Integrated spatial optimization model for renewable energy planning

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Abstract . Renewable Energy is becoming more and more fundamental for the supply of the increasing global energy demand but, it poses some issues concerning the identification of the buildable land, the estimate of its exploitable potential, the integration into the power grid and the setting of efficient energy policies. Addressing these aspects requires interdisciplinary planning that can be integrated in GIS. Nevertheless, the lack of dedicated functions in GIS software in the field of wind and solar energy is a critical aspect when it comes to estimating the economic and technical potential energy production and to quantifying the uncertainties necessary to carry out sensitivity analysis. The aim of this research is the development of a GIS process that optimizes and assesses the technical and economic integration of solar and wind power plants in respect to the energy production and to the impact on the power grid.

Keywords: wind and solar energy, optimization, technical and economic exploitable potential, GIS, energy production.

1 Introduction

The integration of renewable energy in a defined region implies two main issues during the planning phase: the definition of buildable lands where certain constraints have to be taken into account and the integration into the power grid. As renewable energy sources are intermittent and characterized by an irregular spatial distribution, their integration into the power grid represents an issue in terms of absorption and transmission capacity of the generated electricity over the day time and the year. Therefore the planning of renewable energy (RE) energy power plants implies also the forecast of future scenarios in order to optimize both the location of RE power plants in respect to the actual capacity of the power grid and to define further development of the new transmission lines.

Among all RE technologies, solar and wind resource play an important role in the future energy supply. Nevertheless the study of these two resources with GIS presents different issues. Often coarse resolution data are used to find buildable land; buildable sites are identified by applying setbacks from main natural and anthropological elements but neglecting property land. The estimate of the electricity generation of each buildable land is based on basic assumptions such as the mean wind speed value and simplified power curves of wind turbines (WTs). Moreover, the actual economic boundary conditions are neglected and therefore generating additional uncertainties in estimating the economic exploitable potential. This is a fundamental step, as the economic assessment (integrated with the policy measures) of each buildable land represents the actual added value in demonstrating the level of attractiveness of an area. The commercial GIS software suites have predefined functions developed for spatial analysis and lack of specific and dedicated functions for RE analysis. This issue increases the uncertainties when estimating the annual energy production.

In respect to the power grid planning, potential RE sites are located where the transmission lines are often missing or insufficient where the RE resource is available. Moreover, the outline and the quantification of paths and of the costs of new transmission lines that have to link potential sites to the existing grid is often neglected or estimated assuming rough hypotheses such as considering only the land within a 20km distance from main power grid at a fixed cost (1M CHF/km) independently from the topography and the characteristics of the land cover (settlement, water bodies, etc.). The visual impact is often neglected when routing new paths.

2 Previous work

The integration of any RE power plant into a given area is generally more complex than it appears and requires great expertise and experience in order to tackle the diverse problems [1, 2]: finding buildable land for optimal RE resources (i.e., wind resource greater than class 3 in NREL classification[1]), verifying the required condition for the grid connection and the environmental and anthropological constraints (settlements, water bodies, protected areas, infrastructures, etc.), or collecting landowner information. Early research (since the 1990s) focused on estimating the exploitable solar and wind resource in a given region using GIS software [3, 4] with some economic analysis at a large scale [5, 6] that highlighted the need for interdisciplinary approaches. In the first applications, large-scale maps [7] (i.e., regional or larger) and low resolution were used because of the lack of accurate GIS data. Therefore, estimates and scenarios were lacking robustness, reliability, and specifics. In very few cases, GIS was applied for wind farm siting [8, 9] but always lacking in accuracy and information.

With the intensification of RE deployment, the improvement of techniques, enhanced software and data, more detailed analyses have been developed leading to more accurate estimates [10, 11] to optimize the siting of wind farms [12]. Some approaches involved the use of multi-criteria analysis (MCA) [13] to support the energy or environmental planning [14] and the local communities in understanding the impact and benefits of RE projects [15]. Moreover, despite the search of site selection and the optimized location being one of the main features and capabilities of GIS [16], it has not been extensively applied in the RE field yet. New studies were carried out at large scale to quantify more accurately the RE exploitable potential and resulted

1 http://rredc.nrel.gov/wind/pubs/atlas/tables/1-1T.html

in one of the first nationwide GIS tools (called Geospatial Toolkit) of the last decade. It visualizes the main anthropological and natural constraints and uses the solar and wind resources represented at a low resolution (10 to 40 kilometers) with value intervals instead of mean values. Another NREL project called ReEDS[2] estimateted at large scale over multiple time frames the capacity expansion in the electric sector of the U.S using a linear programming model. The United States are divided into 365 regions, corresponding to the areas for actual and future potential power generation. Resolution is low (some 10s to 100s kilometers) and does not take local constraints into account. Moreover, the GIS data used to identify the buildable land are coarse and limited [17]. In Europe, the main projects address the estimate of spatial distribution of wind resource at different heights above ground level (e.g., Wind Atlas of Germany[3], Spain[4]) or for regional assessment of wind energy potential such as the one developed in Austria. GIS tools for the technical and economic analysis and scenarios including nation-wide sensitivity assessment are not present yet except for a few projects at local levels (mainly county-wise).

In 2004, a first project - called "Konzept Windenergie Schweiz" [18] – delivered the first assessment of the wind energy potential in Switzerland. A list of potential sites is provided but with little information about WTs. No additional technical information is provided. One of the limitations of this analysis relates to the limited selection of the WT model to estimate the likely annual power generation:. In general, such analysis lacks the integration of current WT models, the estimate of the costs and the real technical-economic assessment of the RE energy resource at a small scale. In addition, no specific information of the uncertainties of the wind data used for the analysis is explained. Wind sites have to be ranked in function of estimated economic benefits in order to highlight those that are attractive as recently demonstrated [19].

In conclusion, most attempts aimed at resource evaluation and wind farm siting have been performed at a large scale without estimating the real potential and constraints at a small scale (such as parcels).

The assessment of new transmission line paths represents a significant issue in term of spatial planning. Multi Criteria Analysis (MCA) and Least-Cost Path (LCP) will be adopted to identify the suitable routes for new transmission lines as they have been widely applied to support decision makers in assessing the optimal routing of linear infra-structures such as TLs. Research work described the theoretical basis of the MCA to implement efficient methods for decision-aid [20]. LCP is typically used to identify the shortest path between two points and different approaches have been developed in the last decades [21, 22].

The first GIS applications have been proposed in order to offer support in power line routing using a weighting approach [23, 24] to define preferred routings. Other work addressed the routing problems using a "funnel" approach in order to identify the likely corridors with an improved level of accuracy and information [25]. All

2 http://www.nrel.gov/analysis/reeds/

3 http://www.dwd.de/bvbw/

4 http://www.globalwindmap.com/VisorCENER/mapviewer.jsf?width=660&height=587

these studies proposed a solution for the routing, but neglected the constraints of electrical interconnection of RE plants to the existing grid.

For solar energy, a few examples of urban roof-top exploitation have been demonstrated. A first example of estimating solar roof-top potential has been carried out for some counties in the cantons of Saint Gallen and Inner and Outer Rhodes Appenzell [5] and in Germany [6] but no clear selection of the PV technology is possible for the user in respect to the broad range of current PV technologies and their corresponding performances and costs. Similar analyses have been done [26] but neglecting the pitch orientation of the roofs, the lands that can be assigned for potential new PV plants and real costs. For the solar potential analysis of buildable land, some studies have been carried out using a DEM of only 1km resolution. The technical and economical comparison of different sites over a large region with regard to the variation of boundary conditions is another issue, which has not been integrated within the actual tools and its development was suggested in previous work [27].

3 Research questions

This research aims to develop an interactive GIS rule-based tool in order to:

- define, at high resolution, different scenarios with respect to the distribution of the buildable surfaces for wind and solar PV power plants
- estimate the optimal technical and economic performance of each potential land that can host a RE power plant
- identify and optimize the suitable policy measures in order to achieve regional or national energy targets
- assess the impact of the integration of RE into the power grid and thus to identify the optimal implementation of the grid itself.

This novel approach will be applied in the western part of Switzerland (canton Neuchatel and Fribourg) as case study, but designed to fit any other region: the selection of this specific region is motivated by the availability of the geodatabase of the power grid characteristics provided by the local grid operator. The integrated tool will be able to support decisions makers, project developers and grid operators in order to define precisely the exploitable potential and to set energy strategies, to find sites for investments and to identify the impact on the power grid and its weaknesses in order to optimize future development.

4 Methodology

GIS data describing the land features (anthropological and natural constraints) will be used to define the buildable land while a customized code, coupled with computational software and RE resources (solar and wind resource) in GIS format, will be

5 http://www.geoportal.ch/

6 http:/ratingen.publicsolar.de/

developed to estimate the corresponding RE potential for each buildable land (**Figure 1**) and rooftop surfaces (**Figure 3**). The technical specifications of the wind and PV technology are collected from the websites of the manufacturers and converted into a compatible GIS format. Two separated algorithms for wind and solar PV power plants will be developed. The algorithm for wind energy applications will use the spatial distribution of wind data and the technical specifications of the WTs (wind turbines) as input in order to estimate the wind mean annual power generation [19]. It takes the interaction among WTs into account by integrating a wake effect (**Figure 2**) derived from physical models [28].

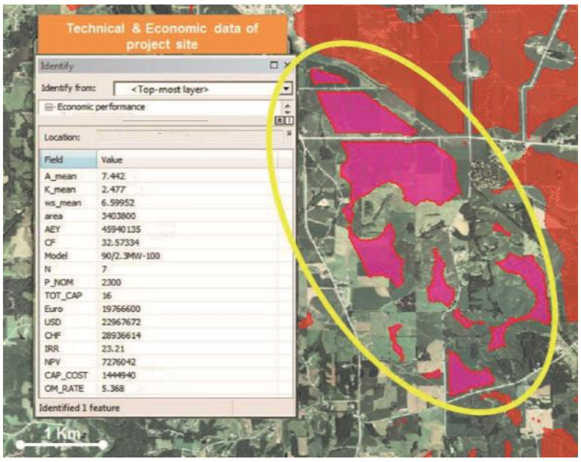

Figure 1: excerpt of the estimated parameters of suitable land for wind farms

The raster analysis of the digital terrain model (DTM), digital surface model (DSM), and the land cover will result in a map of the terrain features. These parameters define the aerodynamic roughness factor that directly affects the wind profile and thus the electricity generation. Wind energy generation will be estimated by coupling the Weibull distribution and the power curve of WTs to estimate more in detail the annual energy production of WTs. An optimization process will be developed in order to determine for each project site the optimal layout of WTs that maximize the economic performance assessed using parameters such as the internal rate of return (IRR) or the net present value (NPV).

The algorithm for solar PV applications will use the spatial distribution of solar radiation data characteristics and the technical specifications of the PV panels in table format as input for the solar mean annual electricity generation.

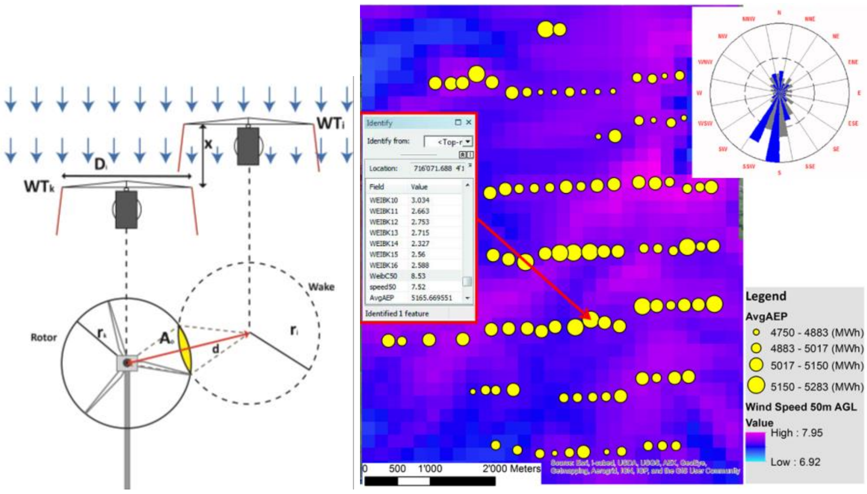

Figure 2: representation of the wake overlapping a downstream WT (left). Estimate of the annual energy production of each WT: the size of the spot is proportional to energy production. A physical model is applied to take into account the wake effect.

The raster analysis will allow to identify and to sort the rooftop in respect to the orientation, shadow over the year, inclination (**Figure 3**). These factors are fundamental for defining which surfaces are suitable to host solar PV plants.

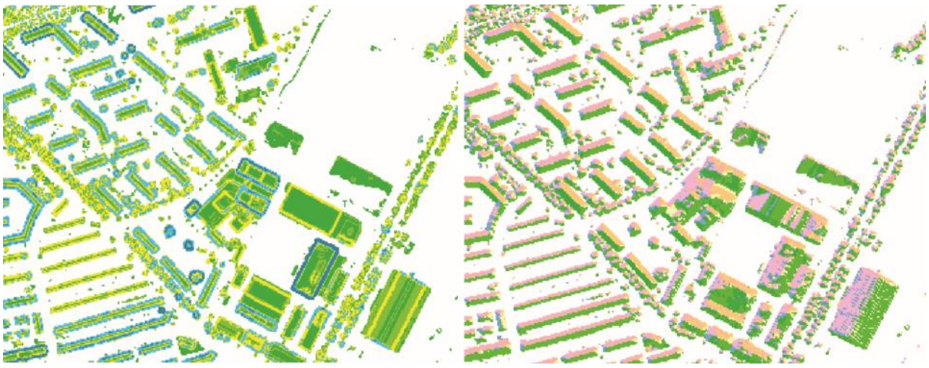

Figure 3: example of extraction of rooftop characteristics such as aspect and slope

Parameters affecting the technical performances of solar and wind technology (array effect, shadow, albedo, temperature, icing, etc.) will be considered and integrated.

In this regard, roof tops will be identified through raster analysis of the DTM mentioned before (≤ 2m resolution), the DOM and the orthophotos.

Optimization processes will be implemented in order to maximize parameters such as electricity generation or economic performance; therefore different options for different users have to be taken into account to draw future scenarios.

A validation process is required in order to quantify the uncertainties and to show the reliability of the tool. The validation will be carried out comparing the estimated wind and solar PV electricity generation to the actual electricity generation data of wind and solar PV plants of Switzerland that is publicly accessible.

The integration of the GIS data of the existing power grid will be used to identify the likely path of the grid interconnection between the buildable sites and the existing grid and the corresponding cost that represents one of the main bottlenecks to diffusion of distributed generation.

Optimizing processes will be developed to assess:

- the optimal location of power plants in respect to the characteristics of the power grid which represents the bottleneck to the development of RE projects.
- the optimal effective energy policy to be implemented in order to achieve specific targets.

5 Conclusion and outlook

The proposed research is aimed at developing an interactive analysis tool to estimate, at high resolution and in short time, the actual technical and economic exploitable potential of solar and wind sources that can be integrated into the grid and to set energy strategies. This tool will fill the gap between the current GIS models and the need for a detailed extensive analysis for RE planning and prospecting fulfilling the need for different users: planners can easily identify new buildable sites and will reduce uncertainties, policy makers can outline different strategies and targets and grid operators can optimize the interconnection of RE projects and the planning of future transmission lines. As one of the main issues of distributed generation is the optimal location and balance between the power generation and the electricity demand, the additional added value is the capability to perform optimization analysis in respect to boundary conditions such as setbacks from anthropological and natural constraints, constraints of the power grid and policy framework.

The integration of the power grid will help to assess how and where the actual structure of the grid has to be enhanced, the impact on the cost and load distribution of the electricity. This will enable us to identify new corridors for further development of new transmission lines in order to link potential exploitable sites for RE to the grid. The following step will be the integration—into a single model—of all power generation systems of Switzerland in order to study the global spatial impact of traditional and RE plants on the electricity (generation and final use), and transmission costs and power grid reinforcement (domestic grid and interconnections).

The results will be represented both through thematic maps and through plots in order to show their spatial distribution and the corresponding characteristics.

The coupling of computational tools and customized function with a GIS tool will enable a more complex and accurate modeling, simulation and optimization of future scenarios including the theory of solar and wind energy analysis that are normally carried out with dedicated tools.

The potential application of the outcome this research is a multifunctional tool for planning and analysis that addresses the needs of different types of users within one single package: energy planners, project developers and grid operators in order to reduce time and uncertainties in planning and to optimize the estimate and the forecasts of the integration of RE projects over a large region. At the moment the commercial tools address a micro-scale analysis (10kmx10km) and enable users to study a single project within a limited region, but there is no tool that estimates at high resolution the potential over a large region in order to identify in detail for each suitable surface the technical and economic characteristics.

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