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Exploring the decision-space for renewable energy generation to enhance spatial efficiency

Claudia Palmas *, Almut Siewert [1], Christina von Haaren [2]

Institute of Environmental Planning, Leibniz University of Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany

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ABSTRACT

Decentralized power generation can play a significant role in contributing to renewable energy (RE) supply. Accordingly, regions can be important players in the transformation of the energy system. However, only scarce spatial capacities are available for a sustainable RE generation. Knowledge gaps exist concerning data and methods for integrating RE assessment and environmental planning methods. This paper presents a methodology for the integrated assessment of different RE potentials and their land requirements. The potential is contrasted with the actual availability of land for RE-generation considering environmental restrictions. An application in the Hanover region demonstrates that using energy capacity maps supports using the most efficient mixture in RE generation. Generally, a combination of wind and solar energies produces the highest energy yield per ha. Furthermore, relying primarily on generalized environmental restrictions for defining exclusion areas can be only a first step: On the one hand the assessment is probably underrating the potential for environmentally sound RE generation due to the undifferentiated exclusion of large areas of a certain protective status. On the other hand, some energy sources, in particular energy crops for bioenergy generation, are malpositioned due to missing spatially explicit information about ecosystem sensitivities and a lack of regulative possibilities. Further research is needed to explore synergistic combinations of energy potentials and their environmentally sound spatial allocation in more detail.

Introduction

The German government's decision to increase the share of renewable energies (REs) in final electricity consumption to at least 80% in 2050 has resulted in a large scale expansion of RE energy generation facilities across the country (BMU, 2011). A legal framework for the systematic development and regulation of decentralized energy systems is formulated in the German Renewable Energy Act (Erneuerbare Energien Gesetz EEG) (2000, latest EEG amendment 2012). This framework follows a feed-in tariff based approach, which guarantees compensations for investors (Kemfert and Horne, 2013). In comparison to fossil and nuclear energy sources, renewable energy production supports sustainability in many ways. For instance, it is an important approach towards climate-neutrality, reduces resource consumption and impacts on human health (Breitschopf and Memmler, 2012; Evans et al., 2009; Krewitt and Schlohmann, 2006). However, the country has also experienced the severe impacts that RE can instigate on ecosystems and landscapes (Bosch and Partner, 2007, 2010; DRL, 2006; Nitsch et al., 2004; Reinhardt and Scheurlen, 2004; Rodrigues et al., 2010), especially due to the initial, largely unregulated, implementation of the different types of RE facilities (Bosch and Peyke, 2010; Chang et al., 2013; Haaren et al., 2013). This conflict was intensified by discussions about the competition between bioenergy and food production in many regions. As a consequence, public protests against wind power stations, electricity grids, or increasing maize cultivation became common in many regions (Althaus, 2012; Becker et al., 2012; Buschmann, 2013; Kemfert and Horne, 2013). This was in spite of the German public largely supporting the energy policy ("*Energiewende*") (AEE, 2013). Moreover, the numerous efforts to implement a regenerative energy system in Germany were hampered by limited capacities of knowledge about specific RE impacts in different environments, instruments to avoid them, as well as sufficient spatial data (Bosch and Peyke, 2010; Calvert et al., 2013; Haaren et al., 2013; Peters, 2013). Sectorial approaches from either energy or environmental policies alone are not capable of solving the abovementioned problems. Instead, it is necessary to adapt or develop new methods for the estimation of renewable energy potentials (Palmas et al., 2012) and to maximize the efficiency of land consumption for RE generation on the regional and local scale (Calvert et al., 2013; Diefenbacher, 2009; Haaren et al., 2013; Peters, 2013). This can be achieved by the optimal exploitation of combined RE potentials with simultaneous minimization of environmental

* Corresponding author. Tel.: +49 511 762 5359.
E-mail addresses: palmas@umwelt.uni-hannover.de (C. Palmas), siewert@umwelt.uni-hannover.de (A. Siewert), haaren@umwelt.uni-hannover.de (C. von Haaren).
[1] Tel.: +49 511 762 5359.
[2] Tel.: +49 511 762 2652.

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trade-offs (Bosch and Partner, 2010; Haaren et al., 2013; Peters, 2013). Until now, methodologies to this end are missing or still unsatisfactorily developed (Palmas et al., 2012; Peters, 2013).

The objective of this paper is to explore the "decision-space" in regional planning for RE development. For this purpose we combine three different kinds of models which are already established in current planning practice but which are often less accurate and spatially explicit. Firstly, we define theoretical RE potentials. The theoretical potential describes the theoretically usable energy supply within a given region in a given period and is only determined by the physical usage limits (cf. Rode et al., 2005). Secondly, we adjust the theoretical potentials under consideration of existing technical requirements which limit their exploitation. Thirdly, we focus on the ecological restrictions of RE exploitation. For an initial approach, we analyze mandatory and recommended exclusion areas (i.e. exclusion areas based on either legally established or general expert standards, as defined by law, or in current planning guidelines). Together, these analyses allow a first, spatial approximation to the technical RE potentials on the regional scale. The technical RE potential is the theoretical potential minus the existing technical limitations, as well as the ecological, economic and social restrictions (ibid.). The technical potential strongly depends on the technical level and describes in this study the energy production per unit area. By applying these integrated models on a given region, the decision-space for spatial planning and RE development becomes significantly more transparent and can therefore support crucial planning decisions, including possible trade-offs and synergies, to a large degree.

The necessary environmental compatibility of RE development should be achieved by a high spatial efficiency of RE production and by considering environmental restrictions. The presented method is designed for using data which should currently exist for many European regions. After a description of the methodology (section 2), the paper presents results of a case study from the Hanover region (section 3). Finally, the implications of the results, for the enlargement of the "decision-spaces", and identified needs for further research are discussed.

Materials and methods

The presented methodology consists of several modules assessing renewable energy, source-specific (sectorial) and combined potentials (wind, solar and biomass/maize energies), as well as actual or recommended environmental restrictions. In this case study, we had access to existing or developed methods and data currently available for the case study region (see Table 1). Such methods and data were similarly available for other German and European regions (e.g. Sliz-Szkliniarz, 2013).

The case study, Hanover region, is situated in the federal state of Lower Saxony and encompasses 21 municipalities and towns, including the City of Hanover, within a total area of around 2300 km^2 (Landeshauptstadt Hannover, 2014). The modules are integrated for defining the current decision-space for both, sectorial and combined power production and facilities. In order to locate and quantify the RE potential (Domínguez et al., 2007), geographical distribution potentials are modeled according to geophysical properties (Calvert et al., 2013), for instance solar irradiation, wind speeds, biomass availability and distribution. These factors are site-specific variables related to land use, latitude, altitude, climate and terrain properties (ibid.). We did not examine surface waters or human settlements ("not analyzed"). The latter were not examined due to methodical reasons, as different criteria are relevant for assessing built environments than for open landscapes. The derived information and the spatial data acquisition are a crucial first step in terms of accuracy and precision of energy mapping. The results are expressed as the technical energy mix potential estimation, which is here defined as the power energy per unit area (power density) in [W/m^2].

In addition to geographical and technical constraints, regional political decisions also define the exploitable RE potentials. Thus the exploitable potential of each RE is only a fraction of its theoretical potential. The modules analyzing spatial restrictions are necessary to prevent an overestimation of energy potentials. Furthermore, other site-specific characteristics, such us the slope, were considered to best identify suitable areas for RE development (i.e. photovoltaics). For instance, a flat surface is suitable for either solar panels or wind turbines, or for biomass use and wind turbines. The different information layers are integrated by GIS layer intersections.

Estimation of renewable energy potentials

Spatial solar energy potential

The solar potential raster map is calculated using open-source solar radiation tools, including the *r.sun* solar radiation model implemented in GRASS GIS (6.4.2) and the PVGIS CM-SAF estimation utility, derived from the Photovoltaic Geographical Information System Interactive Maps (Joint Research Center of the European Commission, 2010). The PVGIS calculation of PV potential for a specific site is based on spatial data automatically taken from the PVGIS database (Palmas et al., 2012). Generally, the overall error for an entire year is quite small (approximately 5%) (ibid.). An important factor in producing reliable maps of solar irradiation is the estimation of sky cloud coverage, as the total amount of cloud cover significantly affects ground irradiation. For this reason, the data was validated using PVGIS. The latitude was computed directly from the DEM raster, while the albedo and the Linke turbidity were believed constant for the entire region, as a first approximation. The clear sky indexes were not available. After validation of the data by using the PVGIS CM-SAF estimation utility, the output raster maps are derived on horizontal surface and show the annual average of global irradiation in the Hanover region [Wh/m^2/d].

Spatial wind energy potential

To create wind energy potential maps, wind speeds at 10 m from the ground level were used with 200 m resolution. The data was derived from the German Weather Service ("Deutscher Wetterdienst"). The reference period is from 1981 to 2000. Factors such as roughness (relief and land characteristics), height above sea level and geographical location were considered in the estimated average annual wind speeds of the German Weather Service. Differences between calculated and measured speed are about ± 0.15. The wind raster map was rescaled on a Digital Elevation Model (DEM) at 50 m. Other wind potential maps at 65, 100, 140 and 180 m were estimated in accordance with the following equation (Eq. (1)) (Counihan, 1975; Touma, 1977), which represents a conventional approach to describing the increase in wind speed with height:

$$v = v_{ref}(z/z_{ref})^{\alpha} \tag{1}$$

where:

v	wind speed at height z above ground level;
v_{ref}	reference speed, i.e. a wind speed we already know at height z_{ref};
z	height above ground level for the desired velocity, v.;
z_{ref}	reference height, i.e. the height where the wind speed is measured v_{ref}.

Eq. (1) assumes that the atmosphere is in a neutral stability condition (i.e. that the ground surface temperature is equal to air temperature). The exponent, α, is an empirically derived coefficient that varies depending on the stability of the atmosphere. For neutral stability conditions, α is approximately 0.143 (ibid.). The wind raster map at 10 m above ground level was obtained by downscaling the data of Weather German Service on DEM (50). Eq. (1) (cf. Counihan, 1975; Touma, 1977) was used to calculate other wind speeds (i.e. at 100 m) on a