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The biodiversity-wind energy-land use nexus in a global biodiversity hotspot

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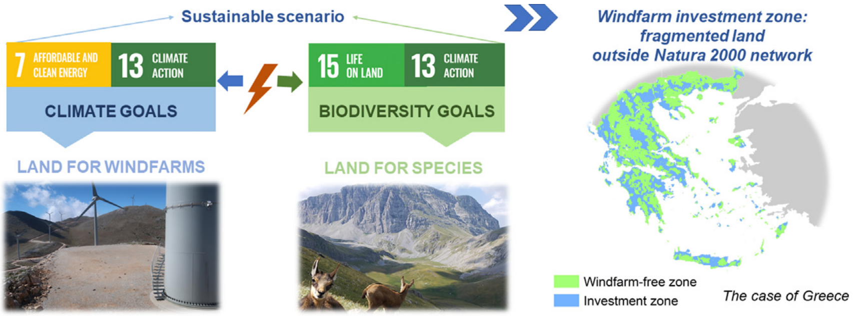
HIGHLIGHTS

- A paradox of impacting on biodiversity to combat climate change emerges.
- Sustainable scenario: locate windfarms in fragmented land outside protected areas.
- The scenario hampers fragmentation and benefits biodiversity in Greece.
- The scenario meets climate goals for 2030 and beyond.
- Need for environmental policy towards the no net land take milestone.

GRAPHICAL ABSTRACT



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ABSTRACT

Wind energy is the leading renewable technology towards achieving climate goals, yet biodiversity trade-offs via land take are emerging. Thus, we are facing the paradox of impacting on biodiversity to combat climate change. We suggest a novel method of spatial planning that enhances windfarm sustainability: investments are prioritized in the most fragmented zones that lie outside the Natura 2000 network of protected areas. We showcase it in Greece, a biodiversity hotspot with a strong climate policy and land conflict between conservation and wind energy schemes. The analysis indicates that the suggested investment zone supports wind harnessing 1.5 times higher than the 2030 national goal, having only marginally lower (4%) wind speed. It performs well for the conservation of the annexed habitats and species of the two Nature Directives and it greatly overlaps with the Important Bird Areas (93%) and the roadless areas (80%) of Greece. It also greatly overlaps (82%–91%) with the exclusion zones suggested according to three sensitivity maps for bird conservation. Since land use change triggers biodiversity decline, we underline the necessity of such approaches for meeting both climate and biodiversity goals and call for a greater environmental policy convergence towards biodiversity conservation and no net land take.

1. Introduction

Climate and the biodiversity crisis are the two major challenges currently facing humanity, seriously threatening human systems and well-being (Cardinale et al., 2012; Hoegh-Guldberg et al., 2018; IPBES, 2019). Land use change is identified as the top threat for biodiversity decline worldwide (IPBES, 2019), with strong interplay between biodiversity, land use and climate (Peters et al., 2019; Ritchie et al., 2020). Meeting climate goals without incurring substantial land-use change and biodiversity loss is pinpointed as one of the key global nexuses (Díaz et al., 2019). A need therefore emerges to equally achieve three of the 17

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Sustainable Development Goals (SDGs), so as to secure "affordable and clean energy" (Goal 7) and support "climate action" (Goal 13), without undermining "life on land" (Goal 15) (UN, 2015) (Fig. 1).

To meet climate goals, energy policies promote the rapid development of renewable energy sources (RES) (Gielen et al., 2019). RES planning requires knowledge of the needs of society and industry (Rao et al., 2019) but equally a consensus from society towards new technologies and their impacts (Boudet, 2019; Gaede and Rowlands, 2018) to increase the transparency of environmental planning through participatory processes (Laurila-Pant et al., 2019). Among RES technologies, wind energy has emerged as the leader, anticipated to provide one quarter to one third of global electricity demand by 2050 (Veers et al., 2019). Windfarms undoubtedly provide substantial benefits for climatic goals (Barthelmie and Pryor, 2014), but there is growing evidence of their adverse direct impacts on biodiversity, such as collision mortality of birds and bats, disturbance and species displacement, barrier effects, or noise pollution (Adeyeye et al., 2020; EC, 2020a; Wang and Wang, 2015) (Fig. 1). Furthermore, although windfarms are less land intensive than other renewables in terms of power produced per square meter (UNCCD, 2017), they still have a substantial land take footprint through vegetation removal, on-site construction of turbines on cement bases, and road sprawl (Diffendorfer et al., 2019). Their impacts extend far beyond their immediate physical footprint when the new roads built penetrate natural ecosystems or former wilderness areas. Road sprawl can trigger a cascade of further adverse anthropogenic pressures to nature, such as further land use change, habitat loss, fragmentation, land degradation, intensive resource extractions or illegal activities (Hoffmann et al., 2020; Ibisch et al., 2016; Kati et al., 2020a; Laurance and Arrea, 2017; Selva et al., 2015).

Besides wind energy infrastructures, conservation actions also require large tracts of land (Fig. 1). Consequently, the green vs green dilemma, i.e. maintaining biodiversity on one hand and achieving climate goals on the other, focuses on areas where RES sprawl overlaps with ecologically valuable areas (Rehbein et al., 2020). In particular, wind energy optimal spatial development is a complex issue, demanding coordinated and integrated approaches including all technical, economic, environmental and social dimensions (Abhinav et al., 2020; Lundquist et al., 2019; Pınarbaşı et al., 2019), while accounting for other competing renewables (Obane et al., 2020).

Wishing to be a world leader in climate neutrality, the EU aims to achieve 32% of RES in its energy mix by 2030, under the "clean energy for all Europeans package" (EU, 2019) and wind harnessing is among the key technologies for decarbonizing EU energy systems (Vrontisi et al., 2020). However, this bold commitment was not followed by an assessment of the land-take footprint of the forthcoming RES investments, with reference to the milestone of "no net land take by 2050" (EC, 2011); nor by an analysis of its synergies and tradeoffs with biodiversity commitments (EC, 2020b). Land use change is currently the top driver of biodiversity decline in the EU (EEA, 2019a). Land conversion to artificial or impervious surfaces is ongoing (EEA, 2019b; EEA, 2020) and landscape fragmentation is increasing (3.7% increase: 2009–2015) (EEA, 2019c).

The EU has so far failed to achieve biodiversity goals (EC, 2020b), despite the extended Natura 2000 network of protected areas (18% of EU land) and its relevant fit-for purpose legal framework (Birds and Habitats Directives) that is, however, weakly implemented (EC, 2016): 55% of species and 72% of habitats are still listed in unfavorable conservation status and 25% of breeding birds have declining population trends) (EEA, 2019a). One of the reasons for this could be the poor implementation of the current frame of licensing projects in the network. Development projects and activities with high land-take footprints are not excluded a priori from Natura 2000 areas in the EU. However, a suite of legal and procedural tools has been made available to ensure their minimal impact (EC, 2020a). For instance, a new windfarm project, should first accord with the Strategic Environmental Assessment (SEA), functioning as an early-stage spatial planning that integrates a suite of socio-economic, environmental and other criteria (SEA Directive 2001/42/EC). It should then be subject to an Environmental Impact Assessment Study (EIA) that addresses cumulative environmental impacts at a site-specific level (EIA Directive 2014/52/EU). If the project affects the annexed habitats and species protected by the Natura 2000 network, it should also undergo an Appropriate Assessment (AA), ensuring that the project will undoubtedly not adversely affect the protected interests of the Natura site. In spite of the adequacy of the above process, it

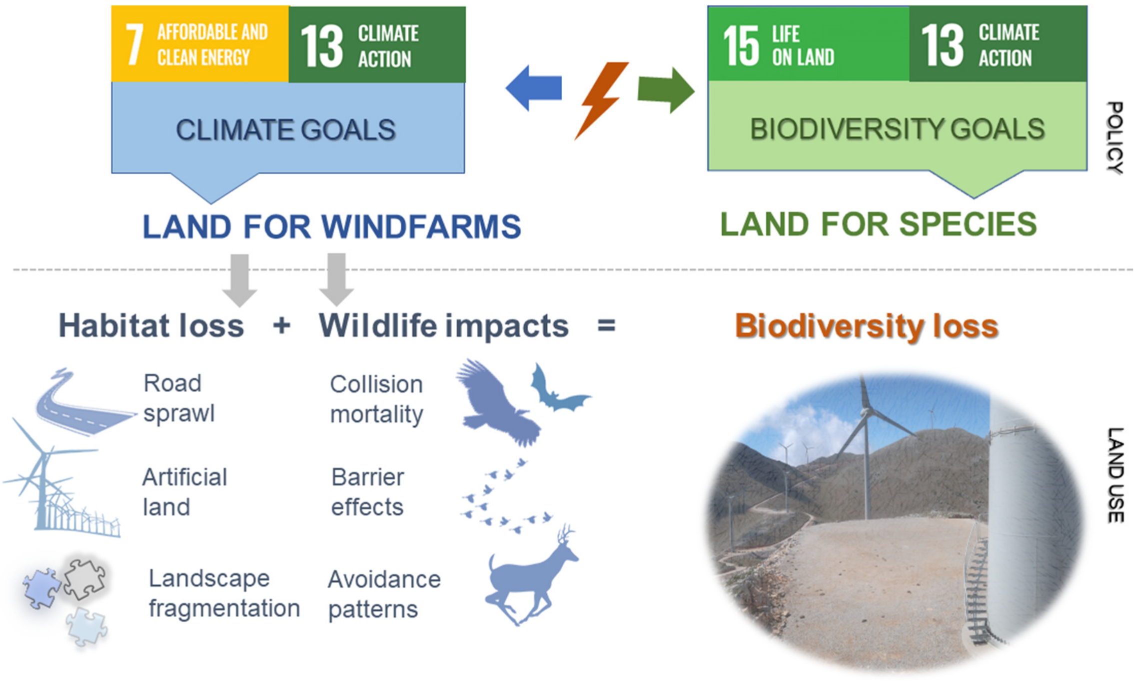

Fig. 1. The biodiversity-climate policy conflict for land demand within the framework of the three relevant Sustainable Development Goals (UN, 2015): the case of wind energy.

is often ignored in practice (Gove et al., 2013) and the poor quality or implementation of EIAs is identified as a major constraint for Natura 2000 to achieve its goals in the EU (Kati et al., 2015).

The new EU Biodiversity Strategy for 2030 (EC, 2020b) promises to reverse biodiversity decline. For example, it commits to expanding the network of protected areas (target: 30% of EU land) and initiates the concept of strict protection within them (target: 10% of EU land). However, it does not commit yet to impeding land take and landscape fragmentation and fails therefore to adequately address the biodiversity-wind energy-land use nexus on EU land.

Greece presents a typical conflict terrain of climate vs biodiversity policies, through land use spatial planning (Fig. 1). It lies in a global biodiversity hotspot (Myers et al., 2000), hosting 5752 and 23,000 known plant and animal species respectively (22% and 17% of them endemic respectively), and has an extensive Natura 2000 network of protected areas (27.3% of land) (OECD, 2020). At the same time, it presents an attractive case for wind energy investments, which have rapidly increased in recent years (12% average annual increase for the period 2006–2017) (MoEE, 2019). This is due to its high wind potential, large availability of public land (about half of the land is covered by forested and grassland areas, of which 77.5% is public) (Spanos et al., 2015), combined with a supportive national climate policy for RES deployment. The national climate policy sets an ambitious national target (NT) of wind harnessing of 7.05 GW by 2030 (MoEE, 2019). However, no study has assessed yet the land take footprint of forthcoming windfarm investments, and the degree to which they may accelerate the already increasing trend of sealed surfaces (EEA, 2020) and fragmentation (EEA, 2019c) nationwide. The recent report on the environmental performance of Greece (OECD, 2020), recognizes the nexus, urging for further RES development, whilst highlighting habitat fragmentation and road sprawl in Greece as key pressures to biodiversity.

This study suggests a novel method for a win - win spatial windfarm planning strategy that accomplishes a sustainable scenario for the biodiversity - wind energy - land use nexus. The suggested sustainable scenario is tested in Greece and refers to onshore wind energy deployment. First, we calculate the wind power produced (GW) based on the current licensing (onshore and offshore operating and planned windfarms). Second, we develop a sustainable scenario of onshore windfarm spatial planning and demonstrate its effectiveness for meeting national climate goals, whilst also comparing it to the business-as-usual scenario. Third, we evaluate the benefits and losses of the sustainable scenario for biodiversity and energy production, cross-checking with biodiversity and wind speed data, respectively. We finally discuss the perspectives of such a sustainable solution under a social and policy framework.

2. Materials and methods

2.1. Windfarm database treatment

We collected data on all windfarm applications for obtaining an operation license submitted to the national Regulatory Authority for Energy, accessing the respective online geospatial database (RAE, 2020). For every windfarm application, information on the installed power (MW: 10^6 W) for the respective investment polygon (polygon geometry shapefile) and the corresponding wind turbines (point geometry shapefile) was available. For hybrid energy investments, which combine several types of RES (i.e. solar panels, hydropower, wind turbines), only polygons containing wind turbines were considered.

In order to obtain a realistic estimate of the anticipated onshore installed wind power, we performed a thorough check to eliminate applications that are likely to be rejected, due to conflicts arising from overlapping windfarm polygons. Overlapping polygons were detected only at the evaluation stage and we adopted a conservative approach to fully or partially exclude them (and their respective power) as follows: For overlapping polygons within the evaluation stage: (i) we counted fully overlapping polygons only once, (ii) we excluded the polygons with the lowest power in case of partial overlap. For overlapping polygons of applications at the evaluation stage with post-evaluation stages: (i) we fully excluded the polygon of the evaluation stage in cases of full overlap, and (ii) we excluded the wind turbines which were at the evaluation stage and their respective power in the overlapping area, in case of partial overlap.

To calculate the current wind power produced, we considered all onshore windfarms with an operating permission, since no offshore windfarms are in operation yet.

2.2. Business-as-usual scenario: future wind harnessing

To calculate the future onshore wind power produced (installed capacity in MW), we considered the windfarm applications of all four permission stages (evaluation, production, construction, operation). To calculate in particular how much of the power will be produced inside the terrestrial Natura 2000 network, we considered its boundaries (MoEE, 2018) and summed the power of the windfarm polygons included in the network (summing only the power of the turbines (MW) included in the Natura 2000 network, in cases where windfarm polygons partially overlapped with the network).

2.3. Sustainable scenario: future wind harnessing

We present here a new methodological approach for sustainable windfarm spatial planning on terrestrial ecosystems. The sustainable scenario defines the windfarm-free zone, banning further windfarm investments inside the Natura 2000 network of protected areas and in the less fragmented land outside the network. It also defines the investment zone, including the more fragmented land outside the Natura 2000 network.

2.3.1. Defining the investment and windfarm-free zones

We considered the fragmentation map of Greece, provided by the European Environmental Agency (EEA, 2019d) for the year 2015, referring to the terrestrial part of the country (130,807.61 km^2). The Landscape Fragmentation Indicator (LFI) assesses how movement between different parts of the landscape is interrupted by impervious surfaces and traffic infrastructure. It is calculated in terms of the number of meshes per 1000 km^2 (seff values) and concludes to five fragmentation zones: very low (0–1.5), low (1.5–10), medium (10–50), high (50–250) and very high (>250) (EEA, 2019c). Furthermore, we considered the boundaries of the network of Natura 2000 in Greece (MoEE, 2018), by clipping the Natura 2000 to the extent of the fragmentation map. A total of 9964 km^2 of the very high, high and medium LFI fragmentation zones are included in the windfarm-free area, as part of the terrestrial Natura 2000 network – 28% of the network.

Using the above datasets, we defined a spatially explicit prioritization zoning system of the investment zone, corresponding to the union of the three most fragmented zones (very high, high, medium) that expand outside the Natura 2000 network. The remaining land, i.e. the Natura 2000 network and the very low and low fragmentation zones outside the network shape the windfarm-free area, where future wind farm construction is banned. Our study focused on terrestrial ecosystems, not considering wetlands and lakes in the analysis (no windfarm applications yet there), as a priori exclusion zones from any windfarm development.

2.3.2. Installed power in the investment and windfarm-free zones

The sustainable scenario can apply under a realistic framework in Greece as follows: (a) the currently operating windfarms continue to operate for their lifetime, (b) the windfarms that have a construction permit are allowed outside the sites of the Natura 2000 network, (c) all other forthcoming windfarm investments are allowed exclusively in the investment zone (Table 1).

In order to calculate the installed power within the investment and windfarm-free zone, we considered the database produced and applied the following procedure for each permission stage: (a) for operating windfarms we summed their respective installed power, (b) for windfarms under construction, we summed their respective installed power outside the Natura 2000 network, irrespective of their fragmentation class and, (c) for windfarms with a production permit or under evaluation, we considered only those polygons within the medium, high and very high fragmentation classes outside the Natura 2000 network and summed their respective installed power. In the case of windfarm polygons spanning two fragmentation zones, we assigned them to the fragmentation zone of the highest percent cover overlap. In the case of windfarm polygons partially overlapping with the Natura 2000 network, we summed the power of their wind turbines located outside the network.

2.4. Sustainable scenario evaluation

2.4.1. Performance for biodiversity conservation

To assess whether our sustainable scenario provides substantial benefits for the terrestrial biodiversity of Greece, we adopted a versatile approach, using six different ecological datasets. First, we considered the geospatial database of the distribution (10 km × 10 km) of the terrestrial protected Greek habitats and species after the Habitats and Birds Directives (monitoring period 2013–2018: 81 habitats, 282 species, 251 bird species) (Hadjicharalambous and Chrysopolitou, 2020). We calculated the percentage of their distribution within the investment and windfarm-free zones and their area-weighted proportion, correcting for the different extents of the two zones. We then tested whether area-weighted proportions of the annexed Greek habitats, species and bird species' distributions significantly differed between the investment and the windfarm-free zones, using a non-parametric Wilcoxon rank sum test ($p < 0.05$).

Second, we tested our sustainable scenario over the three bird sensitivity maps available for Greece, by calculating the spatial overlap of our windfarm-free zone with the respective exclusion zones suggested by the studies. The first national study stipulated a terrestrial exclusion zone of 1618 km^2 for the conservation of the cinereous vulture population in Greece (Vasilakis et al., 2017), on the basis of the species sensitivity map (Vasilakis et al., 2016). The second national study stipulated a terrestrial exclusion zone of 32,572 km^2 for the conservation of 21 protected bird species (Dimalexis et al., 2010). The study used the knowledge baseline prior to 2010 and applied a set of five criteria, related to the occurrence of migratory bottlenecks and corridors, the location of nesting sites and colonies, and the presence of Ramsar wetlands. The third study was regional and suggested a terrestrial exclusion zone of 1445 km^2 in NE Greece for the adequate conservation of 10 protected bird species, using a set of criteria related to the cinereous vulture high use area, the location of bird nesting sites and colonies and the extent of national parks and important habitats for birds in the study area (WWF, 2013).

Third, we tested our scenario over two spatial datasets of important areas for conservation. We considered the terrestrial part of the Important Bird Areas (IBAs) of Greece (30,413 km^2), which are recognized as sites particularly important for bird populations conservation (HOS, 2019). We also considered the map of the roadless areas of Greece (6498 km^2: land patches of a size greater than 1 km^2 that are at least 1 km away from the nearest road) (Kati et al., 2020b), which indicates those areas on Greek land of minimal anthropogenic disturbance and greater naturalness, especially when of large size (Kati et al., 2020a).

2.4.2. Wind speed

We compared the wind speed between the windfarm-free and investment zones using the available geospatial data from the national Regulatory Authority for Energy (RAE, 2020). Data are available as point measurements (5,925,702 measurements in total ranging from 0 to 20 m/s) of wind speed at three heights above the ground, as this is the usual rotor height range of the turbines (80 m, 100 m and 120 m). We compared the wind speed at the points occurring in the two zones by implementing a non-parametric Wilcoxon rank sum test for each height ($p<0.05$).

Geospatial analyses were implemented in ArcGIS 10.7 (ESRI, 2018) using the Greek Grid projected coordinate system and statistical analyses were conducted in R 3.6.3 (R CoreTeam, 2020).

3. Results

3.1. Investment interest for the wind energy sector

The original database (onshore and offshore) comprised 1940 applications (nearly 18,000 wind turbines) as of 10/3/2020 totaling 43.03 GW of power, classified under four successive permission stages: evaluation, production, construction and operation. The overall investment interest in Greece was therefore six times higher than the NT (7.05 GW). Eighty-five applications (3.41 GW) were excluded from the original database (overlapping polygons), leaving a total wind power of 39.61 GW. This is the anticipated power to be installed, if all onshore and offshore windfarm applications as of March 2020 are going to be licensed, which will exceed the NT by over 5 times (532%) (Table A1). The onshore windfarm database that was used in our scenario analysis included 1838 onshore windfarm applications (nearly 16,000 wind turbines) of a total power of 35.36 GW (Table A1).

3.2. Current wind harnessing

Greece has already achieved 44% of the 2030 national target for wind harnessing (NT=7.05 GW) with 23% of wind harnessing currently taking place within the terrestrial Natura 2000 network (0.72 GW, 190 wind farms, ca 700 turbines) (Fig. 2, Table A1).

3.3. Business-as-usual scenario: future wind harnessing

Assuming that all onshore windfarm applications as of March 2020 are licensed (corrected data for overlapping, all permission stages), wind harnessing will increase by eleven-fold (35.36 GW) outpacing the national target by a factor of five (502%). The harnessed wind power in the terrestrial Natura 2000 will increase by 17.5 times (565 more windfarms, ca 4800 more turbines), but the land resources outside the network will themselves be enough to exceed the NT by 3.2 times (1013 more windfarms, ca 9600 more turbines) (Fig. 2, Table A1). If we add the extra installed capacity of the windfarms with a construction

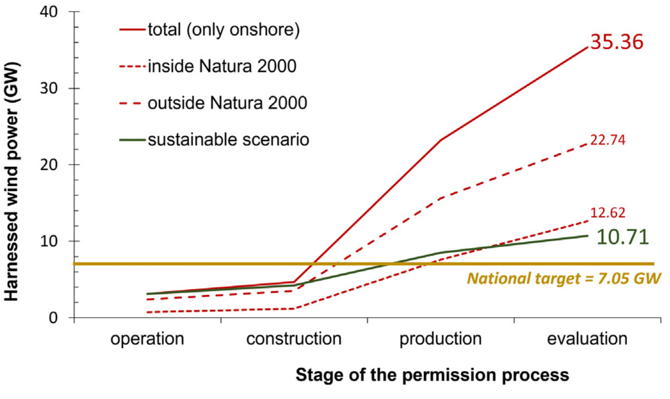

Fig. 2. Cumulative wind power (GW) harnessed across the successive permission stages of onshore windfarm applications (date as of 10/3/2020) in the business as usual scenario (red) and in the sustainable scenario (green) with reference to the Natura 2000 network and the 2030 national target.

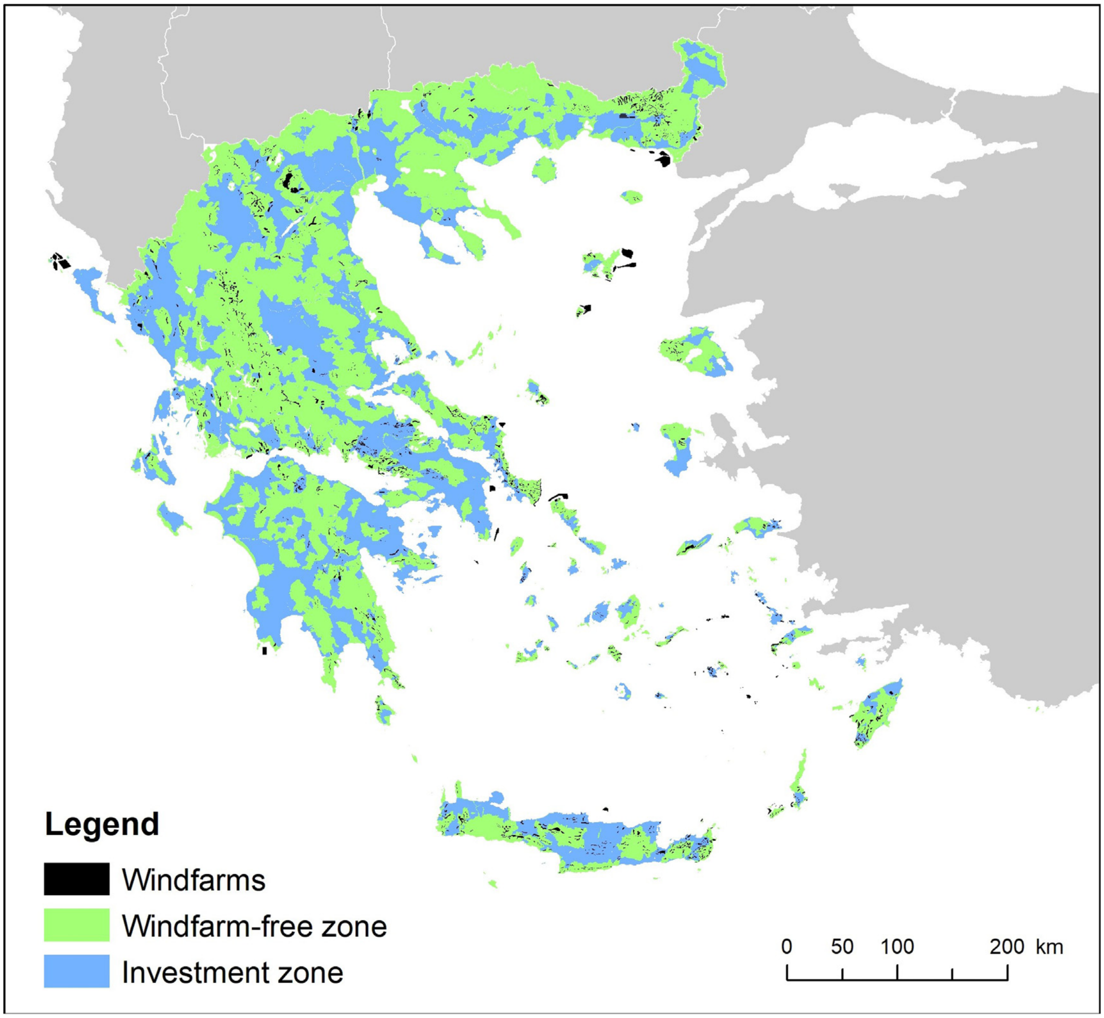

Fig. 3. Sustainable spatial planning map of wind energy in Greece, defining the investment zone (blue) for locating upcoming windfarms and the respective exclusion zone (green) after the sustainable scenario. Windfarms indicated are for all applications up to March 2020. Data are openly available at: http://dx.doi.org/10.17632/kh3fjww93t.1.

permission and of the windfarms at the final production stage that will enter the construction phase soon (with Decision Approving Environmental Terms) to the capacity of the currently operating windfarms, the total installed capacity will already exceed the national target (by 125%) (Table A1).

3.4. Sustainable scenario: future wind harnessing

We propose a windfarm-free zone that accounts for 58.6% of the terrestrial part of the country (76,626 km^2) (Kati and Kassara, 2020). It comprises the terrestrial Natura 2000 territory (35,385 km^2: Special Protection Areas (SPAs) for bird conservation and Sites of Community Importance (SCIs) for habitats and other species conservation), as well as the very low and low fragmented zones of the LFI that extend exclusively outside the Natura 2000 network (41,241 km^2). This contrasts with the suggested investment zone for planting windfarms outside the Natura 2000 network which accounts for 41.4% of Greek land (54,182 km^2) (Fig. 3). The total area of current windfarm applications' polygons would account for 1.22% of the investment zone area.

Table 1
Installed power data (MW = 10^6 W or 10^{-3} GW) inside Natura 2000 network and across the fragmentation zones outside the network (EEA, 2019d). Total power produced under the sustainable scenario of onshore windfarm spatial planning on Greek land (shaded cells) (applications as of 10/3/2020) following three criteria: (a) all windfarms currently operating within the country, (b) windfarms under construction outside the Natura 2000 network, (c) all other forthcoming windfarm investments in the medium and high fragmentation zones outside Natura 2000. The total and cumulative values are also presented as a percentage (%NT) of the national target (NT = 7.05 GW by 2030).

Stage	Installed power (MW)						Sustainable scenario power			
	N2000	Outside N2000					Criterion	Total		Cumulative
		Very low	Low	Medium	High	Very high		MW	%NT	%NT
Operation	722.62	120.90	1326.29	777.63	165.24	0,18	a	3112.86	44.2	44.2
Construction	450.27	208.25	730.95	166.51	8.52		b	1114.23	15.8	60.0
Production	6423.80	2035.32	5798.17	3780.14	503.80		c	4283.94	60.8	120.8
Evaluation	5024.37	655.22	4262.87	1959.86	241.09			2200.95	31.2	152.0
Total	12,621.05	3019.68	12,118.27	6684.13	918.64			10,711.98		

Applying a set of realistic rules (Table 1), we find that the sustainable scenario reduces installed power capacity by 24.65 GW and supports further onshore wind energy investments of 7.60 GW (Fig. 2). It succeeds in achieving the NT, exceeding it by 1.5 times (10.71 GW). Hence, it allows for an overachievement of the 2030 RES target without taking into consideration the future offshore wind investments that would further increase energy production.

3.5. Sustainable scenario evaluation

Results derived from the cross-checking of the sustainable scenario with biodiversity data indicate substantial benefits for biodiversity. The windfarm-free zone covers a significantly greater proportion of the distribution area of the 81 annexed habitats ($W = 1567$, $p<0.001$) and the 282 species under the Habitats Directive ($W = 21,098$, $p<0.001$), as well as the 251 annexed bird species under the BirdsDirective ($W = 20,598$, $p<0.001$) than does the investment zone (Table A2). Furthermore, the windfarm-free zone covers to a greater extent the terrestrial area of the suggested exclusion zones from three relevant ornithological studies as follows: 89% of the cinereous vulture exclusion zone, 82% of the national exclusion zone for birds, and 91% of the regional exclusion zone for birds in NE Greece (Fig. A1-A3). Finally, the windfarm-free zone covers 93% of the terrestrial area of the Important Bird Areas of Greece (Fig. A4), and 80% of the roadless areas of the country (Fig. A5). The ecological value of the investment zone is much lower (6% of IBAs, 20% of roadless areas).

The wind speed in the investment zone is also significantly lower ($p<0.001$) by 4% on average at the three representative heights above ground that encompass wind turbine towers (80 m, 100 m, 120 m) (Table A3).

4. Discussion

4.1. The business-as-usual scenario and the Greek policy

The country is currently implementing an ambitious energy transition for 2030 towards climatic neutrality, through the National Energy and Climate Plan (NECP), phasing out lignite dependence and committing to even more stringent targets for 2030 than the EU requirements (MoEE, 2019). The current electricity consumption in Greece is 56.89 TWh (9% imported) (WorldData, 2020) and it is anticipated to be 57.93 TWh by 2030 (MoEE, 2019). According to the NECP (MoEE, 2019), the share of RES is anticipated to increase from 17% (year 2017) to 35% in the national gross final energy consumption by 2030 and from 24.5% to at least 61% in electricity generation in Greece, with the share attributable to windfarm installed capacity being significant, i.e. 37% of RES (7.05 GW). Although no national target has been set yet for 2050, the continuation of the NECP beyond 2030 is expected to achieve 82% of electricity generation from RES by 2050, according to the national long-term strategy (MoEE, 2020). That would require onshore windfarm installed capacity, reaching 11.2 GW, in case that more intensive climate measures are adopted. The long-term strategy (MoEE, 2020) presents four disruptive innovation scenarios (over 95% of electricity generation from RES) to achieve climatic neutrality, predicting required windfarm installed capacity between 12.1 GW and 17.5 GW. We show that the implementation of the business-as-usual scenario would lead to an excessive windfarm installed capacity (35.36 GW) beyond the 2030 national target and beyond the predictions of the 2050 scenarios. We also underline that there is no convergence of the climate and biodiversity policies. A recent law of environmental modernization (Law 4685/07.05.2020) has corroborated the current favourable policy framework for RES, involving: (a) RES investments on public land at a low price, (b) acceleration and simplification of the licensing process for projects, including RES, particularly so for obtaining an environmental permission, and (c) update of the compatible land uses in the Natura 2000 zones, allowing in principle RES and new roads across the network. Furthermore, a new regulation is also being implemented that further speeds up and simplifies the environmental licensing process for smaller RES investments up to 10 MW (approval of the environmental terms by the Regional Governor, no public consultation stage) (3291/06.08.2020). These recent regulations seem to have neglected the National Biodiversity Strategy and Action Plan calling for ensuring the compatibility of energy production, including that based on renewables, with biodiversity conservation (MoEE, 2014).

While the government is taking steps to speed up environmental licensing procedures, there are serious concerns about the impact of such rapid windfarm development on biodiversity under an ambiguous environmental regulatory framework (OECD, 2020), and during a transition period lacking adequate spatial planning tools in force at national and Natura site level: The current SEA for renewables is deemed outdated and of poor quality (Vasilakis et al., 2017); it was offended by the European Commission because the Natura 2000 goals have not been adequately integrated (case 2014/4073). EIAs and AAs are also often insufficient, failing to prevent adverse project impacts to Natura 2000 habitats and species (Vasilakis et al., 2017). The new SEA is under development as well as the Special Environmental Studies that will define the specific zoning system and the compatible land uses in all Natura 2000 sites in Greece. Therefore, Greece stands at a critical crossroads, making impressive progress towards its climate goals by implementing the business-as-usual scenario, which however might have serious if not irreversible effects on species and habitats.

4.2. The sustainable scenario

4.2.1. The scenario rationale

The suggested windfarm-free zone is delineated to protect species and habitats from the negative impacts of further windfarm deployment on 58.6% of Greek land. Such broad scale scenarios for biodiversity conservation should ideally account for cumulative impacts from windfarm operations under a multicriteria approach, including multispecies sensitivity maps, migratory routes, stepping stones and wildlife corridors (EC, 2020a; Gaultier et al., 2020), but also Key Biodiversity Areas (IUCN, 2016) and ecosystem services (Kokkoris et al., 2018). However, uncertainty is inherent in conservation biology, which is a crisis discipline, requiring rapid conservation decisions often in the absence of an adequate knowledge base (Meffe et al., 2005). A scenario built on robust fine scale biological data would outperform our sustainable scenario, which uses biodiversity surrogates (the Natura 2000 network and least fragmented areas) to define the windfarm-free zone. The network of Natura 2000 was used, because it is a coherent system of sites recognized as well-designed to adequately represent the targeted bird species (Birds Directive 2009/147/EC) and the other targeted species and habitats (Habitats Directive 92/43/EEC) (Milieu et al., 2016).

The zones of very low and low fragmentation were used as they are more ecologically valuable for biodiversity and ecosystem function than the highly fragmented zones containing roads and artificial land. This assumption relies on the acknowledged serious negative impacts of fragmentation on species and ecosystem functions; these are related to habitat loss, increased isolation and edge effects, which in turn are associated with negative time-lagged responses of species extinction and ecosystem function debts (Haddad et al., 2015).

The sustainable scenario suggested siting future windfarms on degraded land, in terms of the most fragmented land outside the Natura 2000 network. Such spatial prioritization approaches of first locating windfarms on the most degraded lands are gaining recognition worldwide as the best practice for achieving both climate and biodiversity goals (Diffendorfer et al., 2019; Kiesecker et al., 2011; Rehbein et al., 2020; Waite, 2017).

4.2.2. The scenario contribution to climate goals

In this study, we have showed that there is no pressing need for the Greek climate policies to accelerate wind energy development, since the national climate target for wind harnessing can be readily achieved in a sustainable way. The sustainable scenario (10.71 GW) demonstrates in quantitative terms that it is possible to meet and exceed the target on 41.4% of Greek land, within the suggested investment zone. Furthermore, the land resources in the investment zone seem to be enough to meet the 2050 target, as identified by the main "no-regret" scenario (11.2 GW) or even other scenario targets (MoEE, 2020), since current applications of windfarms will occupy a small fraction of land in the investment zone (1.22%). We therefore argue that our sustainable approach, defining an investment zone in the most fragmented lands outside the Natura 2000 network, provides a feasible national solution even with the marginally lower wind speeds. Therefore, the Greek paradigm adds to the global best practice experience.

4.2.3. The scenario contribution to biodiversity conservation

The first results evaluating the biodiversity-related performance of our scenario are encouraging. The windfarm-free zone significantly contributes more to the conservation of the annexed habitats and species of the Nature Directives, in terms of their distribution area cover. It is expected to provide significant benefits for bird populations, as by definition it encompasses the total extent of the terrestrial SPAs in the country. It greatly overlaps (93%) with the Important Bird Areas of Greece, which are recognized as sites particularly important for bird conservation, due to their populations of globally or regionally threatened, endemic or congregatory bird species (HOS, 2019). Furthermore, the suggested windfarm-free zone greatly overlaps (82%–91%) with the exclusion zones suggested by other ornithological sensitivity studies (Dimalexis et al., 2010; Vasilakis et al., 2016; WWF, 2013). In the case of cinereous vulture, it was reported that the current predicted collision mortality from operating windfarms takes place almost fully (98%) in the core area of the population distribution that represents the exclusion zone (Vasilakis et al., 2016). Furthermore, it was reported that the annual cumulative collision mortality of the species would be 44% of the current population if all windfarms were to operate without spatial restrictions, whilst this would drop to 1% when applying the exclusion zone (Vasilakis et al., 2017). Although studies combining sensitivity maps, range use modelling and Collision Risk Models are largely lacking for other wildlife species, it is encouraging that our broad-scale sustainable scenario performed well locally. It may serve as a national guideline for windfarm deployment, with further refinement using accurate local biological data. Furthermore, a recent study on the population of griffon vultures on the island of Crete pinpointed that the estimated collision mortality would drop by over 50% if no windfarms were allowed to operate in the Natura 2000 network (Xirouchakis et al., 2019), further corroborating our approach of excluding the Natura 2000 network from the windfarm investment zone. The scenario can also benefit the bat populations included in the windfarm free zone, as they also experience collision mortalities with wind turbines in Greece (Georgiakakis et al., 2012).

The windfarm-free zone greatly overlaps (80%) with the roadless areas of Greece. These roadless areas have value per se as less disturbed areas of great naturalness serving as biodiversity reservoirs, hampering invasive species spread and extreme climatic events, supporting a wide array of ecological processes and providing a suite of social and economic benefits (Hoffmann et al., 2020; Kati et al., 2020a; Selva et al., 2015). In Greece, the Natura 2000 network is reported to be significantly less fragmented than the area outside it and includes about half of the roadless areas of the country (Kati et al., 2020a). The scenario is expected to hinder fragmentation and land take in the network and the windfarm-free zone outside of it, by blocking new road construction and the conversion of land to artificial surfaces both associated with the construction phase of windfarm infrastructures. Besides avoiding land degradation and habitat loss, several species that are directly impacted by roads will be particularly benefited in the windfarm-free zone. For example, the Balkan chamois shows a clear avoidance pattern to human disturbance, selecting roadless areas across all seasons (Kati et al., 2020c). Wolves select their rendezvous sites after the denning period away from forest roads in areas with low forest fragmentation (Iliopoulos et al., 2014). The cinereous vulture is known to select nesting trees away from forest roads as well (Poirazidis et al., 2004). Furthermore, the implementation of our scenario would prevent the anticipated artificial land encroachment in the upland pastures of Crete, that are the main foraging habitat of the griffon vulture, and, consequently, avoid negatively impacting their population (Xirouchakis et al., 2019). Further research is needed to assess the anticipated land take footprint of windfarm infrastructures in Greece, particularly because Greece shows one of the most rapid fragmentation increases in the EU (EEA, 2019a).

4.2.4. Socioeconomic aspect

In the Greek paradigm, the elevenfold increase in windfarm investments, and even more in the Natura 2000 network, will radically alter the Greek landscape, as well as cause other environmental effects. Such an implementation already incurs significant social opposition founded on landscape and socioeconomic values (Botetzagias et al., 2015; Vlami et al., 2020, 2021). Public perceptions regarding intensification of RES and windfarms may be polarized and should not be ignored as RES implementation strongly relies upon their social acceptance (Boudet, 2019). Although it was beyond the aims of our study to assess the acceptance of our scenario, we believe that it could mitigate such oppositions, since it protects the most natural and valuable landscapes, providing less confrontational grounds for wind energy business in the proposed investment zone (Polemis and Spais, 2020).

The sustainable scenario assumes that all current windfarm applications will be licensed to operate soon and impedes investments of 24.65 GW in the windfarm-free zone. However, it is not known how many of the applications will reach the final stage of the operation in both zones of the scenario. Uncertainty is inherent in such estimates and depends on land use policies, procedural frameworks, the technologies used (Rinne et al., 2018), and the dynamic nature of investment interest. Site selection for wind turbines planting is a complex decision to me made by investors. Wind potential is the core economic criterion considered, in terms of average wind speed, direction, stability and wind peaks, besides other criteria such as land availability, distance to roads and transmission lines or electricity demand. We have shown that land resources in the investment zone are enough to meet the national climate target for 2030 and beyond, considering only current and not future applications, whilst wind turbines in the investment zone will be by definition closer to roads, transmission lines and demand. Modern technologies will undoubtedly ameliorate the impacts of land constraints by increasing wind energy yields at sites with lower average wind speeds (Rinne et al., 2018). Profit reduction may occur, but it would be rather marginal, if we consider as an indicator the average wind speed (4% less in investment zone). A similar European scale analysis also showed that if all areas designated for nature protection were theoretically excluded from wind energy infrastructures, there would only be a limited impact on wind energy generation potential (13.7% decrease) (EEA, 2009).

4.2.5. Use and perspectives

Our results show that our sustainable scenario performs well, serving both climate and biodiversity goals. Therefore, we clearly recommend its integration into the forthcoming SEA for renewables, alongside the other environmental and socio-economic criteria to be employed in the study. Our scenario is in line with the provisions of the National Biodiversity Strategy calling for compatibility of renewable energy production with biodiversity conservation (MoEE, 2014). It also responds to the recent OECD recommendation to "better integrate biodiversity considerations into EIA and SEA to avoid loss of birds and bats, especially in sensitive areas such as mountainous regions, wetlands and migration paths" (OECD, 2020).

The sustainable scenario is built on available non-biological data and serves as a fast broad-scale decision tool for the strategic territorial planning of the wind energy sector for the next decade. It does not seek to replace or undervalue the much needed high-quality EIAs; these should be conducted for all RES projects regardless of their size, accounting for cumulative impacts and contributing to the refinement of the scenario implementation at local scale. Further research is urgently needed to compile species-sensitivity maps and improve the biodiversity knowledge base in Greece; this would allow a cross-validation, improvement, and refinement of the suggested scenario.

Finally, we adopted a proactive and broad-scale approach to build our scenario, which is recommended for land use and infrastructure planning (Laurance and Arrea, 2017). We suggest using of the sustainable scenario as a guideline for the strategic territorial planning of other projects that consume land across various sectors, such as transport, industry, tourism or other energy infrastructures (e.g. solar panels) (OECD, 2020), in line with the National Biodiversity Strategy, calling for effective integration of biodiversity conservation at all levels of spatial planning and particularly the minimization of impacts of large infrastructure projects (MoEE, 2014).

4.3. Broader policy insights

Our study underlines the need for a greater convergence of biodiversity vs climate policies (Gardner et al., 2020), since biodiversity conservation is linked to the fulfillment of all SDGs (Blicharska et al., 2019) and is the most cost-effective solution to address climate change (Díaz et al., 2019; Naumann et al., 2011). For example, defining the Natura 2000 network as a windfarm-free zone in the EU is worth considering as an option, given our failure to meet biodiversity goals in the EU (EC, 2020) and the non-risk to achieving the energy supply/ energy demand target required by 2030 (EEA, 2009).

We also call for bolder policies focused more on restraining land take in natural ecosystems. For example, further studies are needed to quantify the capacity-based technical potential for renewable energy generation in the currently built environment (Hernandez et al., 2015), in line with the no net land take milestone (EC, 2011). A land take threshold could be applied as an on-off criterion in the licensing process of investments on EU land, to be considered, especially in case windfarms are continued to be allowed in the network. Finally, land take minimization should be better integrated in global policies, such as the post 2020 Biodiversity Framework to be adopted by the Convention on Biological Diversity (CBD, 2010), or the Land Degradation Neutrality of the United Nations Convention to Combat Desertification (UNCCD, 2019).

5. Conclusions

Our study presents a new methodological approach for the strategic territorial planning of diverse investment projects, excluding protected areas and areas of low fragmentation intensity from the investment zone. The method was used to build the sustainable scenario for the onshore windfarm spatial planning in Greece, in terms of two zones: the investment and windfarm-free zone (i.e. Natura 2000 plus very low and low fragmentation zones). In the case of Greece, the scenario succeeds to resolve the land conflict between wind energy and conservation, by meeting the ambitious national climate goals for wind harnessing, whilst ensuring a low cost to biodiversity conservation. The sustainable scenario has the potential to be implemented in other parts of the world, especially when wildlife sensitivity maps and adequate biological knowledge base is missing, as in the case of Greece.

CRediT authorship contribution statement

Vassiliki Kati: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration. **Christina Kassara:** Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Zoi Vrontisi:** Writing – review & editing. **Aristides Moustakas:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Abhinav, K.A., Collu, M., Benjamins, S., Cai, H., Hughes, A., Jiang, B., Jude, S., Leithead, W., Lin, C., Liu, H., Recalde-Camacho, L., Serpetti, N., Sun, K., Wilson, B., Yue, H., Zhou, B.-Z., 2020. Offshore multi-purpose platforms for a Blue Growth: a technological, environmental and socio-economic review. Sci. Total Environ. 734. https://doi.org/10.1016/j.scitotenv.2020.138256.

Adeyeye, K., Ijumba, N., Colton, J., 2020. Exploring the environmental and economic impacts of wind energy: a cost-benefit perspective. Int. J. Sustainable Dev. & World Ecol., 1–14 https://doi.org/10.1080/13504509.2020.1768171.

Barthelmie, R.J., Pryor, S.C., 2014. Potential contribution of wind energy to climate change mitigation. Nat. Clim. Change 4, 684–688. https://doi.org/10.1038/nclimate2269.

Blicharska, M., Smithers, R.J., Mikusiński, G., Rönnbäck, P., Harrison, P.A., Nilsson, M., Sutherland, W.J., 2019. Biodiversity's contributions to sustainable development. Nat. Sustain. 2, 1083–1093. https://doi.org/10.1038/s41893-019-0417-9.

Botetzagias, I., Malesios, C., Kolokotroni, A., Moysiadis, Y., 2015. The role of NIMBY in opposing the siting of wind farms: evidence from Greece. Environ. Plann. Man. 58, 229–251. https://doi.org/10.1080/09640568.2013.851596.

Boudet, H.S., 2019. Public perceptions of and responses to new energy technologies. Nat. Energy 4, 446–455. https://doi.org/10.1038/s41560-019-0399-x.

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

CBD, 2010. Strategic Plan for Biodiversity 2011–2020, Including Aichi Biodiversity Targets. https://www.cbd.int/sp/targets/. (Accessed 10 May 2020).

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M.A., Garibaldi, L.A., Ichii, K., Liu, J., Subramanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R.R., Shin, J.-J., Visseren-Hamakers, I., Willis, K.J., Zayas, C.N., 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366, eaax3100. https://doi.org/10.1126/science.aax3100.

Diffendorfer, J.E., Dorning, M.A., Keen, J.R., Kramer, L.A., Taylor, R.V., 2019. Geographic context affects the landscape change and fragmentation caused by wind energy facilities. PeerJ 7, e7129. https://doi.org/10.7717/peerj.7129.

Dimalexis, A., Kastritis, T., Manolopoulos, A., Korbeti, M., Fric, J., Saravia Mullin, V., Xirouchakis, S., Bousbouras, D., 2010. Identification and Mapping of Sensitive Bird Areas to Wind Farm Development in Greece. Hellenic Ornithological Society, Athens http://files.ornithologiki.gr/docs/politiki/aiolika/prosdiorismos%20kai%20xartografisi.pdf.

EC, 2011. Roadmap to a resource efficient Europe. Brussels, 20.09.2011, COM (2011) 571 final. https://www.europarl.europa.eu/meetdocs/2009_2014/documents/com/com_com(2011)0571_/com_com(2011)0571_en.pdf (accessed 2 July 2020)

EC, 2016. Commission Staff Working Document. Fitness check of the EU Nature legislation (Birds and Habitats Directives). https://ec.europa.eu/environment/nature/legislation/fitness_check/index_en.htm. (Accessed 10 May 2020).

EC, 2020a. Commission Notice. Guidance Document on Wind Energy Developments and EU Nature Legislation. Brussels, 18.11.2020. COM (2020) 7730 final. https://ec.

europa.eu/environment/nature/natura2000/management/docs/wind_farms_en.pdf. (Accessed 2 December 2020).

EC, 2020b. EU Biodiversity Strategy for 2030. Bringing Nature Back Into Our Lives. Brussels, 20.5.2020.COM (2020) 380 Final. https://ec.europa.eu/info/files/communication-eu-biodiversity-strategy-2030-bringing-nature-back-our-lives_en. (Accessed 25 May 2020).

EEA, 2009. Europe's onshore and offshore wind energy potential. An Assessment of Environmental and Economic Constraints. EEA Technical Report No 6/2009 https://www.energy.eu/publications/a07.pdf. (Accessed 15 May 2020).

EEA, 2019a. The European environment-state and outlook 2020. Knowledge for Transition to a Sustainable Europe https://www.eea.europa.eu/themes/biodiversity/state-of-nature-in-the-eu/state-of-nature-2020. (Accessed 18 May 2020).

EEA, 2019b. Land Take in Europe. https://www.eea.europa.eu/data-and-maps/indicators/land-take-3/assessment. (Accessed 18 May 2020).

EEA, 2019c. Landscape Fragmentation Pressure and Trends in Europe. https://www.eea.europa.eu/data-and-maps/indicators/mobility-and-urbanisation-pressure-on-ecosystems-2/assessment. (Accessed 5 May 2020).

EEA, 2019d. Landscape Fragmentation Effective Mesh Density Time-series: Major and Medium Anthropogenic Fragmenting Elements (FGA2-S). https://www.eea.europa.eu/data-and-maps/data/landscape-fragmentation-effective-mesh-density. (Accessed 5 May 2020).

EEA, 2020. Imperviousness and Imperviousness Change in Europe. https://www.eea.europa.eu/data-and-maps/indicators/imperviousness-change-2/assessment. (Accessed 5 May 2020).

ESRI, 2018. ArcGISDesktop. Environmental Systems Research Institute, Redlands, CA, USA.

EU, 2019. Clean Energy for All Europeans. https://op.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1/language-en?WT.mc_id=Searchresult&WT.ria_c=null&WT.ria_f=3608&WT.ria_ev=search. (Accessed 12 May 2020).

Gaede, J., Rowlands, I.H., 2018. Visualizing social acceptance research: A bibliometric review of the social acceptance literature for energy technology and fuels. Energy Res. Soc. Sci. 40, 142–158. https://doi.org/10.1016/j.erss.2017.12.006.

Gardner, C.J., Struebig, M.J., Davies, Z.G., 2020. Conservation must capitalise on climate's moment. Nat.Commun. 11, 109. https://doi.org/10.1038/s41467-019-13964-y.

Gaultier, S.P., Blomberg, A.S., Ijäs, A., Vasko, V., Vesterinen, E.J., Brommer, J.E., Lilley, T.M., 2020. Bats and wind farms: the role and importance of the Baltic Sea countries in the European context of power transition and biodiversity conservation. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.0c00070.

Georgiakakis, P., Kret, E., Cárcamo, B., Doutau, B., Kafkaletou-Diez, A., Vasilakis, D., Papadatou, E., 2012. Bat fatalities at wind farms in north-eastern Greece. Acta Chiropt. 14, 459–468. https://doi.org/10.3161/150811012X661765.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. Energy Strategy Rev. 24, 38–50. https://doi.org/10.1016/j.esr.2019.01.006.

Gove, B., Langston, R., McCluskie, A., Pullan, J.D., Scrase, I., 2013. In: International B (Ed.), Wind Farms and Birds: An Updated Analysis of the Effects of Wind Farms on Birds, and Best Practice Guidance on Integrated Planning and Impact Assessment. Bern Convention, Strasbourg https://tethys.pnnl.gov/sites/default/files/publications/WindFarmsBirds-Bern-2013.pdf.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sextos, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.0.X., Townshend, J.R., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci. Adv. 1, e1500052. https://doi.org/10.1126/sciadv.1500052.

Hadjicharalambous, H., Chrysopolitou, V., 2020. Deliverables of Public Services Contract for the Preparation of Greek National Reports Under Article 17 of Directive 92/43/EEC and Article 12 of the Directive 2009/47/EU. Greek Biotope/Wetland Center (EKBY).

Hernandez, R.R., Hoffacker, M.K., Field, C.B., 2015. Efficient use of land to meet sustainable energy needs. Nat. Clim. Change 5, 353–358. https://doi.org/10.1038/nclimate2556.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, R., Djalante, R., Ebi, K.L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotta, S., Payne, A., Senevirante, S.I., Thomas, A., Warren, R., Zhou, G., 2018. Impacts of 1.5°C global warming on natural and human systems. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (in press). https://www.ipcc.ch/sr15/chapter/chapter-3/, pp. 175–311.

Hoffmann, M.T., Kreft, S., Kati, V., Ibisch, P.L., 2020. roadless areas as key approach to conservation of functional forest ecosystems. In: Goldstein, M.I., DellaSala, D.A. (Eds.), Encyclopedia of the World's Biomes. Elsevier, Oxford, pp. 237–248.

HOS, 2019. Database of Important Bird Areas in Greece. www.ornithologiki.gr/iba. (Accessed 9 June 2020).

Ibisch, P.L., Hoffmann, M.T., Kreft, S., Pe'er, G., Kati, V., Biber-Freudenberger, L., DellaSala, D.A., Vale, M.M., Hobson, P.R., Selva, N., 2016. A global map of roadless areas and their conservation status. Science 354, 1423–1427. https://doi.org/10.1126/science.aaf7166.

Iliopoulos, Y., Youlatos, D., Sgardelis, S., 2014. Wolf pack rendezvous site selection in Greece is mainly affected by anthropogenic landscape features. E. J. WildL. Res. 60, 23–34. https://doi.org/10.1007/s10344-013-0746-3.

IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://ipbes.net/global-assessment. (Accessed 9 June 2020).

IUCN, 2016. A Global Standard for the Identification of Key Biodiversity Areas, Version 1.0. IUCN, Gland, Switzerland: IUCN. https://portals.iucn.org/library/sites/library/files/documents/2016-048.pdf (accessed 5 June 2020).

Kati, V., Kassara, C., 2020. Sustainable Spatial Planning for Windfarms in Greece. Mendeley Data, v1. http://dx.doi.org/10.17632/kh3fjww93t.1.

Kati, V., Hovardas, T., Dieterich, M., Ibisch, P.L., Mihok, B., Selva, N., 2015. The challenge of implementing the European network of protected areas Natura 2000. Conserv. Biol. 29, 260–270. https://doi.org/10.1111/cobi.12366.

Kati, V., Kassara, C., Psaralexi, M., Tzortzakaki, O., Petridou, M., Galani, A., Hoffmann, M.T., 2020a. Conservation policy under a roadless perspective: minimizing fragmentation in Greece. Biol. Conserv. https://doi.org/10.1016/j.biocon.2020.108828

Kati, V., Kassara, C., Psaraleksi, M., Tzortzakaki, O., Petridou, M., Galani, A., Hoffmann, M.T., 2020b. The Roadless Map of Greece. Mendeley Data, v1. http://dx.doi.org/10.17632/s6zh89fb5c.1.

Kati, V., Kassara, C., Vassilakis, D., Papaioannou, H., 2020c. Balkan Chamois (*Rupicapra rupicapra balcanica*) avoids roads, settlements, and hunting grounds: an ecological overview from Timfi Mountain, Greece. Diversity 12, 124. https://doi.org/10.3390/d12040124.

Kiesecker, J.M., Evans, J.S., Fargione, J., Doherty, K., Foresman, K.R., Kunz, T.H., Naugle, D., Nibbelink, N.P., Niemuth, N.D., 2011. Win-win for wind and wildlife: a vision to facilitate sustainable development. PLOS ONE 6, e17566. https://doi.org/10.1371/journal.pone.0017566.

Kokkoris, I.P., Drakou, E.G., Maes, J., Dimopoulos, P., 2018. Ecosystem services supply in protected mountains of Greece: setting the baseline for conservation management. Int. J. Biodivers. Sci. Ecosyst. Serv. Manag. 14, 45–59. https://doi.org/10.1080/21513732.2017.1415974.

Laurance, W.F., Arrea, I.B., 2017. Roads to riches or ruin? Science 358, 442–444. https://doi.org/10.1126/science.aao0312.

Laurila-Pant, M., Mäntyniemi, S., Venesjärvi, R., Lehikoinen, A., 2019. Incorporating stakeholders' values into environmental decision support: a Bayesian Belief Network approach. Sci. Total Environ. 697. https://doi.org/10.1016/j.scitotenv.2019.134026.

Lundquist, J.K., DuVivier, K.K., Kaffine, D., Tomaszewski, J.M., 2019. Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development. Nat. Energy 4, 26–34. https://doi.org/10.1038/s41560-018-0281-2.

Meffe, G.K., Ronald Carrol, C., Groom, M.J., 2005. What is conservation biology? In: Groom, M.J., Meffe, G.K., Ronald Carroll, C. (Eds.), Principles of Conservation Biology. Sinauer Associates, Inc, U.S.A, pp. 3–23

Milieu, IEEP, ICF, 2016. Evaluation Study to Support the Fitness Check of the Birds and Habitats Directives. https://ec.europa.eu/environment/nature/legislation/fitness_check/docs/study_evaluation_support_fitness_check_nature_directives.pdf. (Accessed 10 June 2020).

MoEE, 2014. National Biodiversity Strategy & Action Plan. www.cbd.int/doc/world/gr/gr-nbsap-01-en.pdf. (Accessed 12 June 2020).

MoEE, 2018. Natura 2000 Database Version 30. http://www.ypeka.gr/. (Accessed 16 January 2018).

MoEE, 2019. National Energy and Climate Plan, December 2019. https://ec.europa.eu/energy/sites/ener/files/el_final_necp_main_en.pdf. (Accessed 10 May 2020).

MoEE, 2020. Long-term Strategy to 2050, January. https://ec.europa.eu/clima/sites/lts/lts_gr_el.pdf. (Accessed 10 June 2020).

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Naumann, S., Anzaldua, G., Berry, P., Burch, S., Davis, M., Frelih-Larsen, A., Gerdes, H., Sanders, M., 2011. Assessment of the potential of ecosystem-based approaches to climate change adaptation and mitigation in Europe. Final report to the European Commission, DG Environment https://ec.europa.eu/environment/nature/climatechange/pdf/EbA_EBM_CC_FinalReport.pdf. (Accessed 10 May 2019).

Obane, H., Nagai, Y., Asano, K., 2020. Assessing land use and potential conflict in solar and onshore wind energy in Japan. Renew. Energy 160, 842–851. https://doi.org/10.1016/j.renene.2020.06.018.

OECD, 2020. OECD Environmental Performance Reviews: Greece 2020. https://www.oecd-ilibrary.org/content/publication/cec20289-en. (Accessed 20 October 2020).

Peters, M.K., Hemp, A., Appelhans, T., Becker, J.N., Behler, C., Classen, A., Detsch, F., Ensslin, A., Ferger, S.W., Frederiksen, S.B., Gebert, F., Gerschlauer, F., Gütlein, A., Helbig-Bonitz, M., Hemp, C., Kindeketa, W.J., Kühnel, A., Mayr, A.V., Mwangomo, E., Ngereza, C., Njovu, H.K., Otte, I., Pabst, H., Renner, M., Röder, J., Rutten, G., Costa, D.S., Sierra-Cornejo, N., Vollstädt, M.G.R., Dulle, H.I., Eardley, C.D., Howell, K.M., Keller, A., Peters, R.S., Ssymank, A., Kakengi, V., Zhang, J., Bogner, C., Böhning-Gaese, K., Brandl, R., Hertel, D., Huwe, B., Kiese, R., Kleyer, M., Kuzyakov, Y., Nauss, T., Schleuning, M., Tschapka, M., Fischer, M., Steffan-Dewenter, I., 2019. Climate–land-use interactions shape tropical mountain biodiversity and ecosystem functions. Nature 568, 88–92. https://doi.org/10.1038/s41586-019-1048-z.

Pınarbaşı, K., Galparsoro, I., Depellegrin, D., Bald, J., Pérez-Morán, G., Borja, Á., 2019. A modelling approach for offshore wind farm feasibility with respect to ecosystem-based marine spatial planning. Sci. Total Environ. 667, 306–317. https://doi.org/10.1016/j.scitotenv.2019.02.268.

Poirazidis, K., Goutner, V., Skartsi, T., Stamou, G., 2004. Modelling nesting habitat as a conservation tool for the Eurasian black vulture (*Aegypius monachus*) in Dadia Nature Reserve, northeastern Greece. Biol. Conserv. 118, 235–248. https://doi.org/10.1016/j.biocon.2003.08.016.

Polemis, M.L., Spais, A., 2020. Disentangling the drivers of renewable energy investments: The role of behavioral factors. Bus.Strategy Environ. 29, 2170–2180. https://doi.org/10.1002/bse.2493.

R Core Team, 2020. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing.R Core Team. https://www.R-project.org/.

RAE, 2020. Geospatial Map for Energy Units and Requests. http://www.rae.gr/geo/?lang=EN. (Accessed 10 March 2020).

Rao, N.D., Min, J., Mastrucci, A., 2019. Energy requirements for decent living in India, Brazil and South Africa. Nat.Energy 4, 1025–1032. https://doi.org/10.1038/s41560-019-0497-9.

Rehbein, J.A., Watson, J.E.M., Lane, J.L., Sonter, L.J., Venter, O., Atkinson, S.C., Allan, J.R., 2020. Renewable energy development threatens many globally important biodiversity areas. Global Change Biol. 26, 3040–3051. https://doi.org/10.1111/gcb.15067.

Rinne, E., Holttinen, H., Kiviluoma, J., Rissanen, S., 2018. Effects of turbine technology and land use on wind power resource potential. Nat. Energy 3, 494–500. https://doi.org/10.1038/s41560-018-0137-9.

Ritchie, P.D.L., Smith, G.S., Davis, K.J., Fezzi, C., Halleck-Vega, S., Harper, A.B., Boulton, C.A., Binner, A.R., Day, B.H., Gallego-Sala, A.V., Mecking, J.V., Sitch, S.A., Lenton, T.M., Bateman, I.J., 2020. Shifts in national land use and food production in Great Britain after a climate tipping point. Nat. Food 1, 76–83. https://doi.org/10.1038/s43016-019-0011-3.

Selva, N., Switalski, A., Kreft, S., Ibisch, P.L., 2015. Why keep areas road-free? The importance of roadless areas. In: Van Der Ree, R., Smith, D.J., Grilo, C. (Eds.), Handbook of Road Ecology. Wiley Blackwell, pp. 10–26.

Spanos, I., Meliadis, I., Platis, P., Mantzanas, K., Samara, T., Meliadis, M., 2015. Forest Land Ownership Change in Greece. COST Action FP1201 FACESMAP Country Report. European Forest Institute Central-East and South-East European Regional Office, Vienna. http://facesmap.boku.ac.at/library/FP1201_Country%20Report_GREECE.pdf. (Accessed 19 May 2020).

UN, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development, A/RES/70/1,United Nations. http://www.undp.org/content/undp/en/home/sustainable-development-goals.html. (Accessed 15 May 2020).

UNCCD, 2017. Global Land Outlook. first edition. https://www.unccd.int/actions/global-land-outlook-glo. (Accessed 15 May 2020).

UNCCD, 2019. Land Degradation Neutrality for Biodiversity Conservation. https://catalogue.unccd.int/1339_Briefing_Note_Biodiversity.pdf. (Accessed 15 May 2020).

Vasilakis, D.P., Whitfield, D.P., Schindler, S., Poirazidis, K.S., Kati, V., 2016. Reconciling endangered species conservation with wind farm development: Cinereous vultures (*Aegypius monachus*) in south-eastern Europe. Biol. Conserv. 196, 10–17. https://doi.org/10.1016/j.biocon.2016.01.014.

Vasilakis, D.P., Whitfield, D.P., Kati, V., 2017. A balanced solution to the cumulative threat of industrialized wind farm development on cinereous vultures (*Aegypius monachus*) in south-eastern Europe. PLoS ONE 12. https://doi.org/10.1371/journal.pone.0172685.

Veers, P., Dykes, K., Lantz, E., Barth, S., Bottasso, C.L., Carlson, O., Clifton, A., Green, J., Green, P., Holttinen, H., Laird, D., Lehtomäki, V., Lundquist, J.K., Manwell, J., Marquis, M., Menevau, C., Moriarty, P., Munduate, X., Muskulus, M., Naughton, J., Pao, L., Paquette, J., Peinke, J., Robertson, A., Rodrigo, J.S., Sempreviva, A.M., Smith, J.S., Tuihy, A., Wiser, R., 2019. Grand challenges in the science of wind energy. Science 366, eaau2027. https://doi.org/10.1126/science.aau2027.

Vlami, V., Danek, J., Zogaris, S., Gallou, E., Kokkoris, I.P., Kehayias, G., Dimopoulos, P., 2020. Residents' views on landscape and ecosystem services during a wind farm proposal in an island protected area. Sustainability 12, 2442. https://doi.org/10.3390/su12062442.

Vlami, V., Kokkoris, I.P., Zogaris, S., Kehayias, G., Dimopoulos, P., 2021. Cultural ecosystem services in the natura 2000 network: introducing proxy indicators and conflict risk in Greece. Land 10 (4). https://doi.org/10.3390/land10010004.

Vrontisi, Z., Fragkiadakis, K., Kannavou, M., Capros, P., 2020. Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2 °C climate stabilization. Climatic Change 162, 1857–1875. https://doi.org/10.1007/s10584-019-02440-7.

Waite, J.L., 2017. Land reuse in support of renewable energy development. Land Use Policy 66, 105–110. https://doi.org/10.1016/j.landusepol.2017.04.030.

Wang, S., Wang, S., 2015. Impacts of wind energy on environment: a review. Renew. Sust. Energ. Rev. 49, 437–443. https://doi.org/10.1016/j.rser.2015.04.137.

WorldData, 2020. Energy Consumption in Greece. https://www.worlddata.info/europe/greece/energy-consumption.php. (Accessed 11 October 2020).

WWF, 2013. Wind Farms in Thrace: Updating the Proposal for Proper Site Selection. https://tethys.pnnl.gov/sites/default/files/publications/WWF-windfarms-Thrace.pdf. (Accessed 15 May 2020).

Xirouchakis, S.M., Armeni, E., Nikolopoulou, S., Halley, J., 2019. Estimating the potential mortality of griffon vultures (*Gyps fulvus*) due to wind energy development on the Island of Crete (Greece). In: Bispo, R., Bernardino, J., Coelho, H., Costa, J.L. (Eds.), Wind Energy and Wildlife Impacts. Balancing Energy Sustainability With Wildlife Conservation. Springer Nature, Switzerland, pp. 205–221.