cannot automatically be considered available for solar PV, also co-use and nature restoration potential must always be considered site by site.

Grey areas are previously developed or heavily modified areas where current use is below their potential, including brownfields and low-intensity built-up land (Jacek et al., 2022). Solar PV on grey areas represents an underexplored resource for development, reuse and restoration. Such sites can contribute to more land-efficient energy deployment, particularly where projects also improve ecological connectivity and local environmental quality. Previous work estimated a technical potential of 5.7 TWh on about 70 km² of grey areas, of which only 0.8 TWh was estimated to be economically

viable under the report's assumptions (Sunde et al., 2024). Our GIS-analyses identified 264 km² of continuous grey areas larger than 1 ha with transformation potential in Mid- and southern Norway. This represents a mapped potential land resource rather than a realistic estimate of solar PV potential, as we did not assess land tenure, redevelopment costs, solar irradiation, grid capacity or competing land uses within the identified grey areas with transformation potential. Our scenarios indicate that placing half of the installed capacity in grey areas would require 7, 28 and 134 km² by 2050 under the low growth (1 GWp), medium growth (4 GWp) and high growth (21 GWp) pathways in 2050 respectively. These requirements correspond to 3%, 11% and 51% of the available mapped grey area resources. Realising this potential will require active incentives and land use policies to address site-specific barriers related to land ownership, redevelopment costs and competing land uses. A detailed spatial multi-criteria inventory is therefore needed to identify available grey areas which are also technically suitable and profitable.

4.3 Design choices and mitigation measures

Regardless of siting and co-use strategy, the area requirements identified in this study underline the need to apply the mitigation hierarchy to avoid, minimise, restore and offset negative impacts on land systems and their services (Arlidge et al., 2018). Environmental impact assessments and project-level ecosystem accounting can support this by providing consistent information on ecosystem extent, condition, carbon storage and competing ecosystem services for alternative siting options (Czucz et al., 2025). Low-disturbance forest installations that minimise grading, drainage and soil removal and retain ground vegetation can reduce soil disturbance and carbon losses compared with full-conversion designs. By contrast, projects that involve substantial levelling, drainage or soil replacement can increase emissions, especially on organic soils where changes in hydrology strongly affect greenhouse-gas fluxes. Mitigation measures designed to reduce the degree of physical alterations from PV installation are key to minimise environmental impacts in semi-natural and natural ecosystems (Lafitte et al., 2023). Measures to re-establish vegetation in disturbed areas are routinely carried in energy production projects to reduce negative impacts on biodiversity, but goals of mitigation measures in Norwegian development projects have often been unclear (Mehlhoop et al., 2022). Defining a realistic and achievable target vegetation for each solar PV project in relation to desired land use (and co-use), adjacent vegetation type and successional stage will be key for successful biodiversity measures.

Design and management choices are particularly important for co-use concepts such as Agri-PV and low-disturbance forest installations. Agri-PV offers both potential and clear trade-offs (Hobrak et al.; Honningdalsnes et al., 2025). PV installations invariably occupy part of the land, precluding harvesting directly underneath the mounting structures. They also introduce shading and

wind sheltering, leading to altered soil and growth conditions, but can offer benefits by increasing biotope connectivity across the agricultural field and by protecting crops from hail, sunburn, or untimely frost. Overall, its agricultural performance depends strongly on system design, site conditions and adaptation to local farming practices (Scholten et al., 2026). Currently, projects labelled as Agri-PV range from minor adaptations such as seasonal sheep grazing under arrays to systems specifically designed to maintain productive agriculture, with higher panel clearance, wider row spacing, different foundations and tailored management. These variants differ both in capacity density (MWp per km²), in how much of the site is effectively converted to infrastructure, and in yield or performance for the relevant co-use, including biodiversity (Trommsdorff et al., 2025).

4.4 Limitations and further research needs

Key uncertainties in this study arise because Norwegian ground-mounted PV is still an emerging land use, meaning that many inputs are derived from concession applications and generic assumptions rather than post-construction measurements. Mapped project polygons represent the perimeter of planned facilities, whereas direct physical conversion depends on detailed layout and construction practices (e.g., road density, degree of ground levelling, foundation type, drainage interventions, and whether vegetation and soils are maintained under and between arrays). Net carbon outcomes depend on both land-use change and the electricity assumed to be displaced. This displacement is uncertain in an interconnected and decarbonising European power system. Comparison with the low-carbon Norwegian mix may understate the decarbonisation potential of PV, whereas applying the European average might overstate its potential. These estimates should therefore be interpreted as contrasting scenarios rather than precise predictions of net project emissions. All scenarios and results should therefore be interpreted as plausible, exploratory planning-relevant futures rather than predictions.

In 2026, empirical evidence on the land-system effects of PV in cool temperate and northern boreal environments remains limited. To support evidence-based planning and reduce reliance on findings and evidence from dissimilar ecosystems, PV expansion should be accompanied by systematic research on land use and ecosystem impacts under boreal conditions. From landscape-ecology and land-system science perspectives, priorities are to: (1) establish empirical baselines for realised capacity and energy-yield densities and effects on land use, ecosystem structure and functioning, including carbon storage and sequestration; (2) quantify how site design affects co-use performance and biodiversity; and (3) develop spatial planning tools that reveal landscape-scale trade-offs among deployment strategies, including the suitability and transformation potential of grey areas. Such evidence would support spatially explicit and empirically grounded scenarios.

5. Conclusion

Ground-mounted PV is emerging as a new type of land-use in cool-temperate and boreal land systems. Solar PV is a flexible and scalable energy production technology, with a range of potential siting options, allowing different land use policies for upscaling. This study provides an early empirical basis for assessing its land requirements and alternative siting strategies in Norway. We find that current and planned projects are strongly concentrated in forests and woodlands. Continuing this pattern can diminish the climate benefits of solar PV, since forest conversion releases stored carbon and reduces future sequestration. Climate outcomes therefore depend on both siting strategies and the electricity displaced. Our simplified comparison including PV life-cycle emissions indicated a net emissions increase relative to displacement of electricity with the emission intensity of the current Norwegian mix, but a reduction relative to the EU-27 mix.

We recommend a more diverse siting strategy, with an increasing share of ground-mounted PV on heavily modified land (grey areas) and within agricultural areas suitable for co-use, alongside suitable forest sites. A shift towards agricultural and grey areas would require slightly larger total area but could reduce emissions from land-use and land-cover change, reduce biodiversity impacts enable co-use and create opportunities for biodiversity mitigation measures.

Further deployment of solar PV should be accompanied by monitoring of energy production, land-cover change, carbon dynamics, co-use performance and ecosystem condition. Regularly updating land-use policies with evidence from monitoring, experiments and supported by refined scenarios would enable knowledge-based land use planning for solar PV development as the sector develops in northern regions.

Declaration of generative AI use

The authors used SIKT KI, a Norwegian-developed artificial intelligence service for the university and knowledge sector during manuscript preparation for language editing language refinement. The authors also used Posit Assistant (RStudio), version: 1.4.1 to support coding and analysis in R. The authors take full responsibility for the content of the manuscript.

6. References

- Arlidge, W. N. S., Bull, J. W., Addison, P. F. E., Burgass, M. J., Gianuca, D., Gorham, T. M., Jacob, C., Shumway, N., Sinclair, S. P., Watson, J. E. M., Wilcox, C., & Milner-Gulland, E. J. (2018). A Global Mitigation Hierarchy for Nature Conservation. *BioScience*, 68(5), 336–347. <https://doi.org/10.1093/biosci/biy029>
- Borgelt, J., Gilad, D., May, R., & Veronesi, F. (2026). Renewable energy growth amplifies land pressure on Norwegian biodiversity. *Cleaner Energy Systems*, 13, 100238. <https://doi.org/10.1016/j.cles.2026.100238>
- Czucz, B., Simensen, T., Skrindo, A. B., Rusch, G. M., Nybø, S., Grainger, M., & Töpper, J. P. (2025). No net loss accounting: Aligning biodiversity offsets with ecosystem accounts. *Ecological Solutions and Evidence*, 6(1), e70006. <https://doi.org/10.1002/2688-8319.70006>
- de Wit, H. A., Austnes, K., Hylen, G., & Dalsgaard, L. (2015). A carbon balance of Norway: terrestrial and aquatic carbon fluxes. *Biogeochemistry*, 123(1), 147–173. <https://doi.org/10.1007/s10533-014-0060-5>
- Diffendorfer, J. E., Sergi, B., Lopez, A., Williams, T., Gleason, M., Ancona, Z., & Cole, W. (2024). The interplay of future solar energy, land cover change, and their projected impacts on natural lands and croplands in the US. *Science of the Total Environment*, 947, 173872. <https://doi.org/10.1016/j.scitotenv.2024.173872>
- European Environment Agency. (2025). Greenhouse gas emission intensity of electricity generation in Europe. *EEA Indicators*. <https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1>
- Eurostat. (2026). EU ecosystem typology (July 2026 version) [Technical note]. European Commission. <https://ec.europa.eu/eurostat/documents/d/environment/eu-ecosystem-typology-2026>
- Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S., & Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, 29, 766–779. <https://doi.org/10.1016/j.rser.2013.08.041>
- Hernandez, R. R., Hoffacker, M. K., Murphy-Mariscal, M. L., Wu, G. C., & Allen, M. F. (2015). Solar energy development impacts on land cover change and protected areas. *Proceedings of the National Academy of Sciences*, 112(44), 13579–13584. <https://doi.org/10.1073/pnas.1517656112>
- Hobrak, K. T., Hjelkrem, A.-G. R., Bakken, A. K., Borchsenius, B., Mathiesen, H. F., Mohr, C. W., Søgaard, G., & Frydenlund, J. (2024). *Solkraftverk på jord- og skogareal* [Solar power plants on agricultural and forest land] NIBIO Report 10(9). <https://hdl.handle.net/11250/3115161>

- Honningdalsnes, E. H., Marstein, E. S., Lindholm, D., Bonesmo, H., & Riise, H. N. (2025). Wind sheltering in vertical agrivoltaics can increase crop yields: A modeling study for Northern Europe. *Energy Nexus*, 19, 100516. <https://doi.org/10.1016/j.nexus.2025.100516>
- IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Institute for Global Environmental Strategies (IGES). <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>
- IPCC. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change (IPCC). <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>
- Jacek, G., Rozan, A., Desrousseaux, M., & Combroux, I. (2022). Brownfields over the years: from definition to sustainable reuse. *Environmental Reviews*, 30(1), 50–60. <https://doi.org/10.1139/er-2021-0017>
- Johnson, J. A., Kennedy, C. M., Oakleaf, J. R., Baruch-Mordo, S., Polasky, S., & Kiesecker, J. (2021). Energy matters: Mitigating the impacts of future land expansion will require managing energy and extractive footprints. *Ecological Economics*, 187, 107106. <https://doi.org/10.1016/j.ecolecon.2021.107106>
- Kenawi, M. S., Hedger, R. D., Alfredsen, K. T., Sandercock, B. K., Korpås, M., & Bakken, T. H. (2025). Land efficiency of renewable energy in Norway: A synthesis of footprint and production density. *Renewable Energy*, 252, 123514. <https://doi.org/10.1016/j.renene.2025.123514>
- Lafitte, A., Sordello, R., Ouédraogo, D.-Y., Thierry, C., Marx, G., Froidevaux, J., Schatz, B., Kerbiriou, C., Gourdain, P., & Reyjol, Y. (2023). Existing evidence on the effects of photovoltaic panels on biodiversity: a systematic map with critical appraisal of study validity. *Environmental Evidence*, 12(1), 25. <https://doi.org/10.1186/s13750-023-00318-x>
- Mathiesen, H. F., Bjørkelo, K., Hobrak, K. T., Mohr, C. W., Frydenlund, J., Lillesund, V. F., Sætershagen, B., & Verne, I. K. (2026). *Kartbasert klimagasskalkulator for arealbrukssektoren - Beregningsmetoder og datagrunnlag* [Map-based greenhouse gas calculator for the land-use sector: Calculation methods and underlying data] NIBIO Report 12(10). <https://doi.org/10.21350/1mv8-d695>
- Mehlhoop, A. C., Skringo, A. B., Evju, M., & Hagen, D. (2022). Best practice—Is natural revegetation sufficient to achieve mitigation goals in road construction? *Applied Vegetation Science*, 25(3), e12673. <https://doi.org/10.1111/avsc.12673>
- Ministry of Climate and Environment. (2024). *Bærekraftig bruk og bevaring av natur: Norsk handlingsplan for naturmangfold* [Sustainable use and conservation of nature: Norway's national biodiversity action plan] (Meld. St. 35 (2023–2024)). <https://www.regjeringen.no/contentassets/c8122f7641734da2b892738b796d4725/no/pdfs/stm202320240035000dddpdfs.pdf>

- Meyfroidt, P., de Bremond, A., Ryan, C. M., Archer, E., Aspinall, R., Chhabra, A., Camara, G., Corbera, E., DeFries, R., Díaz, S., Dong, J., Ellis, E. C., Erb, K.-H., Fisher, J. A., Garrett, R. D., Golubiewski, N. E., Grau, H. R., Grove, J. M., Haberl, H., ... zu Ermgassen, E. K. H. J. (2022). Ten facts about land systems for sustainability. *Proceedings of the National Academy of Sciences*, 119(7), e2109217118. <https://doi.org/10.1073/pnas.2109217118>
- Norwegian Environment Agency. (2025). *Kart over grå arealer* [Map of grey areas] [Data set]. <https://kartkatalog.geonorge.no/metadata/kart-over-graa-arealer/c5f09d79-1546-495c-8b36-91efd4008bd7>
- Norwegian Water Resources and Energy Directorate. (2024). *NVEs svar på oppdrag om solkraft og annen lokal energiproduksjon* [NVE's response to the commission on solar power and other local energy production] (NVE-reference 202311163-63). <https://www.nve.no/media/16752/notatet-nves-svar-paa-oppdrag-om-solkraft-og-annen-lokal-energiproduksjon.pdf>
- Norwegian Water Resources and Energy Directorate. (2025). *Langsiktig kraftmarkedsanalyse 2025: Energiomstilling i urolige tider* [Long-term power market analysis 2025: Energy transition in turbulent times] (NVE Report 15/2025). https://publikasjoner.nve.no/rapport/2025/rapport2025_15.pdf
- Norwegian Water Resources and Energy Directorate. (2026). Strømdeklarasjoner [Electricity declarations]. <https://www.nve.no/energi/energisystem/energibruk/stroemdeklarasjoner/>
- NOU 2023:3 (2023). *Mer av alt – raskere. Energikommisjonens rapport*. [More of everything—faster: Report of the Energy Commission]. Ministry of Petroleum and Energy. <https://www.regjeringen.no/no/dokumenter/nou-2023-3/id2961311/>
- Nøland, J. K., Auxepaules, J., Rousset, A., Perney, B., & Falletti, G. (2022). Spatial energy density of large-scale electricity generation from power sources worldwide. *Scientific Reports*, 12(1), 21280. <https://doi.org/10.1038/s41598-022-25341-9>
- Palmer-Wilson, K., Donald, J., Robertson, B., Lyseng, B., Keller, V., Fowler, M., Wade, C., Scholtysik, S., Wild, P., & Rowe, A. (2019). Impact of land requirements on electricity system decarbonisation pathways. *Energy Policy*, 129, 193–205. <https://doi.org/10.1016/j.enpol.2019.01.071>
- Saxena, A., Brown, C., Arneth, A., & Rounsevell, M. (2024). Advanced photovoltaic technology can reduce land requirements and climate impact on energy generation. *Communications Earth & Environment*, 5(1), 586. <https://doi.org/10.1038/s43247-024-01754-4>
- Scholten, L., de Goede, R. G. M., Edlinger, A., Van Aken, B. B., & De Deyn, G. B. (2026). Sharing the light, impact of solar parks on plant productivity, soil microbes and soil organic matter. *Plants, People, Planet*, 8(3), 1000–1013. <https://doi.org/10.1002/ppp3.70011>

- Schwarz, R., & Ziv, Y. (2025). Shedding light on biodiversity: reviewing existing knowledge and exploring hypothesised impacts of agrophotovoltaics. *Biological Reviews*, 100(2), 855–870. <https://doi.org/10.1111/brv.13165>
- Smil, V. (2015). *Power density: a key to understanding energy sources and uses*. MIT Press.
- Statistics Norway. (2026). *Land use and land cover* [Data set] <https://www.ssb.no/en/statbank1/table/09594>
- Stucki, M., Götz, M., de Wild-Scholten, M., & Frischknecht, R. (2024). *Environmental Life Cycle Assessment of Electricity from PV Systems: 2023 Data Update* (IEA PVPS Task 12 Fact Sheet). International Energy Agency Photovoltaic Power Systems Programme. <https://iea-pvps.org/wp-content/uploads/2024/05/Task-12-Fact-Sheet-v2-1.pdf>
- Sturite, I., Lunnan, T., & Østrem, L. (2024). Species dynamics in forage seed mixtures exposed to different lengths of growing season. *Grass and Forage Science*, 79(4), 619–629. <https://doi.org/10.1111/gfs.12692>
- Sunde, S., Hansen, T. D., Flesjø, J., Kanestrøm, M. K., Evensen, T., & Amwoka, E. (2024). *Solkraftpotensial på nedbygde arealer i Norge*. https://www.fornybarnorge.no/contentassets/5464eb5b7e80443e81cd156cb4c0fbc4/solkraftpotensial-pa-nedbygde-arealer-i-norge_final.pdf
- Trommsdorff, M., Campana, P. E., Macknick, J., Fernandez Solas, A., Gorjian, S., & Tsanakas, I. (2025). *Dual land use for agriculture and solar power production: overview and performance of agrivoltaic systems*. International Energy Agency Report IEA-PVPS T13-29:2025 [Dual Land Use for Agriculture and Solar Power Production: Overview and Performance of Agrivoltaic Systems - IEA-PVPS](https://www.iea-pvps.org/publications/2025/02/13/Dual-Land-Use-for-Agriculture-and-Solar-Power-Production-Overview-and-Performance-of-Agrivoltaic-Systems-IEA-PVPS)
- Turney, D., & Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. *Renewable and Sustainable Energy Reviews*, 15(6), 3261–3270. <https://doi.org/10.1016/j.rser.2011.04.023>
- van de Ven, D.-J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021). The potential land requirements and related land use change emissions of solar energy. *Scientific Reports*, 11(1), 2907. <https://doi.org/10.1038/s41598-021-82042-5>
- van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, 123, 83–91. <https://doi.org/10.1016/j.enpol.2018.08.023>
- VDMA. (2026). International Technology Roadmap for Photovoltaics (ITRPV). Results. [ITRPV: Seventeenth Edition Results - vdma.eu - VDMA](https://www.vdma.eu/energy/energy-technology-roadmap-for-photovoltaics)
- Venter, Z. S., Czúcz, B., Kumano-Ensby, A. L., Salzenstein, L., Simensen, T., Solvang, R., & Støstad, M. N. (2026). Europe's land take and the loss of nature and cropland to artificial surfaces. *Nature Communications*, 17(1), 5122. <https://doi.org/10.1038/s41467-026-71931-w>

- Wu, G. C., Jones, R. A., Leslie, E., Williams, J. H., Pascale, A., Brand, E., Parker, S. S., Cohen, B. S., Fargione, J. E., Souder, J., Batres, M., Gleason, M. G., Schindel, M. H., & Stanley, C. K. (2023). Minimizing habitat conflicts in meeting net-zero energy targets in the western United States. *Proceedings of the National Academy of Sciences*, 120(4), e2204098120. <https://doi.org/10.1073/pnas.2204098120>
- Zainali, S., Lu, S. M., Fernández-Solas, Á., Cruz-Escabias, A., Fernández, E. F., Zidane, T. E. K., Honningdalsnes, E. H., Nygård, M. M., Leloux, J., Berwind, M., Trommsdorff, M., Amaducci, S., Gorjian, S., & Campana, P. E. (2025). Modelling, simulation, and optimisation of agrivoltaic systems: a comprehensive review. *Applied Energy*, 386, 125558. <https://doi.org/10.1016/j.apenergy.2025.125558>

Supplementary material

Potential impacts of Ground-mounted photovoltaic panels on ecosystems and carbon storage in Norway - a scenario analysis

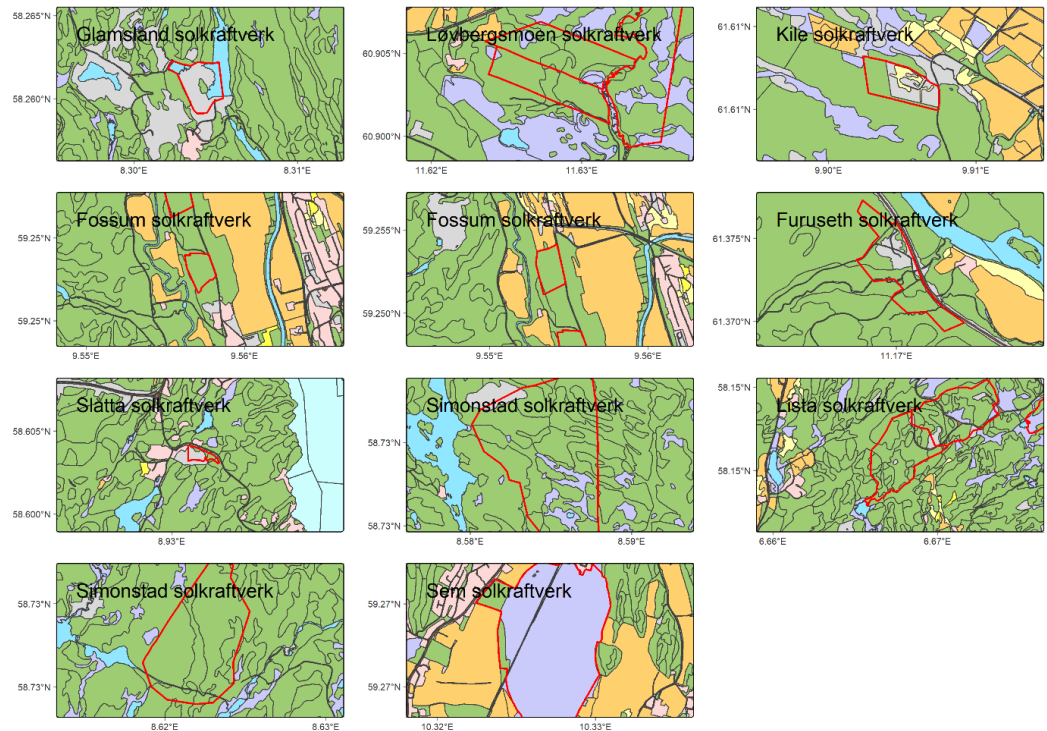


Figure S1. A sample of planned solar facilities proposed solar facilities downloaded from The Norwegian Water Resources and Energy Directorate (NVE), January 2026.

Table S1. Carbon emissions in 5, 20 and 75 years given the current land cover as calculated with the tool Klimagasskalkulator.

Land cover	Emission after 5 years	Emission after 20 years	Emission after 75 years
Forest and woodlands	-106,935	-427,736	-1,604,014
Settlements and other artificial areas	287	1,161	4,350
Inland wetlands	131	528	1,980
Heathland and shrub	0	0	0
Cropland	27	101	377
Sparsely vegetated ecosystems	0	0	0
Grassland	-1	-8	-38
Lakes and reservoirs, rivers and canals	0	0	-1
Sum	-106,491	-425,954	-1,597,346

Table S2. Assumptions, intermediate calculations and outputs of a simplified carbon calculator used to estimate annual and lifetime net carbon emissions from the ground-mounted photovoltaic projects. The calculator uses a predefined yield density, while the emission intensity associated with land-use change is the one obtained by using the klimagasskalkulator tool, with site-specific values. Lifetime net carbon emissions are reported based on both the EU-27 and Norwegian electricity mixes.

Assumptions	Value	unit
Total area of considered concessions	49.2	km ²
Total emissions from landuse over 30 years*	2,878,960	tons
Emission per kWh from land use change*	22.9	g CO ₂ e/kWh
Emission per kWh from component production, installation, operation and decommissioning	35.8	g CO ₂ e/kWh
Energy yield density	85,100,000	kWh/km ² /yr
Emission factor EU-27	187.1	g CO ₂ e/kWh
Emission factor NOR	11.9	g CO ₂ e/kWh
PV project lifetime	30	yr
Annual emissions (carbon footprint) per km ²		
Land use change	1,951	tons CO ₂ e/km ² /yr
Materials	3,047	tons CO ₂ e/km ² /yr
Total emission	4,997	tons CO ₂ e/km ² /yr
Lifetime emissions (carbon footprint) per km ²		
Land use change *	58,515	tons CO ₂ e/km ²
Materials	91,397	tons CO ₂ e/km ²
Total emission	149,913	tons CO ₂ e/km ²
Annual displaced electricity emission per km ²		
European electricity mix	15,922	tons CO ₂ e/km ² /yr
Norwegian electricity mix	1,013	tons CO ₂ e/km ² /yr
Lifetime displaced electricity emission per km ²		
European electricity mix	477,666	tons CO ₂ e/km ²
Norwegian electricity mix	30,381	tons CO ₂ e/km ²
Annual net carbon emissions		
European electricity mix	-10,925	tons CO ₂ e/km ² /yr
Norwegian electricity mix	3,984	tons CO ₂ e/km ² /yr
Lifetime net carbon emissions in tons		
European electricity mix	-327,753	tons CO ₂ e/km ²
Norwegian electricity mix	119,532	tons CO ₂ e/km ²

*: these values are site specific, and therefore base on the considered concessions.

Detailed method grey areas

The analysis was based on Kartverket's GraastrukturFlate dataset, representing land substantially altered by human activity. Areas considered to be in active or intensive use were removed based on land-use classes (including residential, agricultural, public services, green areas and transport infrastructure) and a building share threshold of maximum 25%. The resulting dataset represents potentially underutilised grey areas, and potential sites for solar energy development.

To improve the geometric quality, polygons smaller than 0.5 decares were removed and a small negative buffer (−2 m) was applied to eliminate sliver geometries. The filtered polygons were then aggregated into contiguous areas using a buffer-based approach: polygons were merged and expanded by 10 m to connect features separated by less than approximately 20 m, dissolved into clusters, and subsequently buffered inward by 10 m to restore the outer extent. Cluster area was calculated in decares.

To remove narrow extensions and improve shape stability, clusters were further refined using an asymmetric buffering operation consisting of a −5 m inward buffer followed by a +7 m outward buffer. The resulting geometry was clipped against the original cluster footprint to prevent artificial expansion, and cluster areas were recalculated. Clusters smaller than 10 decares were excluded. The refined clusters were then intersected with the filtered grey area dataset to recover detailed geometry and assign each polygon to a cluster. Small residual polygons (<1 decare) generated by the intersection were removed. The final dataset represents contiguous grey land resources, parameterised by size, spatial structure, and building coverage, and can be further evaluated using purpose-specific criteria.

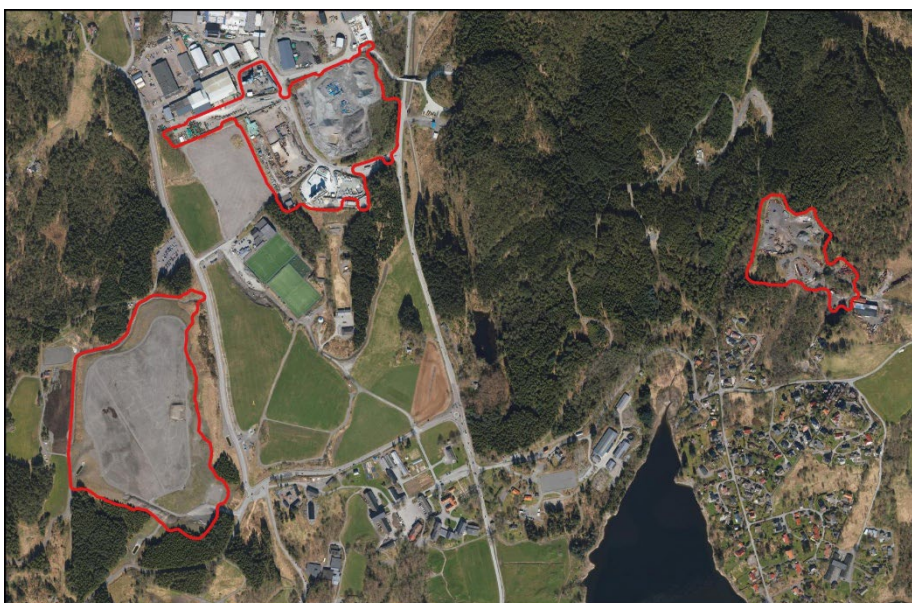


Figure S2. Part of the map of grey area resources, i.e. potentially underutilised grey areas, and potential sites for solar energy development.

Table S3. Projected total land demand (km²) in 2030 and 2050 under BAU and Agri-PV + grey allocation (50/50 split). Values are medians with 90% intervals (5th–95th percentiles) from Monte Carlo simulations ($n = 5,000$). Agri-PV + grey totals are scaled by the fixed Agri-PV co-use factor (1.5) with a 50/50 Agri/Grey split.

Scenario	Year	Business as usual, Total area (km ²) median (p05–p95)	AgriPV + Grey areas, Total area (km ²) median (p05–p95)
Low growth	2030	3.3 (2.2–6.0)	4.1 (2.8–7.5)
Low growth	2050	14.6 (10.0–26.7)	18.3 (12.5–33.3)
Medium growth	2030	3.9 (2.7–7.1)	4.9 (3.3–8.9)
Medium growth	2050	56.3 (38.6–103.0)	70.3 (48.3–128.3)
High growth	2030	4.7 (3.2–8.5)	5.8 (4.0–10.6)
High growth	2050	268.4 (184.0–490.0)	335.5 (230.2–612.2)

Table S4. Land-cover group requirements in 2050 under BAU and Agri-PV + grey allocation (50/50 split). Values are medians with 90% intervals (5th–95th percentiles) from Monte Carlo simulations ($n = 5,000$). Grey areas are defined as ‘settlements and other artificial areas’. Agriculture includes cropland and grassland. In BAU, rare classes in the 2026 footprint (wetlands, heathland, water) contribute little and are not shown separately in the table.

Scenario	Land-cover group	BAU area in 2050 (km ²) median (p05–p95)	Agri+Grey (50/50) area in 2050 (km ²) median (p05–p95)
Low growth	Forest & woodlands	12.7 (8.5–22.8)	0.0 (0.0–0.0)
Low growth	Agriculture	0.1 (0.1–0.3)	11.0 (7.5–20.0)
Low growth	Grey/modified	1.1 (0.7–2.0)	7.3 (5.0–13.3)
Low growth	Other semi-natural	0.5 (0.3–1.1)	0.0 (0.0–0.0)
Low growth	Water	0.1 (0.0–0.2)	0.0 (0.0–0.0)
Medium growth	Forest & woodlands	48.7 (32.8–87.6)	0.0 (0.0–0.0)
Medium growth	Agriculture	0.6 (0.2–1.3)	42.2 (29.0–77.0)
Medium growth	Grey/modified	4.3 (2.5–7.9)	28.1 (19.3–51.3)
Medium growth	Other semi-natural	2.1 (1.1–4.1)	0.0 (0.0–0.0)
Medium growth	Water	0.2 (0.0–0.6)	0.0 (0.0–0.0)
High growth	Forest & woodlands	232.3 (156.6–418.1)	0.0 (0.0–0.0)
High growth	Agriculture	2.6 (1.0–6.3)	201.3 (138.1–367.3)
High growth	Grey/modified	20.5 (12.1–37.5)	134.2 (92.1–244.9)
High growth	Other semi-natural	10.0 (5.4–19.6)	0.0 (0.0–0.0)
High growth	Water	0.9 (0.2–3.0)	0.0 (0.0–0.0)

Table S5. Agricultural and grey-area land requirements in 2050 under the Agri-PV + grey allocation strategy for different assumed shares of Agri-PV (30%, 50%, 70%). Values are medians with 90% uncertainty intervals (5th–95th percentiles) derived from Monte Carlo simulations ($n = 5,000$). Grey areas are defined as settlements and other artificial areas.

Scenario	Land-use type	30% Agri	50% Agri	70% Agri
Low growth	Agriculture	6.6 (4.5–12.0)	11.0 (7.5–20.0)	15.4 (10.5–28.0)
	Grey areas	10.2 (7.0–18.7)	7.3 (5.0–13.3)	4.4 (3.0–8.0)
Medium growth	Agriculture	25.3 (17.4–46.2)	42.2 (29.0–77.0)	59.1 (40.5–107.8)
	Grey areas	39.4 (27.0–71.9)	28.1 (19.3–51.3)	16.9 (11.6–30.8)
High growth	Agriculture	120.8 (82.9–220.4)	201.3 (138.1–367.3)	281.8 (193.4–514.2)
	Grey areas	187.9 (128.9–342.8)	134.2 (92.1–244.9)	80.5 (55.9–146.9)