Received: 28 February 2020 | Revised: 6 July 2020 | Accepted: 24 July 2020
DOI: 10.1002/er.5870

SPECIAL ISSUE RESEARCH ARTICLE

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

# Nothing to regret: Reconciling renewable energies with human wellbeing and nature in the German Energy Transition

**Julia Wiehe**[1] | **Julia Thiele**[1] | **Anna Walter**[1] | **Ali Hashemifarzad**[2] | **Jens Zum Hingst**[2] | **Christina von Haaren**[1]

[1]Leibniz University Hannover, Institute of Environmental Planning, Hannover, Germany

[2]Clausthaler Umwelttechnik Forschungszentrum (CUTEC), Clausthal-Zellerfeld, Germany

**Correspondence**
Julia Wiehe, Leibniz University Hannover, Institute of Environmental Planning, Herrenhaeuser Str. 2, 30419 Hannover, Germany.
Email: wiehe@umwelt.uni-hannover.de

**Summary**

Although the transition to energy supply through renewables (RE) is, in general, politically accepted in Germany, its progress is slowed by conflicting interests, primarily nature conservation and protesting residents. This study aims to find ways to solve these conflicts in Germany. To this end, the researchers developed a geospatial model that calculates RE potentials and vulnerabilities of nature and humans. Both data input and some evaluation standards are variables in the model. The outcomes are compared to an estimated total energy demand in 2050. Two ambitious scenarios ("no regret" and "compromise") show that a maximum of 4% of the German territory is available to meet the energy demand. This demand can be met using PV in urban areas and wind in rural landscapes without significantly impairing nature's and people's wellbeing. Solar parks and other potentials not considered in the model are treated as a reserve, which can be included if the energy targets are not met under the assumed scenario conditions. Such reserves also provide flexibility for co-determination in public participation.

**KEYWORDS**

energy transition, GIS modeling, nature protection, renewable energy potentials, target scenario, wind power

## 1 | INTRODUCTION

The transition to energy supply through renewables is one of the central global challenges of the 21st century. It is a major component of national strategies for achieving the international climate change agreements (COP 21) and ensures sustainable energy supply without the use of fossil fuels. Globally, the share of renewable energies (RE) in total primary energy was 14% in 2015.[1] Still, climate change is not the only challenge we face. The loss of biodiversity appears to exceed the planetary boundaries, even more than greenhouse gas emissions,[2-5] and it requires an integrated governance approach. Although the necessity of the energy transition is undisputed, the concrete implementation faces many conflicts concerning the scarcity of land and the impacts of RE installations on human health and nature. On the one hand, strong incentive mechanisms have motivated the expansion of renewable energies in several countries and especially in Germany. On the other, citizens' protests have delayed the construction of power grids and wind turbines in the vicinity of residential areas and in recreational landscapes. These challenges require an approach that integrates the modeling of future RE development potential with the respective vulnerabilities of nature and humans and the possibility to downscale sustainable energy targets. Furthermore, a recent analysis of data-uncertainty revealed that the use of coarse spatial data strongly affects the calculations of available area at the national level[6,7] and thus the projected energy revenue. Consequently, models should use the most current and detailed data in calculations on the national level, especially if targets should be downscaled.

Many approaches to determine RE generation potential have been developed for different countries with different input parameters, target values for energy demand or time frames for the conversion of the energy system. One early approach at the regional scale aimed to integrate nature conservation and energy transition. It used a broad set of criteria that included different ecosystem services, which are used to calculate the potential for sustainable RE use. This model can help identify the tradeoffs between efficient energy generation and impairment of the environment.[8,9] As of yet, scenarios until 2030 for many countries primarily use the LUT model, developed at LUT University Finland. It aims to minimize the total system costs and employs regional data such as: power and heat demand, existing power and heat capacities, financial and technical parameters, as well as limits for installed capacity of all available technologies.[10] The calculations were made for large areas such as the Middle East and North Africa region (MENA region)[11] or Europe.[12] The model gives a good overview of the effective energy potential and its relation to demand. However, it offers only course spatial specificity and does not consider nature conservation restrictions in sufficient detail.

Furthermore, economic criteria that determine the total system costs drive the scenarios calculated for a Europe of 100% RE in 2050.[13] The spatial analyses used in these scenarios are based on wind and photovoltaic capacities in locations with optimized energy potential that are outside protected conservation areas. The potential is calculated on the basis of the European Reanalysis Interim (ERA-Interim) weather dataset and Corine Land Cover (CLC), and thus they remain spatially unprecise.

Although these modeling approaches provide good overviews, they cannot replace necessary national analyses that are required to achieve the national obligations under the Paris agreement. The LUT model was used for several national case studies that calculate, for example, the potential future developments in the energy system of Kazakhstan,[10] Turkey[14] and South Africa.[15] Othernational studies have calculated the energy potential using rather coarse input data[16,17] and considering only nature within protected areas. Furthermore, all studies assume present-day conditions and do not consider future developments in electricity demand, expected for technological innovations or land availability in the next 30 years.[18-21] Kienast et al[16] also work on the national level and also include selected landscape services similar to Palmas et al.[9] Their research also reveals the limits of studies that are economically focused by highlighting the conflicts and restraints at the local level of expanding renewable energies. Once again, their study assumes the existing generation technologies and land uses as the status quo and does not consider future development opportunities. For Germany, the existing studies on the national level face a similar situation with respect to spatial resolution[22] and limited scope.

In light of the described gaps in research, our study aims to determine whether Germany can produce enough RE on the national territory to meet the demand in 2050 without impairing humans or nature. Furthermore, our study allows for flexibility at the local level in shaping the energy landscape. This required an approach that permits us to estimate the future demand for renewable energy and calculate possible RE generation, while considering the evolving technologies as well as societal and natural restrictions. For this purpose, the energy demand in 2050 was projected and a spatial model was developed that considers both the potential RE production and the vulnerability of nature and humans. From the beginning, the research has been closely aligned with the planning process, as this facilitates the transfer of scientific results into practice and uses the language and approach of local actors.

The model uses scenarios to explore the potentials and limits of a sustainable energy transition. The scenarios and resulting policy and governance implications help decision makers identify implementation measures that can be used for a nature-friendly design of the energy transition process. In the initial development of the model, we concentrated on wind energy in rural areas and photovoltaic (PV) in urban areas because this selection reflected the current political stipulations and societal attitudes in Germany.[23,24] The model can illustrate the maximum potential of wind and solar energy, which in case of roof PV is not likely to be fully implemented. Ground mounted PV, in contrast, is perceived to be in competition with land uses such as agriculture, nature conservation, leisure and recreation. There is a fear that the displacement of such land uses could lead to land use intensification and impact biological diversity elsewhere.[25] However, its potential must be considered, for example, if electricity production by wind and roof PV cannot be fully exploited. In general, input variables related to political decisions that define the scenario path may vary and need adjusting to reflect societal preferences on different political levels.

Because many factors influence the implementation of energy projects, such as national and European funding programmes, we have not yet performed cost calculations. Rather, we focused initially on land availability, as it greatly influences the financing and realization options of RE. Thus, the determination of potential land areas forms the basis for planning the implementation of the energy transition.

## 2 | METHODS

### 2.1 | Projection of the energy demand in 2050 and assumptions

The projection of energy demand in 2050 was based on: the extrapolated population and economic development, an expected rate of electrification in the transportation sector, as well as assumptions for building renovations, and so on (see Table 1). The assumptions can be adapted to different future preconditions. Under these conditions, we projected the final energy demand for the year 2050 that uses both ambitious and moderate assumptions. The energy demand represents possible target values that are used to assess the modeling results. If the demand cannot be met, either more ambitious demand reductions are required or more RE must be produced to meet the 100% target.

The transition to a predominantly electric power supply system was assumed for all scenarios. This enables the coupling of all sectors of the energy system such as electricity, heating, mobility and industry. In addition to the basic electricity demand, we had to consider fluctuations in the daily and annual cycle of the energy production. These fluctuations lead to a high storage demand with corresponding conversion losses. Only some industrial processes and air transportation will continue torely on liquid raw materials. For this demand, combustibles must be provided from biomass (biogenic residues) and from "Power-to-X." Power-to-X refers to technologies that convert electricity generated from renewable sources into physical energy stores, energy carriers, and energy-intensive chemical products.

Furthermore, the energy demand is based on the assumptions that heat pumps, which use ambient heat, are used to heat and cool households. The electricity demand for this technique is included in the calculation of the total energy demand.

### 2.2 | Modeling the sustainable electricity yield potential

#### 2.2.1 | Overview of the modeling component

A spatial approach was chosen to model the sustainable electricity production because land availability is a decisive limiting factor and the protection of nature and as of humans occurs in a spatial context. The challenges and conflicts between nature conservation and energy production can be identified only on a site-specific basis by placing RE power generators in areas with a low vulnerability for humans and nature.[16] For this reason, the nationwide calculation of potentials for a supply of RE requires the utilization of spatial data.[18,20] Furthermore, downscaling in spatial planning requires spatially explicit information. Consequently, the model was built in a geographical information system (GIS). We used the GIS-software ArcGIS 10.5 with the extensions "Geostatistical Analyst" and "Spatial Analyst".

The model includes the following components:

1. The assessment of valuable areas for nature and humans (nature conservation, recreation, noise

**TABLE 1** Variables for the projection of energy demand in 2050

| Population development by 2050 | Mobility | Building heat | Process heat | Power/light/ICT and refrigeration |
|---|---|---|---|---|
| Decline: −12%[26] | Electrification of 88% of passenger and freight traffic on roads and railways[27] | Annual renovation rate of 2.64%[27] | Reduction of process heat demand by 24% | Use of efficiency measures to reduce to 82% |
| Per capita GDP increases by 48%[28,29] | 11% reduced fuel consumption with remaining combustion engines[30] | Use of electric heat pumps (energy sources: electricity and ambient heat)[27] | | |

protection) and the determination of vulnerability classes with respect to RE generation (focus on wind and PV), in order to identify areas that should not be used for wind energy or only under specific conditions. This was achieved through: (i) literature-based definition of habitats and species sensitivity to power plants; (ii) expert-based definition of protection distances around other sensitive areas such as recreation landscapes; (iii) identification of areas of outstanding landscape beauty (according to[31]). Furthermore, the objectives and targets of the German biodiversity strategy[32] were spatially specified in order to consider nature conservation development until 2050.

2. Area-specific calculation of electricity yield potential for onshore wind energy and PV on rooftops;
3. Overlay of the results of the previous analyses to identify low vulnerability areas for wind energy that are suitable for power plants and calculating the resulting overall potential electricity production for Germany.

### 2.2.2 | Scenario design and input variables

In order to avoid risks to humans and nature, the scenarios calculated for Germany consider only areas where wind energy is not expected to have relevant adverse effects. Four categories of spatial vulnerability were created, whereby high spatial vulnerable areas are excluded from the production of wind energy. In contrast, in areas of low spatial vulnerability the production of wind energy is compatible with humans and nature.

One scenario, called "no regret", takes a particularly strict approach to a nature- and human-compatible expansion with renewables. The scenario "no regret" considers only areas that have a low spatial vulnerability to wind energy production, and thus, energy production in this scenario is compatible with human and nature needs without reservations. The second scenario, "compromise", also includes areas with medium vulnerability for allocating wind turbines that can be used with specific precautionary measures.

Details about the normative preconditions were defined in a transdisciplinary process with decision makers from federal administrations as well as NGOs. This process resulted in the decision that the project should focus on wind power generated outside urban areas and PV located inside urban areas. Thus, we have calculated the yield potentials for onshore wind energy and PV on roofs in a geoprocessing workflow, whereas the yield potentials of geothermal, hydropower and offshore wind energy were derived from existing studies (see Table 2).[41,42] A further project assumption was that the agricultural land presently used for food production should not be reduced in size.

**TABLE 2** Input variables for the scenarios

| | **Expected future technologies:** |
|---|---|
| Wind energy onshore | • Nominal power: 7.58 MW[33]<br>• Rotor diameter: 127 m<br>• Hub height: 200 m<br>• Max. sound power level: 108.5 dB(A)<br>• Safety distance between systems: 508 m<br>• Shutdown algorithms reduce environmental impact on bats[34] |
| Wind energy offshore | Expansion of offshore wind energy: 25 GW[35] |
| Photovoltaics on roofs | • Use of 51.8 million existing buildings[36]<br>• Extension of 4.9 million buildings by 2050[37]<br>• Use of the roof surfaces with a deviation of ±90° to the south orientation<br>• Percentage reduction in yield due to alignment<br>• Inclined roof (residential areas): 60% of the roof area can be used[38,39]<br>• Flat roof (industry and commerce): 80% of the roof area can be used, elevation 10°, east/west orientation[40]<br>• Efficiency 30%[40]<br>• Increase of usable facades and sealed traffic areas by approx. 10%[41] |

Using input from experts, we chose a single type of wind turbines that represents the future technology for 2050as the technical input variable. Furthermore, experts also determined the assumptions about the efficiency of photovoltaics; making it possible to consider the further development of the technology up to the year 2050. Table 2 shows the technical layout of the two scenarios.

In addition to the technological developments until 2050, the research considers nature conservation objectives; this includes the present state of nature protection as well as the official objectives for 2050, that is, the "National Strategy on Biodiversity".[32] Potentially, these objectives could conflict with both the existing and future RE plants as well as the yet unimplemented requirements of the Federal Nature Conservation Act. For example, the rotor blades of wind turbines represent a vertical, movable element that protrudes into the airspace of birds and bats, resulting in collision casualties. The collision risk depends on the location, the height of the turbine, the rotor diameter as well as the number, density and arrangement of the turbines in the wind farm.[43]

For the calculation of the individual spatial vulnerability classes (see Table 3), the vector data of the respective area categories were first transformed into a raster

**TABLE 3** Classification of the landscapes vulnerability concerning the selected wind energy turbine

| Vulnerability | In 2019 existing land categories | Areas with the potential for nature conservation according to the German biodiversity strategy |
|---|---|---|
| Very high vulnerability | • Surfaces with a slope of ≥30°[a]<br>• Settlements[b]<br>• Infrastructure[b,c]<br>• Areas with importance for leisure and recreation[b]<br>• Water areas[b]<br>• National parks[d]<br>• Wildlife sanctuaries[d]<br>• Natura 2000 network: FFH areas, bird sanctuaries[d]Buffer zone around settlement and infrastructure areas, calculated according to the height and sound level of the example plant[44]:<br>• Residential areas: 750 m<br>• Industry/Commercial areas: 75 m<br>• Motorways: 103,5 m[45]<br>• Federal roads: 83,5 m[45]<br>• Cables: 127 m[46]<br>• Routes to BNetzA: 127 m[46]<br>• Cable cars: 395,25 m[45]<br>• Rail routes: 263,5 m[45]<br>• Airports: 5.000 m[45] | • Green Belt Germany[47] (national monument along the former inner German border)[e]<br>• Military training areas & post-mining landscapes[d]<br>• Wilderness development areas[48] [g]<br>• Forest development areas[48] [g] |
| High vulnerability | • Ramsar Wetlands[d]<br>• Historical forest locations[f]<br>• Occurrence of sensitive bird species outside protected areas of category very high plus buffer zones[g]<br>• 200 m buffer zone around national parks, nature reserves, Natura 2000 areas,<br>• Biosphere reserves(core areas)[d] | • Landscape with high visual quality rating > 54 on a scale of 100[31] |
| Medium vulnerability | • Landscape conservation areas (German cat.) [d]<br>• Deciduous and mixed forests [d]<br>• Biosphere reserves (buffer zones and transition areas)[d]<br>• Buffer around recreation areas: 1000 m | • Areas and corridors of national importance for the biotope network[47] [g]<br>• Undissected low-traffic areas[d]<br>• Morphological riparian zones[e] |
| Low vulnerability | remaining areas without significant conservation value:<br>• Grassland[d]<br>• Arable land[d]<br>• Coniferous forests[d] | • Landscape with high visual quality rating < 54 on a scale of 100[31] |

[a] Digital elevation model (DGM 50): Federal Agency for Cartography and Geodesy (© GeoBasis-DE/BKG 2017).

[b] "Basis Landscape Model" of the "Authoritative Topographic Cartographic Information System" (ATKIS Basis-DLM): Federal Agency for Cartography and Geodesy (© GeoBasis-DE/BKG 2018).

[c] Extension of the lines of the power grid: Federal Network Agency (© BNetzA 2016).

[d] Federal Office for Nature Conservation (© BfN 2016-2018);

[e] Federal Office for Nature Conservation.

[f] Collection of historically old forest sites and important Hude forests in Germany: Federal Office for Nature Conservation (© BfN 2002).

[g] Based on Atlas of German Breeding Birds and Corine Land Cover 2018 (CLC v18_5_1, EEA), according to Reference 49·

format with a resolution of 50 m × 50 m. We used only high resolution input data, such as the "Digital Basis Landscape Model" of the "Authoritative Topographic Cartographic Information System" (ATKIS Basis-DLM) from 2018, which has a positional accuracy of ±3 m and is based on the Topographic Maps 1:10000/1:25000.[50] Infrastructure, such as roads or railway lines, were depicted as lines in the spatial input data and buffered with average width before transformation into raster. Noise protection buffer zones were mapped around residential settlements that could be affected by noise emissions from future wind technology. Furthermore, the spatial vulnerability classes encompassed existing protected areas, other valuable ecosystems and habitats of sensitive species as well as areas with high visual landscape quality.[31] We also spatially specified future nature conservation goals related to the German biodiversity strategy and defined potential areas for nature conservation until 2050.[32] These extended nature reserves include military training areas, post-mining landscapes and forest or wilderness development areas that are excluded from wind park development. Areas with medium vulnerability include, for example, undissected low-traffic areas, morphological riparian zones, areas not strictly protected in the National Biotope Network or buffer zones and transition areas of biosphere reserves (see Table 3).

Locations of wind turbines were identified by applying a fishnet of rectangular cells with a resolution of 508 × 508 m to Germany. Wind turbines were then located in the center of fishnet cells in areas of the low spatial vulnerability (scenario "no regret") and the medium spatial vulnerability class (scenario "compromise"). The wind turbines were arranged with a safety distance of four times the rotor diameter (508 m, Table 2).[51]

The on-site potential wind energy yield was calculated based on the average wind speed determined by the German Meteorological Service. This data depicts the wind speed at a height of 100 m above ground.[52] However, the wind speed was calculated at hub height of the wind turbine using the logarithmic wind profile, which can be taken to calculate the average wind speed at any given height.[22]

$$\text{Log wind profile}: v(h_2) = v(h_1) \times \frac{\ln \frac{h_2}{z_0}}{\ln \frac{h_1}{z_0}}$$

where[33] $h_1$ is the Reference height in m, $h_2$ is the new height in m, $v(h_1)$ is the wind speed at reference height in m/s, $v(h_2)$ is the wind speed at new height m/s, $hz_0$ is the ground roughness in m.

The calculation assumes a ground roughness of 0.10 m. In view of the spatial vulnerability, agricultural land was considered more suitable for wind turbines than structurally rich, forested areas or in built-up areas.[22,53]

The framework for calculating the potential electricity yield uses the performance curve of the wind turbine[54] and the average on-site wind speed. Because the wind does not blow uniformly throughout, we calculated the relative distribution of the wind speeds. The relative wind speed frequency represents how consistently a wind speed occurs at a location. The relative frequency distribution was calculated using the Rayleigh distribution because the German Meteorological Service does not provide the Weibull parameters for all heights. $K$ is assumed to be monotonically increasing in most cases. However, measurements have shown that this extrapolation is only valid to a limited extent.[55] From a height of 70-80 m the $k$-value decreases more strongly, making it difficult to determine $k$. Since the form parameter in Northern Europe is on average 2, we calculated the Rayleigh distribution using $\underline{k} = 2$, which makes it possible to approximate the relative frequency distribution.

Rayleigh distribution ($a_{k = 2}$ and $k = 2$):[22]

$$(v) = \frac{\pi}{2} \times \frac{v}{\bar{v}^2} \times \exp\left(-\frac{\pi}{4} \times \frac{v^2}{\bar{v}^2}\right)$$

We used the usable roof areas and irradiation data (average values) to determine the potential electricity yield of PV. In addition to the existing buildings, we included the projected growth by 2050. To determine the usable roof area, we distinguished between residential buildings and industrial and commercial buildings. A saddle roof was assumed for residential buildings and a flat roof for industrial and commercial buildings.[22] However, not the entire surface of both pitched and flat roofs can be used for PV, because installations, ventilation shafts, chimneys or windows reduce the usable area.[56] We have assumed that on pitched roofs 60%[38,39] and on flat roofs 80%[22] of the surface can be used for modules with an efficiency of 30% (see Table 2).

The calculation of the usable roof area is based on the data set "house surrounds." The house surrounds describe georeferenced ring polygons of building floor plans and show the shape, location and extent of buildings. For flat roofs, the roof area corresponds to the ground area of the building. For pitched roofs, the roof area is calculated using the ground area and the pitch angle of the roof,[57] which is between 20° and 50°in Germany.[58] For the calculation of pitched roof areas, we assumed an average roof angle of 35°[57] and included the south-facing half of the roof. We calculated the pitched roof potential (A) as follows:

$$A = a \times b \times \frac{1}{2 \times \cos\sigma}$$

where $a$ is the longer side of the ground plan, $b$ is the shorter side of the ground plan.

A map of site-related PV production for Germany (showing kWh per year for the installation of 1 kWp) served as the basis for calculating the yield of PV on roofs, considering 30% efficiency and the potentially usable roof area. The efficiency of the PV systems was recalculated to determine the required area for the installation of 1 kWp, whereby 100% efficiency corresponds to 1 $m^2$/kWp. On the basis of the roof area and information about the required area of the PV modules for the installation of 1 kWp, we determined how much kWp capacity can be installed on a building. Since pitched roofs rarely have an exact orientation to the south, the potential electricity yield was reduced depending on the orientation of the buildings.

$$\text{Yield calculation for PV on roof areas (Y)}:$$
$$Y = pra \times \frac{ur}{m} \times yr$$

where *pra* is the potential roof area, *ur* is the usable roof area factor, *m* is the $m^2$ required for 1 kWp, $\alpha$ is the roof angle, yr is the yield reduction due to orientation/slope.

The higher deviation from the south orientation was, the greater the reduction in yield was. For example, 15% was deducted from the yield calculation of flat roofs because of the east–west orientation and 10° mounting of the modules.

In general, it should be added that nationwide only the used house surrounds are available as spatial data for the calculation of the potential area for rooftop PV. Therefore, we derived the assumptions that all house surrounds outside of industrial areas are covered with pitched roofs. This assumption in the model holds uncertainties, since flat roofs occur outside of industrial areas and industrial buildings can have pitched roofs.

## 3 | RESULTS

The main findings of the study are illustrated in two exemplary scenarios or snapshots of 2050. The snapshots clarify what is possible and point out alternative management variables.

### 3.1 | Energy demand in 2050

The projection shows that 1771 TWh/a are required to meet the German energy demand in 2050 under ambitious assumptions for demand reduction. The demand includes: 1227 TWh/a electricity (consisting of 818 TWh/a consumption plus an additional 50% of the electricity demand in order to compensate for storage and conversion losses) and 229 TWh/a ambient heat for use in electric heat pumps. In addition, other energy supply sectors must be decarbonized, for example raw materials for the chemical industry or fuels for air transportation. For these non-electrical sectors, a demand of 315 TWh/a was calculated, of which 60 TWh/a can be obtained from biogenic residues and waste materials. Furthermore, the electricity surplus that was calculated for the scenarios can also be used to meet the demand. The remaining 255 TWh/a can be produced in Power-to-X processes (ie, Power-to-Heat, Power-to-Gas, Power-to-Chemicals). However, the approx. 50% conversion losses of the Power-to-X may require 510 TWh/a of electricity in order to meet the 255 TWh/a demand. The demand for electricity thus increases to around 1737 TWh/a.

The projected total energy demand can be compared to the results of other studies that also simulate the German energy system for the year 2050.[59-61] They all assume a reduction in energy demand to around half of today's consumption, even though electricity demand will increase. This would require implementing intensive energy efficiency measures.

### 3.2 | Area potentials in 2050

In order to determine the area potentials for wind energy in the "no regret" scenario, the land area of Germany was classified into four classes that reflect the different levels of vulnerability of nature and human wellbeing to an exemplary standard wind turbine 2050 and its projected mechanical, visual and acoustic impact on the environment (see Figure 1).

The areas of the low vulnerability class cover a total of 5320 $km^2$ and thus represent 1.5% of Germany's land area (Figure 1). The areas of the medium vulnerability class cover 8303 $km^2$, which represents 2.3% of the land area in Germany. The respective areas can be used for the production of wind power after a case-by-case examination of the local conditions. Thus, in areas with low or medium vulnerability the installation of wind turbines is, in principle, possible without causing unsolvable conflicts. For the PV potential, we calculated the possible energy yield using data about building perimeters. The potentially usable area of the pitched roofs comprises 2005 $km^2$ and 282 $km^2$ of the flat roofs are potentially usable for the installation of PV modules.

### 3.3 | Energy potential in the scenarios

In the first scenario "no regret," the calculation of the potential electricity yields included only areas with low vulnerability. Thus, on 5320 $km^2$ of land approximately 310 TWh/a electricity from onshore wind power can be produced. In addition, 900 TWh/a of solar power could be produced on the potential area of approximately

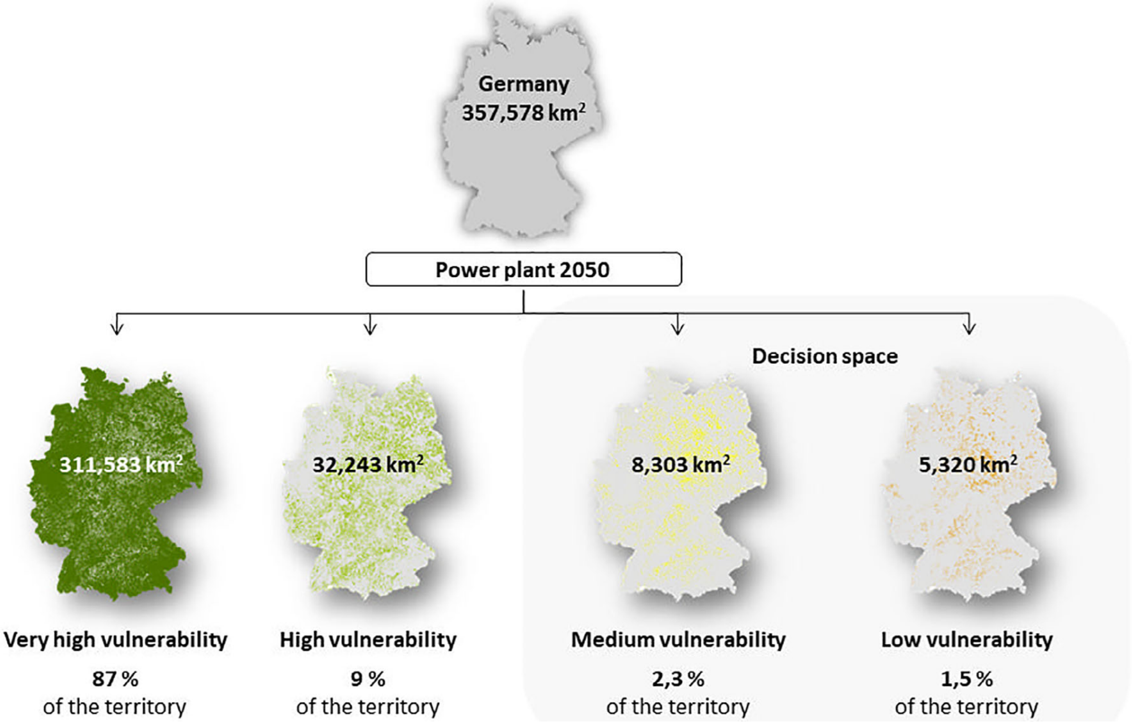

**FIGURE 1** Vulnerability of the German territory to the standard wind power plant 2050 and potential area for the nature and human compatible production of wind power in Germany using strict nature conservation criteria and the standard power plant 2050 (Nominal power: 7.58 MW, hub height: 200 m, rotor diameter: 127 m, Sound power level: 108.5 dB[A]) [Colour figure can be viewed at wileyonlinelibrary.com]

3000 km$^2$ of rooftops, facades and sealed traffic areas in Germany. Thus, a human- and nature-compatible total electricity yield potential of approx. 1 Wh/a can be produced sustainably. This would exceed the projected electricity demand in the target year 2050. PV electricity accounts for the largest share of the electricity mix at 64% (see Figure 2 and Table 4). We assume that this potential would even increase if spatial data were available nationwide to depict roof types. With a raise in the share of flat roofs, the potentially usable area would increase and thus the electricity yields. These uncertainties are integrated in the bar chart (Figure 2) by a “phasing out” of yields. The electricity potential from onshore wind turbines has a share of 22%. Furthermore, we assumed 8% from offshore wind energy on the basis of present production as well as current contribution from hydropower and geothermal power.

In a second scenario “compromise”, the areas with medium vulnerability to nature and human wellbeing were included in the calculation (an additional 8303 km$^2$). The production area for solar power remains unchanged. Under these assumptions, the potential electricity yield increases to nearly 1900 TWh/a (see Table 4).

Our model results show that the suitable area would be sufficient to cover the electricity demand of 818 TWh/a (+409 TWh/a electricity storage) in the year 2050 (see Figure 2). A surplus of 181 TWh/a (scenario “no regret”) up to 664 TWh/a (scenario “compromise”) of electricity could be produced. This surplus can cover the projected demand for non-electric uses, which adds up to 510 TWh/a including 50% conversion losses. Additionally, about 60 TWh/a would be available from residual organic substances as an energy source for non-electric demand.

The land use for wind power plants is about 1.5% of Germany's land area in scenario “no regret” and 3.8% in scenario “compromise.”

The scenarios' assumptions still do not encompass all of the options to reduce or satisfy the energy demand in 2050 (see Figure 3). The potentials that have been excluded are: solar parks outside urban areas, a supplementary potential of off-shore wind and geothermal energy. Other factors not yet considered include changes in lifestyle, for example, in mobility, as well as using innovative technology that are still being tested, for example, technologies to avoid bird collisions or technological development in the field of energy efficiency. Furthermore, the import of sustainably generated energy from other countries was not considered in the defined limits of the scenarios. However, these unconsidered

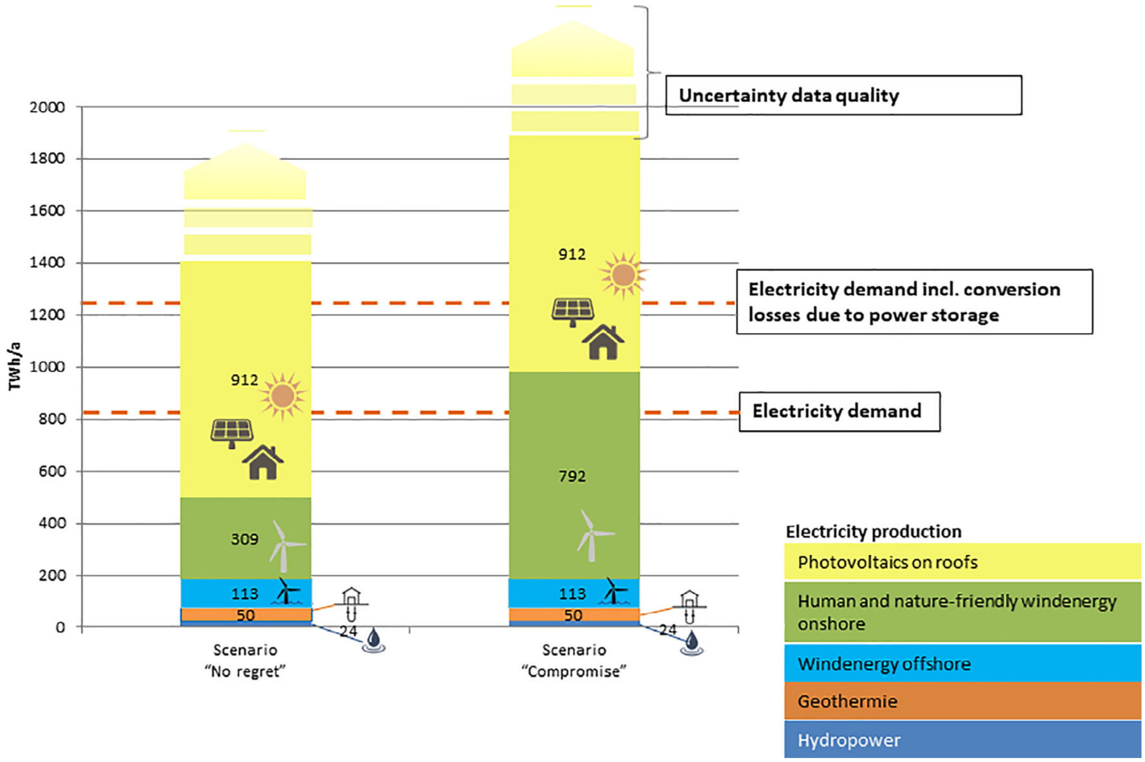

**FIGURE 2** Comparison between the potential to generate electricity in 2050 in a way compatible to nature and humans and a projected electricity demand under ambitious assumptions about electrification and energy efficiency [Colour figure can be viewed at wileyonlinelibrary.com]

**TABLE 4** Overview of the electricity yield potentials of the energy sources considered for Germany in 2050

| Energy source | potential electricity yield in scenario "no regret" | potential electricity yield in scenario "compromise" |
|---|---|---|
| Wind energy offshore | 113 TWh/a | 113 TWh/a |
| Wind energy onshore | 309 TWh/a | 792 TWh/a |
| Photovoltaics on roofs | 912 TWh/a | 912 TWh/a |
| Hydropower | 24 TWh/a | 24 TWh/a |
| Geothermics | 50 TWh/a | 50 TWh/a |
| *Total potential electricity yield* | *1408 TWh/a* | *1891 TWh/a* |

potentials can be seen as a "reserve" for the calculation of further scenarios. These untapped potentials for RE saving and generation also provide fall-back options. These options can be considered if poor implementation does not achieve the smart trajectory of the calculated scenarios or to provide public participation with additional options.

For political management of the energy transition, the model offers a flexible tool that brings demand and supply in line and helps to identify the necessary political action (Figure 3). If monitoring shows that implementation fails in one field then other variables can be introduced. For example, when the targets for site related energy generation are not achieved then demand can be decreased or other generation potentials can be activated. Furthermore, the model provides the information basis for defining local priorities that consider the trade-offs between impact on nature and energy yield. For instance, if areas that have medium vulnerability but very high potential electricity yields could be prioritized, then the overall space required for the energy transition would be minimized.

In summary, the study shows that human and nature compatible energy supply from 100% renewables are possible in 2050. The expansion of RE can be achieved when there is an optimal allocation of energy generation plants that follows the assumed, strict and very ambitious goals for landscape conservation and noise protection. Reserve potentials provide additional options for implementation, uncertainties and public participation.

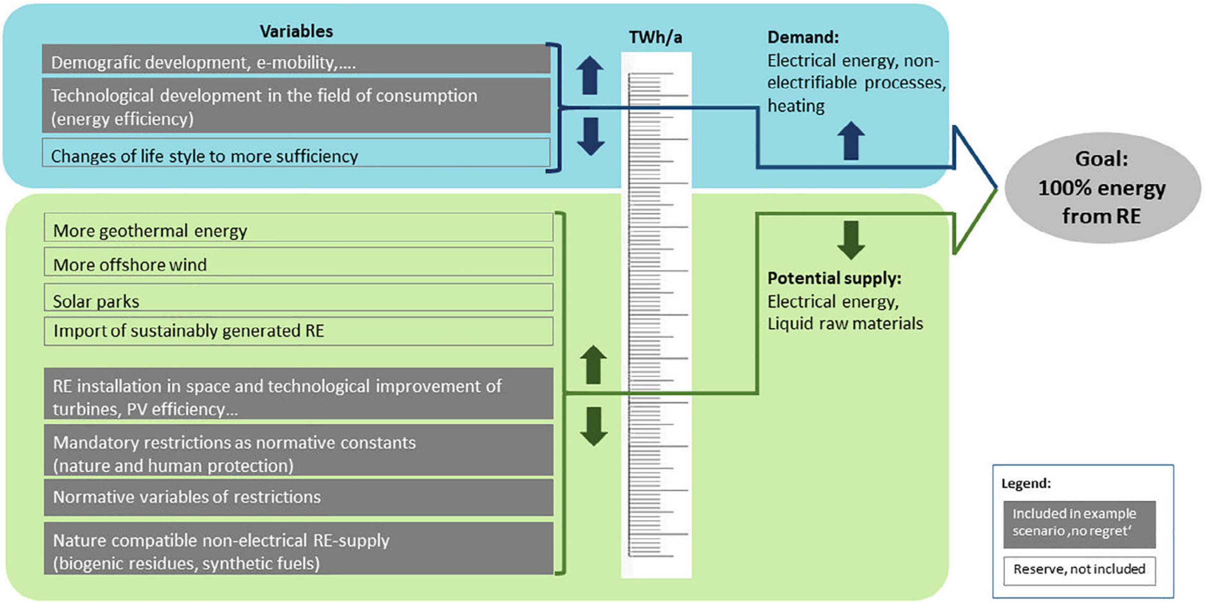

**FIGURE 3** Variables of calculating energy demand and supply in RE100: Change of variables leads to different energy demands or yields, thus supporting decision makers in choosing the transition path without losing sight of the goal. Blue = energy demand, green = potential energy supply [Colour figure can be viewed at wileyonlinelibrary.com]

## 4 | DISCUSSION

The scenarios show that, in Germany, an energy transition to 100% renewable energies can meet the projected energy demand in 2050, without compromising the goals of nature conservation and impacting human wellbeing. The model considers transmission and conversion losses during electricity storage. Furthermore, the scenarios include ambitious assumptions concerning the energy demand until 2050 as well as an additional reduction of energy demands through new technologies. However, the assumptions remain quite schematic in the first application of the model because it does not use local variations of wind and solar technology. Electrical engineers guided our assumptions about future development of the RE plants. Therefore, both the energy yield of the individual plant types and the total area used are different from current practice. The very ambitious target assumptions for the year 2050 help to articulate political options for action, without previously considering their political feasibility.

Although the implementation of the modeled scenarios requires determined political action, it would be a crucial step toward fulfilling the obligations of the Paris agreement without compromising biodiversity conservation or human wellbeing.

Some assumptions have been defined and implemented in the two scenarios. Others, such as the identified “reserves” (Figure 3), offer flexibility in further scenarios to react to changes in realization, while still bringing demand and supply into line. For example, although life style changes are variable, they should be included in the estimation of the renewable energy demand assigned to mobility (see Table 2). Similarly, energy supply could be achieved by using wind-only in areas that are not built-up, as shown in the scenario example, or by including ground mounted PV in rural areas. Our model shows the spatial changes that occur when assumptions are altered. Changes can lead to larger or smaller restricted areas for onshore wind. This, in turn, would change the yields from renewables.

In order to use the model to define the leeway for locally specified energy targets, a more detailed exploration of the model's uncertainties is necessary. The position accuracy and actuality of spatial input data is decisive for the reduction of uncertainties. For this reason, we used the “Basis Landscape Model” of the “Authoritative Topographic Cartographic Information System” (ATKIS Basis-DLM) for the display of infrastructures, settlements, agricultural land and forests. It is the land cover model with the highest positional accuracy in Germany; unfortunately, it is only available free of charge to research projects. The modeling assumptions include another source of uncertainties, which for example, stem from the assumption that all residential buildings have saddle roofs and all industrial and commercial buildings are covered by flat roofs. Furthermore, this input data could be improved. For instance, potentially 3D building models[62,63] could be used to specify actually usable roof area and facade potential. Much harder to quantify are the uncertainties related to the projection of the demand (demographic development or willingness to introduce new technologies).

In contrast to the ambitious assumptions of the scenarios, the present reality of energy governance in Germany is quite different. The established energy production paths and instruments are not yet sufficient to meet the challenges of a human- and nature-friendly energy supply.

Overall, the energy transition is stagnating in Germany, which has long considered itself a pioneer of energy transition. In the Annual Energy Transition Index, a worldwide ranking of the World Economic Forum[64] Germany has dropped to 20th place. Currently, a vast majority of the German population supports the energy transition process.[23,65] The "Social Sustainability Barometer of Energy system transformation" found that an average of 79% of interviewees view energy system transformation as a joint task to which everyone in society should contribute.[65] However, only 19% of those surveyed are "strongly in favor" of onshore wind energy, and a further 28% are "in favor" of it. However, 36% of the respondents supported the expansion of offshore wind energy.

This attitude is also evident in the implementation of the energy transition on the local level. In 2019, wind energy registered its lowest growth rate in more than 20 years. The newly installed plant capacity was 77% below the average new plant capacity of the previous five years.[66] The reasons for the slow expansion are diverse. In addition to the complex legal and economic framework conditions, citizen protests are becoming increasingly frequent, making it difficult to realize the energy potential. The conflicts arise on many levels: between the population and the decision-makers, but also within the community between those who benefit from the energy transition and the supposedly disadvantaged. The decisive factor for acceptance of energy system transformation seems to be the personal attitudes and participation options of individuals.[67]

In many cases the overall goals of the energy system transition remain unclear, which makes the concrete implementation of energy projects at the local level more difficult.[68,69] As a result, the potential human and nature-compatible areas of the "no regret" scenario cannot be implemented without discussion and participatory processes.

In this context, the model can be used as a basis for public participation on the regional or local level when tailor-made targets for minimum RE generation are defined for individual political units. Such quantitative energy targets for local or regional political units, which in sum equal the national target, would enable flexible allocation and selection of energy mixes at the local level and avoid "not in my backyard" attitudes that jeopardize national targets. The definition of such energy targets would be based on the same national criteria and would clarify local responsibilities for the overall energy transition. At the same time, decision makers and citizens would be able to define their own implementation pathway within the context of the national target. Additionally, the model can help monitor how well regions achieve the national targets. Finally, the energy "reserves" offer additional options for an appropriate integration of local or regional preferences through local policies and public participation.

The changes to legislation and incentives that are required to make a difference are not extensive, but they are politically sensitive. Energy transition requires ambitious political frameworks that can be used to plan the energy system and the rapid implementation of energy technology innovations. This requires research about suitable combinations of legal, economic and communicative strategies and instruments.

A successful energy transition is also dependent on research and solutions from engineering science. For example, new developments in energy storage and grid expansion are immensely important. Future research can build on our approach by using spatial data to expand the possible applications of technical projections. Our scenarios are the first steps for the integrative modeling of energy systems that incorporate the spatial distribution of RE potentials as well as modeling consequences for grids and storage. The results of the study could also be used to calculate the cost of the transformation and to simulate transformation processes over time.

## 5 | CONCLUSIONS

Our study has demonstrated that conflicts between the goals of the transition to energy supply through renewables and the protection of humans and nature from impairments can be solved by intelligently allocating energy generation plants. Spatial modeling has proven to be a suitable approach to integrate both interests. Local targets for energy generation can be derived from the model and should, in sum total, achieve the national target. As long as targets for local energy saving and generation can be met, then local decision makers have flexibility concerning the RE mix and spatial allocation. Consequently, acceptance by the local population and decision making can be fostered without jeopardizing national targets through local "not in my backyard" attitudes.

Finally, the model offers a flexible tool to bring demand and supply in line and to deduce the necessary political action at the national scale. If monitoring shows that implementation fails to decrease demand or increase RE generation in one option, then other variables can be introduced. The model helps decision makers to recognize which alternative management variables are at their disposal.

Further research work should thus focus in particular on analyzing different approaches of implementing the energy transition at local level.

The specific results of the scenarios cannot be directly transferred to other countries. However, the basic approach could be applied elsewhere, as the model can use country specific data. Nevertheless, further research is necessary in order to adapt the model to the specific data and implementation situation of different countries. Working out such concepts for all countries with RE surplus for export, will for instance avoid eco-dumping in a globalized market for hydrogen.

Germany is a densely populated country where different land uses are competing for the same land area. Therefore, the overall results are especially encouraging and informative for countries with similar pressures, where the approach can be instrumental for designing a sustainable energy policy.

## ORCID

*Julia Wiehe* https://orcid.org/0000-0002-1224-4825

## REFERENCES

1. Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. *Energy Strat Rev*. 2019;24:38-50. https://doi.org/10.1016/j.esr.2019.01.006.
2. Rockström J, Steffen W, Noone K, et al. Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc*. 2009;14(2):32. https://doi.org/10.5751/ES-03180-140232.
3. Tanentzap AJ, Lamb A, Walker S, Farmer A. Resolving conflicts between agriculture and the natural environment. *PLoS Biol*. 2015;13(9):e1002242. https://doi.org/10.1371/journal.pbio.1002242.
4. WWF. *Living Planet Report - 2018: Aiming Higher*. Gland, Switzerland: World Wide Fund For Nature (WWF); 2018. https://wwf.panda.org/knowledge_hub/all_publications/living_planet_report_2018/.
5. Bundesamt für Naturschutz. *Daten zur Natur*. Bonn, Germany: Bundesamt für Naturschutz (BfN); 2016. https://www.bfn.de/fileadmin/BfN/daten_fakten/Downloads/Daten_zur_Natur_2016_BfN.pdf.
6. Thiele J, Wiehe J, Gauglitz P, et al. Eine mensch- und naturverträgliche Energiewende in Deutschland ist machbar. *Natur Und Landschaft*. in prep. 2020.
7. Neuendorf F, von Haaren C, Albert C. Assessing and coping with uncertainties in landscape planning: an overview. *Landsc Ecol*. 2018;33(6):861-878. https://doi.org/10.1007/s10980-018-0643-y.
8. Palmas C, Siewert A, Dossola F, von Haaren C, Rode, M. Smart spatial. In: Hofmann L, Sonnenschein M, eds. *Smart Nord: Final Report*. Hannover; 2015:235–258. http://smartnord.de/downloads/SmartNordFinalReport.pdf.
9. Palmas C, Siewert A, von Haaren C. Exploring the decision-space for renewable energy generation to enhance spatial efficiency. *Environ Impact Assess Rev*. 2015;52:9-17. https://doi.org/10.1016/j.eiar.2014.06.005.
10. Bogdanov D, Toktarova A, Breyer C. Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: case for Kazakhstan. *Appl Energy*. 2019;253:113606. https://doi.org/10.1016/j.apenergy.2019.113606.
11. Aghahosseini A, Bogdanov D, Breyer C. Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030. *Energy Strat Rev*. 2020;28:100466. https://doi.org/10.1016/j.esr.2020.100466.
12. Child M, Kemfert C, Bogdanov D, Breyer C. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renew Energy*. 2019;139:80-101. https://doi.org/10.1016/j.renene.2019.02.077.
13. Zappa W, Junginger M, van den Broek M. Is a 100% renewable European power system feasible by 2050? *Appl Energy*. 2019;233-234:1027-1050. https://doi.org/10.1016/j.apenergy.2018.08.109.
14. Kilickaplan A, Bogdanov D, Peker O, Caldera U, Aghahosseini A, Breyer C. An energy transition pathway for Turkey to achieve 100% renewable energy powered electricity, desalination and non-energetic industrial gas demand sectors by 2050. *Solar Energy*. 2017;158:218-235. https://doi.org/10.1016/j.solener.2017.09.030.
15. Oyewo AS, Aghahosseini A, Ram M, Lohrmann A, Breyer C. Pathway towards achieving 100% renewable electricity by 2050 for South Africa. *Solar Energy*. 2019;191:549-565. https://doi.org/10.1016/j.solener.2019.09.039.
16. Kienast F, Huber N, Hergert R, Bolliger J, Moran LS, Hersperger AM. Conflicts between decentralized renewable electricity production and landscape services – a spatially-explicit quantitative assessment for Switzerland. *Renew Sustain Energy Rev*. 2017;67:397-407. https://doi.org/10.1016/j.rser.2016.09.045.
17. Allen P, Varga L. Modelling sustainable energy futures for the UK. *Futures*. 2014;57:28-40. https://doi.org/10.1016/j.futures.2014.01.005.
18. Barrington-Leigh C, Ouliaris M. The renewable energy landscape in Canada: a spatial analysis. *Renew Sustain Energy Rev*. 2017;75:809-819. https://doi.org/10.1016/j.rser.2016.11.061.
19. Güngör-Demirci G. Spatial analysis of renewable energy potential and use in Turkey. *J Renew Sustain Energy*. 2015;7(1):13126. https://doi.org/10.1063/1.4907921.
20. Drechsler M, Egerer J, Lange M, Masurowski F, Meyerhoff J, Oehlmann M. Efficient and equitable spatial allocation of renewable power plants at the country scale. *Nat Energy*. 2017;2(9):289. https://doi.org/10.1038/nenergy.2017.124.
21. Rinne E, Holttinen H, Kiviluoma J, Rissanen S. Effects of turbine technology and land use on wind power resource potential. *Nat Energy*. 2018;3(6):494-500. https://doi.org/10.1038/s41560-018-0137-9.

22. Walter A, Wiehe J, Schlömer G, et al. *Naturverträgliche Energieversorgung aus 100% erneuerbaren Energien 2050*. Bonn, Germany: Bundesamt für Naturschutz (BfN); 2018 BfN-Skripten 501. https://www.bfn.de/fileadmin/BfN/service/Dokumente/skripten/Skript501.pdf.
23. Agora Energiewende. Die Energiewende im Stromsektor: Stand der Dinge 2018: Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2019. Berlin; 2019.
24. Firestone J, Kirk H. A strong relative preference for wind turbines in the United States among those who live near them. *Nat Energy*. 2019;4(4):311-320. https://doi.org/10.1038/s41560-019-0347-9.
25. BMU. Naturschutz und Photovoltaik. https://www.bmu.de/themen/natur-biologische-vielfalt-arten/naturschutz-biologische-vielfalt/naturschutz-und-energie/naturschutz-und-photovoltaik/. Accessed June 19, 2020.
26. STATISTA – Statistisches Bundesamt. 12. koordinierte Bevölkerungsvorausberechnung. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsvorausberechnung/Tabellen/altersgruppen-bis2060.html. Accessed December 12, 2019.
27. Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz. *Szenarien zur Energieversorgung in Niedersachsen im Jahr 2050: Gutachten*. Hannover; 2016.
28. WWF DEUTSCHLAND. *Modell Deutschland*: Klimaschutz bis 2050: Vom Ziel her denken; 2009.
29. Umweltbundesamt. Treibhausgasneutrales Deutschland im Jahr 2050. Dessau-Roßlau; 2013.
30. Pehnt M, Lutz C, Seefeldt F, et al. Klimaschutz, Energieeffizienz und Beschäftigung: Potenziale und volkswirtschaftliche Effekte einer ambitionierten Energieeffizienzstrategie für Deutschland. Berlin, Germany; 2009. https://www.ifeu.de/wp-content/uploads/Klimaschutz_Energieeffizienz_undBeschaeftigung.pdf.
31. Hermes J, Albert C, von Haaren C. Assessing the aesthetic quality of landscapes in Germany. *Ecosyst Serv*. 2018;31:296-307. https://doi.org/10.1016/j.ecoser.2018.02.015.
32. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. *Nationale Strategie zur biologischen Vielfalt: Kabinettsbeschluss vom* 7. November 2007. Ther Ber; 2007.
33. Walter A, Wiehe J, Schlömer G, et al., eds. Naturverträgliche Energieversorgung aus 100% erneuerbaren Energien 2050 (EE100): Anhang zum BfN-Skript 501.
34. Brinkmann R, Behr O, Niermann I, Reich M. *Entwi uktion des Kollisionsrisikos von Fledermäusen an Onshore-Windenergieanlagen*. 1st ed. Göttingen, Germany: Cuvillier Verlag; 2011. Umwelt und Raum. Schriftenreihe Institut für Umweltplanung; 4. https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5023208.
35. Bundesministerium für Wirtschaft und Technologie. *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*. Berlin, Germany: Bundesministerium für Wirtschaft und Technologie (BMWi); 2010. https://www.bmwi.de/Redaktion/DE/Downloads/E/energiekonzept-2010.html.
36. Datensatz der Zentralen Stelle Hauskoordinaten und Hausumringe (ZSHH) der Vermessungs- und Katasterverwaltungen der Bundesländer. Hausumringe (HU): Bundesamt für Kartographie und Geodäsie (BKG); 2014.
37. Statistisches Bundesamt. *Bautätigkeit und Wohnungen: Bautätigkeit*. Fachserie 5.
38. Quaschning V. *Systemtechnik einer klimaverträglichen Elektrizitätsversorgung in Deutschland für das 21. Jahrhundert*. [Zugl.: Berlin, Techn. Univ., Habil-Schr]. Als Ms. gedr. Düsseldorf: VDI-Verl; 2000. Fortschritt-Berichte VDI Reihe 6, Energietechnik; 437.
39. Kaltschmitt M, Streicher W, Wiese A, eds. *Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte. 4., aktualisierte, korrigierte und ergänzte Auflage*. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg; 2006.
40. Brendel R, Niepelt R. Kurzgutachten Photovoltaik zum Workshop I – Schwerpunkt Technologieentwicklung bis 2050 für das Projekt, Naturverträgliche Energieversorgung aus 100% erneuerbaren Energien 2050″. In: Walter A, Wiehe J, Schlömer G, et al., eds. *Naturverträgliche Energieversorgung aus 100% erneuerbaren Energien 2050 (EE100): Anhang zum BfN-Skript 501*:82–110.
41. Umweltbundesamt. Energieziel 2050: 100% Strom aus erneuerbaren Quellen. Dessau-Roßlau; 2010.
42. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz-EEG 2017). Ausfertigungsdatum: July 21, 2014. Zuletzt geändert durch Art. 5 G v. 13.5.2019 I 706.
43. Deutschen Rat für Landespflege e. V., ed. *Die Auswirkungen erneuerbarer Energien auf Natur und Landschaft: Gutachtliche Stellungnahme und Ergebnisse des gleichnamigen Symposiums vom19./20. Oktober* 2005 *in Berlin*; 2006; 79.
44. *Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (Technische Anleitung zum Schutz gegen Lärm – TA Lärm) vom 26. August* 1998 *(GMBl S. 503). Zuletzt geändert durch die Verwaltungsvorschrift vom 1. Juni 2017 (BAnz AT 08.06.2017 B5)*.
45. *Bundesfernstraßengesetz in der Fassung der Bekanntmachung vom 28. Juni* 2007 *(BGBl. I S. 1206), das zuletzt durch Artikel 1 des Gesetzes vom 29. November 2018 (BGBl. I S. 2237) geändert worden ist*.
46. Overhead electrical lines exceeding AC 45 kV - Part 3. National Normative Aspects (NNA), German Version EN 50341–3-4 (VDE 0210–3: 2011–01).
47. Fuchs D, Hänel, K., et al., eds. Länderübergreifender Biotopverbund in Deutschland: Grundlagen und Fachkonzept. Bonn- Bad Godesberg: Bundesamt für Naturschutz; 2010. Naturschutz und biologische Vielfalt; 96.
48. Rosenthal G, Mengel A, Reif A, Opitz S, Schoof N, Reppin N. *Umsetzung des 2% - Ziels für Wildnisgebiete aus der Nationalen Biodiversitätsstrategie: Abschlussbericht des gleichnamigen F+E-Vorhabens (FKZ 3512 85 0300 unter Integration von Zusatzauswertungen, FKZ 3515 85 0900)*. Bonn-Bad Godesberg: Bundesamt für Naturschutz; 2015. BfN-Skripten; 422. https://www.bfn.de/0502_skriptliste.html.
49. Busch M, Trautmann S, Gerlach B. Overlap between breeding season distribution and wind farm risks: a spatial approach: Überlappung zwischen Brutzeithabitat und Windkraftrisiken: Ein räumlicher ansatz. *Die Vogelwelt Wiebelsheim*. 2017;137(2):169-180.
50. AdV. Produktblatt: Digitales Basis-Landschaftsmodell (Basis-DLM); 2018.
51. Lütkehus I, Salecker H, Adlunger K. Potenzial der Windenergie an Land: Studie zur Ermittlung des bundesweiten Flächen- und Leistungspotenzials der Windenergienutzung an Land; 2013.

https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/potenzial_der_windenergie.pdf.

52. Windklimatologie in Höhen über 100 m für Gegenwart und Zukunft: DWD; 2016. https://opendata.dwd.de/climate_environment/CDC/grids_germany/multi_annual/wind_parameters/Project_QuWind100/. Accessed May 7, 2020.
53. Troen I, Petersen EL. *Europäischer Windatlas: [Annex]*. Roskilde, Denmark: Ris/o National Laboratory, Meteorological and Wind Energy Dept; 1990.
54. ENERCON GmbH. Für jeden Standort die passende Windenergieanlage: ENERCON Produktübersicht; 2015.
55. Seifert M. Windenergieanlagen mit großen Nabenhöhen. https://www.efiwind.de/fileadmin/user_upload/downloads/nh_und_ertraege_deu.pdf. Accessed May 7, 2020.
56. Mainzer K, Fath K, McKenna R, Stengel J, Fichtner W, Schultmann F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. *Solar Energy*. 2014;105:715-731. https://doi.org/10.1016/j.solener.2014.04.015.
57. Lödl M, Kerber G, Witzmann R, Hoffmann C, Metzger M. *Abschätzung des Photovoltaik-Potentials auf Dachflächen in Deutschland*. 11. Symposium Energieinnovation; 2010.
58. Schilling. Raum- und Siedlungsstrukturmodell zur vereinfachten Beschreibung der räumlichen Verteilung photovoltaisch nutzbarer Flächen: Dissertation. Paderborn.
59. Öko-Institut, Fraunhofer ISI. Klimaschutzszenario 2050: 2. Endbericht. [Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit]; 2015.
60. Nitsch J, Pregger T, Naegler T, et al. >Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global: Schlussbericht; 2012. https://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf. Accessed October 9, 2019.
61. Umweltbundesamt. Treibhausgasneutrales Deutschland im Jahr 2050. Dessau-Roßlau: Umweltbundesamt; 2014. Climate change; 2014,07.
62. Liang J, Gong J, Zhou J, Ibrahim AN, Li M. An open-source 3D solar radiation model integrated with a 3D geographic information system. *Environ Model Software*. 2015;64:94-101. https://doi.org/10.1016/j.envsoft.2014.11.019.
63. Imenes AG, Kanters J. 3D solar maps for the evaluation of building integrated photovoltaics in future city districts: A norwegian case study. Paper presented at: 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC): 5–10 June 2016 Piscataway, NJ: IEEE; 2016:3141–3146.
64. World Economic Forum. Fostering Effective Energy Transition: 2020 edition. [Insight Report]; 2020.
65. Institut für transformative Nachhaltigkeitsforschung. *Soziales Nachhaltigkeitsbarometer der Energiewende*; 2018. Accessed April 29, 2020.
66. Wind FA. Ausbausituation der Windenergie an Land im Jahr 2019. Auswertung windenergiespezifischer Daten im Marktstammdatenregister für den Zeitraum Januar bis Dezember 2019; 2019.
67. Hoeft C, Messinger-Zimmer S, Zilles J. 13. Bürgerproteste in Zeiten der Energiewende Ein Fazit in neun Thesen. In: Hoeft C, Messinger-Zimmer S, Zilles J, eds. Bürgerproteste in Zeiten der Energiewende. Bielefeld: transcript Verlag; 2017.
68. Wiehe J, von Haaren C, Walter A. How to achieve the climate targets?: spatial planning in the context of the German energy transition. *Energy Sustain Soc*. 2020;10(1):471. https://doi.org/10.1186/s13705-020-0244-x.
69. Ohlhorst D. Germany's energy transition policy between national targets and decentralized responsibilities. *J Integr Environ Sci*. 2015;12(4):303-322. https://doi.org/10.1080/1943815X.2015.1125373.

**How to cite this article:** Wiehe J, Thiele J, Walter A, Hashemifarzad A, Zum Hingst J, von Haaren C. Nothing to regret: Reconciling renewable energies with human wellbeing and nature in the German Energy Transition. *Int J Energy Res*. 2021;45:745–758. https://doi.org/10.1002/er.5870