Optimizing decentralized renewable energy production by combining potentials and integrated environmental impact analysis - A case study in the Hannover region

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Abstract

In Europe, the integration of decentralized renewable energy production in regional planning processes plays a crucial role. In particular, regions face a major challenge in order to set up renewable decentralized energy systems and incorporate them into the electricity grid. This paper presents a methodological concept and preliminary tests of applications in order to create an optimization model for an improved renewable energy development and planning practice: firstly, the energy potentials of micro renewable resources are estimated, and secondly the outcomes are combined with an estimation of resulting environmental impacts. Including these data into the spatial analysis, different scenarios can be developed in order to support decision making in landscape planning on the basis of environmental and landscape criteria as well as energy issues, including technical aspects and costs. The case study area is the Hannover region. First results show good energy potentials, which will be in a next step evaluated and combined with environmental impacts in order to improve energy efficiency by integrating renewable, decentralized power plants and energy mix.

1. Introduction

In Europe, energy efficiency in combination with the minimization of environmental impacts is a key objective. Decentralized energy production from renewable technologies (such as wind, solar, biomass, hydroelectric power and geothermal) can provide a significant source of renewable climate-friendly energy. Thereby, decentralized power generation can be defined as *an electric power source connected directly to the distribution network or on the customer side of the meter (*Ackermann et al., 2001). Today, micro energy plants as well as the household, originally conceived as passive in receiving energy, is expected to become active in producing energy itself. Yet, the energy produced should be varied, reacting to demand (cf. BEER, 2009).

Thereby, **s**mart grids are expected to transform today's power distribution systems from centralized energy production and one-way transmission to flexible, interactive, bidirectional and efficient distribution systems (NIST 2010). Smart grids, also called intelligent grids, may be the key for reducing peaks in electricity demand at the local level in order to increase the capacity to host renewable and distributed electricity sources. According to the European Technology Platform, smart grids are defined as *electricity networks that can intelligently integrate the behavior and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies* **(**European Technology Platform, 2010).

The large-scale installation and utilization of decentralized renewable energy technologies presupposes significant investment, relevant changes of all sectors of energy use, legislative and organizational modifications, integration of multicriteria environmental considerations and the adjustment of regional planning and public participation (Haaren et al., 2012).

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These technologies have many advantages: high energy efficiency, reliability, safety, blackout prevention and mitigation, low noise levels, as well as low impacts on climate change due to reduced GHG emissions (Beith et al., 2004).

While the use of renewable energy sources significantly lowers GHG emissions, it can at the same time significantly increase the consumption of land and moreover cause severe environmental impacts (Haaren et al., 2012; Nitzsch et al., 2004). In particular, the lack of planning causes unnecessary trade-offs between the need of climate change prevention on the one hand, and nature conservation as well as environmental protection on the other hand, becomes obvious (Haaren et al., 2012). In Germany, this trade-off between climate protection and nature conservation has led to several public conflicts over energy-related land-use issues (Haaren et. al, 2012; Bosch/Peike 2010).

This situation leads to the need of new planning approaches, which integrate the objectives of decentralized energy generation, energy efficiency, and sustainable landscape and housing development. In order to cope with this complex task, methodological approaches are needed which enable planners to find the most suitable and sustainable sites for new renewable power plants or decentralized micro generation. Present scientific knowledge can support this task, but is partly incomplete or has to be put into a new methodological context (Duvarci/Kutluca 2008).

Sustainable energy development focuses on the prospects of changes in the transport sector and urban structure in order to reduce energy consumption; specifically, this need addresses transport management, building design, energy efficiency, and land use planning. However, current planning practice does not include an effective land-use energy evaluation (ibid.). Moreover, inappropriately planned locations cannot wholly exploit renewable energy potentials (Rode et al., 2005).

In this study, the proposed approach for estimating renewable energy potentials at the regional/subregional scale was improved on the regional level and the results will be optimized according to environmental as well as social needs in order to support decision making in regional and landscape planning processes.

2. Research Objectives

The main objective of the research presented here is to improve the integration of renewable technologies in local planning processes by combining renewable energy potentials, energy needs, and issues of environmental protection. As a means to this end, alternative scenarios for decentralized, renewable energy plants will be modeled which can be utilized, in combination with smart grids, in order to support a sustainable development Finally, planning practice can be improved by selecting the best suited areas with the highest energy potentials and least environmental impacts, or possibly by the integration of land-use related improvements.

Accordingly, the main research questions are:

- How to improve the estimation of micro renewable energy potentials? Which methods and algorithms criteria are needed for these improvements?
- How to forecast environmental impacts including summative / cumulative impacts of different renewable energy sources
- How to optimize both energy output and environmental performance by spatial allocation energy production and generation facilities?

The expected outcome for the further analyses will be a GIS-based, semi-automated optimization model. This model can enable planners and public participants in an integrative planning process, to including regional preferences. This way, the most efficient and environmentally sound energy mix within a particular region can be found. All in all, this approach can increase as sustainability as well as public acceptance of the “Energiewende”.

3. Methods

Here, we present our general approach as well as our first results in order to improve sustainable energy development, exemplified for the Hannover region. Firstly, our methodical approaches, going beyond the state of the art, will be explained in detail. Secondly, the estimation of theoretical spatial energy potentials (solar and wind power) will be presented. Thirdly, a first example will be given regarding the prediction of environmental impacts (bioenergy).

3.1 General methodological approach

The first methodical step is to analyze the different theoretical renewable energy potentials. The theoretical potential describes the theoretically available energy supply within a particular region in a given period (Rode et al., 2005). The estimation of these potentials is based on the methods used in a pre-tested area, the Hannover region, Germany (by master students in cooperation with the State Office for Mining, Energy and Geology (LBEG)) and adapted to local conditions in Germany from the study in the Eastern Metropolitan Area of Cagliari, Sardinia, Italy (Palmas et al., 2012). Thereby, methods are improved and adapted to data availability in the region of Hannover, Germany.
Because of existing technical, ecological, economic and social restrictions, the theoretical potential can be only exploited up to a certain percentage (Rode et al., 2005).
Regarding necessary ecological restrictions for a sustainable development, the estimation of environmental risks follows the DPSIR concept (EEA, 2003). In order to estimate possible impacts across the different renewable power technologies, ecological impact assessments according to Bachfischer (1978) are applied, finally integrating all different types of renewable energy sources into one GIS-based model. The results will be estimated environmental impacts on various essential landscape functions or ecosystem services according to Haaren (2004). It is intended to include environmental balances on a quantitative basis. This level of integration in combination with the use of quantified research results is recently lacking previous analyses (Haaren et al. 2012; Vogt et al. 2008). Due to the need of keeping the consumption of land as small as possible (Haaren et al., 2012), we support the idea of combined use of the same areas for several types of renewable energy production (Bosch & Peyke, 2010), and therefore explicitly consider possible cumulative impacts (Stratman et al., 2007), which could derive from this kind of multiple land use. In fact, these cumulative effects have so far hardly been recognized within the German planning practice at all (Siedentop, 2005), yet are recently an emerging field of research (ZALF, 2012). In the special case of renewably energy production, a previous case study shows the crucial importance of analyzing these cumulative impacts on ecosystem services (Rhoden, 2013).
The results from the formerly presented analyses will finally be combined with different spatial scenarios across possible multiple uses of different renewable energy technologies. This way, the consequences of various energetic land-use options can be visualized on the sub-/regional level. By integrating stakeholder participation, public acceptance can be increased, taking into account preferences, synergies and trade-offs.

3.2 Data

The Region of Hannover is located in Lower Saxony. It hosts 21 municipalities and towns, including the City of Hannover, on a total area of around 2.300 km² (Kinder, 2009). The regions' policy sets a strong political focus on climate protection and the use of renewable energies, and set the goal of reaching 100% renewable energy supply by 2050 (Region Hannover 2013).

Table 1 lists the main geographical data sources used in combination with data from various other sources.

Table 1: Main input data.

Data	Scale/unit	Data origin
Digital Elevation Model (DEM 30)	30 x 30 m	ASTER Satellite Data
Wind speeds at 10 m	dm/s	GERMAN WEATHER SERVICE
Regional Plan	1:50.000	REGION HANNOVER (2011)
EEA Technical Report 12/2007	categories A, B, C	EEA (2006)
LCA Cultivation Practices	various	BREDEMEIER ET. AL (2013)
SUNREG II- Project	various	WIEHE ET AL (2010)

3.3 Methodology for the estimation of the spatial micro 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 web-based estimation utility provides an on-site assessment of potential PV electricity production for Europe and Africa. The PVGIS calculation of PV potential for a specific site is based on spatial data automatically taken from the PVGIS database. Generally, the overall error for the whole year is quite small (approximately 5%) (ibid.). The database is based on climatic data from 566 meteorological stations covering the 1981–1990 periods and includes monthly averages of daily sums of global and diffuse irradiation and Linke atmospheric turbidity. Elevations and terrain features are represented by a 1-km digital elevation model. More details about the European solar database implemented in the PVGIS estimation utility can be found on its website (ibid.). The *r.sun* model an estimation of global solar radiation (beam, diffuse and reflected), for both clear sky and overcast atmospheric conditions from the digital elevation model (DEM) (Šuri et al. 2007). An important factor in producing reliable maps of solar irradiation was 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 output of this model is a raster map of the global irradiation annual average for a horizontal surface.

3.4 Methodology for the estimation of the spatial micro wind energy potential

To create wind energy potential maps, the 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 Wetterdiest”). 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 $\mp$ 0.15. The wind raster map was rescaled on a Digital Elevation Model (DEM) 30 m and other wind potential maps at

65,100, 140, 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:

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

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}.

Equation 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.).

3.5 Methodology for the estimation of environmental risks caused by the use of renewable energies

According to the DPSIR concept, **D**riving forces [the political and financial support for the “Energiewende”] result in environmental **P**ressures [initiated by the construction of renewable energy plants], which, under a certain **S**tate of the environment [e.g. vulnerability of soil parameters], result in higher or lower **I**mpacts [e.g. enhanced soil erosion] on the environment, being modified by the societal **R**esponse [e.g. agri-environmental measures] (EEA 2003). Following this approach as well as familiar methods in both, research and planning (Fürst/Scholles 2008; Vogt et al. 2008), ecological risk assessments according to Bachfischer (1978) are applied in order to estimate the risk of environmental impacts on various essential functions according to Haaren (2004). Thereby, the quantified intensities of different pressures deriving from the use of the different renewable energy sources,combined with the specific vulnerabilities of a certain area [e.g. soil region] are linked to ordinal or quantified impact estimations in a matrix , (Bachfischer, 1978; Fürst/Scholles 2008; Haaren 2004). Regarding the environmental risk analyses for renewable energy sources, this is a field of active research, and there are several studies available, especially in the case of energy crops, that generally follow the presented methodology (e.g. Bredemeier, 2013; Karp, 2006; Wiehe et al., 2010). Yet, the available data are still very incomplete, and especially collections of data over different types of renewable energy sources are currently based on expert surveys rather than quantified analyses (e.g. EEA 2007; Nitzsch et al. 2004; Reinhardt/Scheurlen, 2004; Schultze et al., 2008; Vogt et al., 2008). Other studies that are based on quantified data might focus on a different spatial scale (e.g. Brinkmann et al., 2011; Rhoden, 2013; Wiehe et al., 2010; Rhoden, 2013), which might be complicated to make use of for the regional scale (Albert, 2013). Moreover, for the first time across all types of renewable energy plants, cumulative impacts or effects will be analyzed. They can be defined as several impacts, deriving from one or – as in this case – several land uses, affecting the same natural resource or landscape function (Stratman et al., 2007:145). Thereby, the following kinds of effects are considered: [1.] no cumulative effect, [2.] linear addition of effects, [3.] reduction of effects, [4.] exponential increase of effects.

The result will be regional environmental balances of the current as well as predicted environmental risks as well as GIS-based projections of optimized allocations for single and combined uses of the various regenerative energy sources. These will enable planners to easily scope different land use options within their region and make decisions on an environmentally sound basis.

4. Results

4.1 Solar energy potential map

The latitude was computed directly from the DEM raster, while the albedo and the Linke turbidity were believed constant over the entire region, as a first approximation. The clear sky indexes were not available. After validation of the date, the output raster map representing the annual average of global irradiation daily sums estimated on optimally inclined plane (Figure 1). The output units are [Wh/m^2/day].

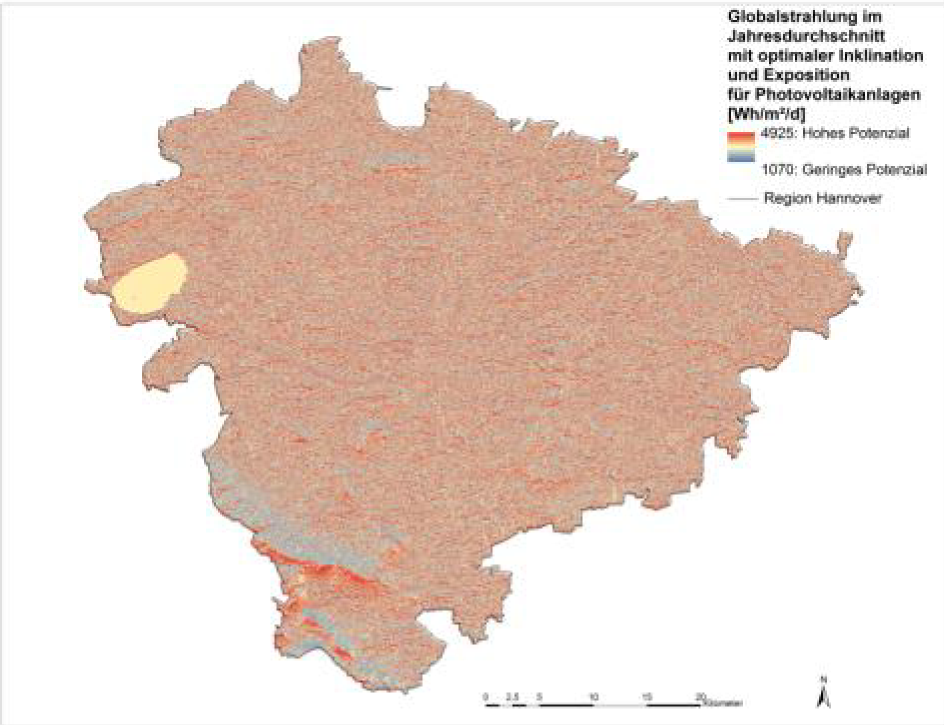


Figure 1: Annual average of daily sums of global irradiation on optimally inclined plane [Wh/m^2/day].

4.2 Wind energy potential map

The wind raster map at 10 m above ground level was obtained by downscaling the data of Weather German Serviced on DEM (30). Equation (1) (cf. Counihan, 1975; Touma, 1977) was used to calculate other wind speeds (i.e. at 80 m) on a Digital Elevation Model and the resulting output was wind speed at 80 m rescaled on a DEM (30).

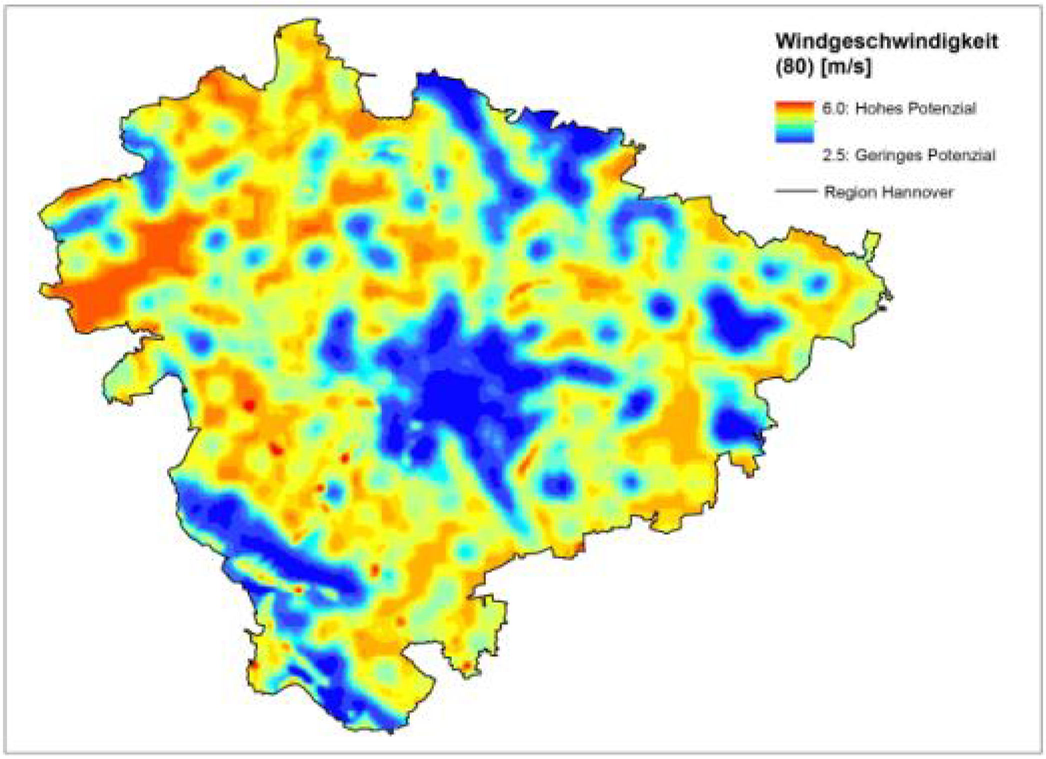


Figure 2: Wind speeds at 80 m above the ground [m/s].

4.3 Matrix of an environmental impact analysis [annual biomass cultures]

The presented matrix (figure 3) shows a first quantified estimation of the impact of cultivation of the annual biomass plants maize and rye (Bredemeier, 2013) in relation to the evaluated specific vulnerabilities of different landscape functions (Wiehe et al., 2010).

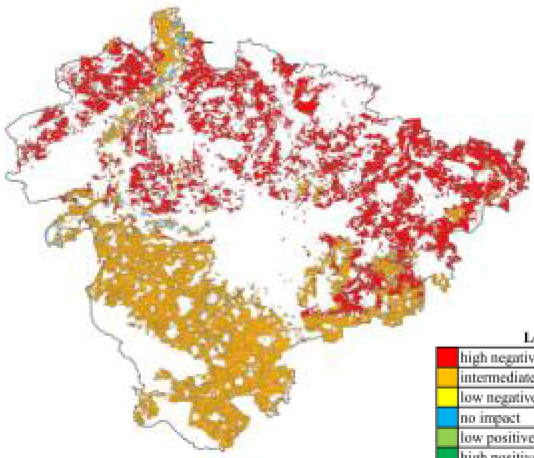
As can be seen from the matrix, the quantified data are transformed here to an ordinal scale in order to classify the estimated, resulting risk as “high” (red), “medium” (orange), or “low” (yellow), which can then be visualized in a map of the analyzed region.

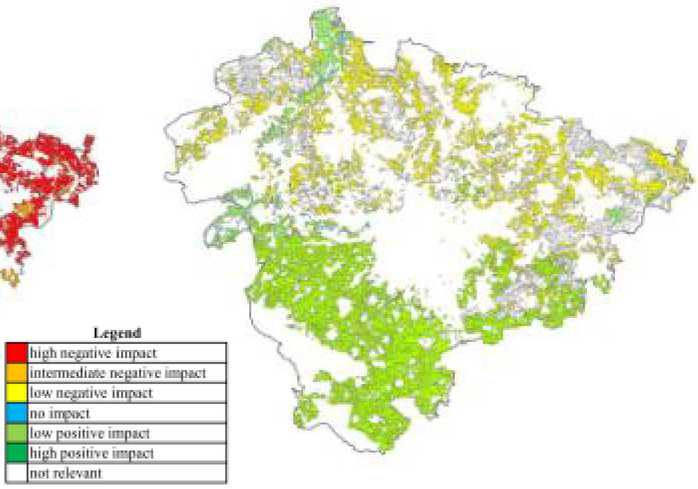
			Vulnerabiltity of Landscape Functions						
			Natural Yield Function				Water Resources Function		
			Water Erosion	Wind Erosion	Soil Compaction	Herbicides	Rate of Infiltration	Nitrate Leaching	Heavy Metal Pollution
		Region	**high:** 30 to > 55 **medium:** 10 to < 30 **low:** < 1 to < 10	**high:** Level 4-5 **medium:** Level 2-3 **low:** Level 0-1	**high:** Level 5-6 **medium:** Level 3-4 **low:** Level 0-2	**high:** Level 4-5 **medium:** Level 3 **low:** Level 1-2	**high:** < 192mm **medium:** 193-255 mm **low:** > 256 mm	**high:** > 1,5 **medium:** > 1 to 1,5 **low:** 0 to 1	**high:** Level 0-2 **medium:** Level 3 **low:** Level 4-5
Intensity of Pressures	Crops and Cultivation Practices								
Soil Cultivation System	Maize	convetional agriculture; tillage passes: 3	low	high	low				
	Rye	convetional agriculture; tillage passes: 4	low	high	low				
Nitrate-Fertilization	Maize	360 kg/ha						high	high
	Rye	81 kg/ha						high	medium
Application of Herbicides	Maize	treatment index: 1,3				high			medium
	Rye	treatment index: 1,0				medium			low
Water Consumption	Maize	transpiration coefficient: 1,20					high		
	Rye	transpiration coefficient: 1,15					medium		

Figure 3
Matrix (detail) of a possible environmental risk analysis for annual biomass cultures [Maize and Rye]
(Input Data: Bredemeier et al., 2013; Wiehe et al., 2010)

Example of a regional projection of energetic land-use options regarding wind erosion

The presented maps show an example of how energetic land-use options, the factor response in the DPSIR concept (EEA 2003), can influence one indicator of the natural yield landscape function, namely wind erosion. Thereby, the wind erosion risk caused by the cultivation of the annual energy crop maize is compared to the wind erosion risk caused by the hypothetical cultivation of tree species in short rotation coppices in the Hannover region. The estimation of the impacts was given by the European Environmental Agency, yet they are based on expert consultations rather than quantified analysis (EEA 2006). The specific vulnerability of the landscape was taken from the Regional Plan of the Hannover region (Region Hannover, 2011). Combining the intensities of these two indicators by a linkage rule (Fürst/Scholles 2008), both energy crops exhibit a more or less positive or negative impact on the specific landscape. For the case of soil erosion, it can be clearly seen here, that the cultivation of maize causes a much more negative impact on the indicator wind erosion than an innovation in energy crop production, the use of perennial crops. From this small example it becomes obvious that the risk of wind erosion can be significantly reduced by a shift in cultivation options. Though the cultivation of perennial energy crops is believed to exhibit several positive impacts on a number of ecosystem functions EEA 2006; Bosch/Partner 2010), it must be noted that this is not a final estimation of all impacts caused by the two kinds of cultures – the rel-





evant data have not yet been collected and processed on a quantified basis, which is one of the major tasks of the present research.

Figure 4 (left)
Estimation of the risk of wind erosion caused by the cultivation of maize in the Hannover region

Figure 5 (right)
Estimation of the risk of wind erosion under the hypothetical cultivation of tree species in short rotation coppices in the Hannover region
(Input Data: EEA 2006; REGION HANNOVER 2011)

5. Discussion

The integration of renewable power generating sources into urban and regional planning can play a key role in climate protection and reducing the region's dependence on external fuels. Regional planning can optimize this integration by estimating energy potentials with existing methods or developing them in case they are missing (biomass, water and geothermal energy).
The identification of complete energy potentials and possible mixes helps planners by selecting the best suited areas with the highest energy potentials, thereby reducing land consumption and environmental impacts. The first results from the proposed approach were implemented into GIS in order to fulfill the need to integrate information into a spatial context and support decision making procedures. GIS can help the decision-makers by the visualization and evaluation of land–use alternatives.
Although the proposed approach for estimating micro renewable energy potential at regional/sub-regional scale is still under improvement, the preliminary results encourage continuing the research in this direction. The solar energy potential can be estimated in every region, because it depends on the application of the *r.sun* model and on the *pvgis* database to validate data. However, the accuracy depends on Digital Elevation Model (DEM) as input data and on *pvgis* database availability.
Normally, data of wind speeds are also available for every country. Wind energy potential can be calculated for different height in order to optimize the planning of decentralized wind power plants.

Regarding the environmental impacts, it will be a major task to find and combine data from recent studies in order to conduct the intended quantified environmental analyses and generate a model. Moreover, the inherent complexity of ecosystems as well as the very different pressures deriving from the use of the different renewable energy sources, including cumulative impacts, further complicates this issue. After all, an appropriate balance must be found between this complexity and the need to produce an easily usable GIS-tool on the basis of available regional data.

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