Chair of Renewable and Sustainable Energy Systems
TUM School of Engineering and Design
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Renewable Energy Potential Analysis in Bavaria

A High-Resolution Study Using pyGRETA

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August 28, 2024

1 Introduction

Renewable potential analysis is a key part of any energy system modeling. There are several existing studies on potentials in Germany and some specific to Bavaria. Bundesverband WindEnergie (BWE) [1] estimated a maximum potential for wind in Bavaria as high as 316 GW but also mentioned a potential of 41 GW with a 2% land area usage limit. A more recent study from TUM and ZAE Bayern [2] showed a PV potential of 68.4 TWh from 66.57 GW with 1,027 full-load hours and a Wind potential of 80 TWh from 32.3 GW of capacity with an excellent 2.479 full-load hours in their renewable energy system analysis. Later in the same study, an analysis is done to show that these potentials are very much in the realizable range. An extensive study by Agentur fuer Erneuerbare Energien [3] estimated a total of 315,800 TJ (87.7 TWh) of biomass potential in Bavaria, consisting of energy plants, forestry, industrial wood, old wood, Straw, animal manure, and organic waste. ENSPRESO [4] estimated a range of 32.7 to 153 TWh biomass potential in Bavaria by 2050, for various productivity scenarios.

The potentials from literature often come short in terms of providing high spatial as well as high temporal resolution. The differences we see in these estimates come from differences in input data used and/or varied range of the assumptions on land eligibility criteria considered. In addition to that, the results from these studies are rarely in the format of ready-to-use in the further analyses of our interest, as studies either present the potential in terms of available land area or total installable power or energy density at each location. In most cases, the temporal profile of generation should be taken from somewhere else. All these concerns together point towards the need to have customable tool for potential analysis. Having said that, developing such a tool that not only gives a customized result format but also relies on the best features and findings of existing literature is of high importance.

Potential analysis has been carried out using an open-source tool called pyGRETA-v2 [5]. It generates high-resolution potential maps and time series for any user-defined region across the world. Various renewable technologies have been analyzed as part of this work package. The spatial resolution of the tool is 250m x 250m, which is further referred to as a pixel in this report, whereas temporal resolution is one hour. The tool depends on land availability criteria, historical weather data, and technical characteristics of the renewable technologies to calculate potentials for PV and Wind technologies. The biomass potential analysis focuses on estimating the energy generation capabilities from agricultural residues, forestry logging residues, and livestock manure in Bavaria. By using the pyGRETA tool, we allocate these biomass resources across the region, providing high-resolution data crucial for understanding the role of biomass in Bavaria's renewable energy landscape.

2 Land Eligibility Analysis

For PV and wind technologies, the availability of each pixel is evaluated based on numerous customizable land use criteria [6]. These criteria are usually set due to technical, ecological, or political considerations and are explained in detail in [7]. This section gives a short overview of this analysis in the context of Bavaria. Land cover type and protected areas are the main factors for eligibility analysis. Figure 1 shows a map of Bavaria with several land types identified. The colorless areas are protected for nature conservation. These areas are not part of the available land for all technologies.

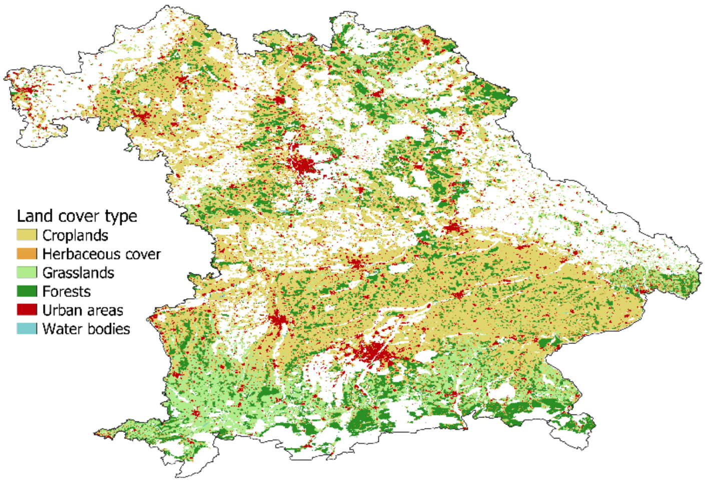

Figure 1: Land cover types in Bavaria after removing the protected areas (white) [8] [9]

The available land area for open-field PV is calculated by removing croplands, grasslands, forests, urban settlement areas, and water bodies. In addition, highways, railway lines, mining sites, etc. are also removed. An appropriate amount of buffer is also given around some of these areas. A slope exclusion of more than 10 degrees is also considered. On the other hand, only the settlement areas are considered for the roof-top PV potentials. Roughly 40% of these areas are assumed to be consisting of southward-facing roofs, which are available for installation of PV panels. The resulting available pixels can be seen in Figure 2.

The exclusion criteria are different for open-field PV and onshore wind because the forests are available for wind, airports are excluded, and the slope exclusion is taken as 17 degrees. The buffer distances also vary significantly. The resultant available pixels are mapped in Figure 3.

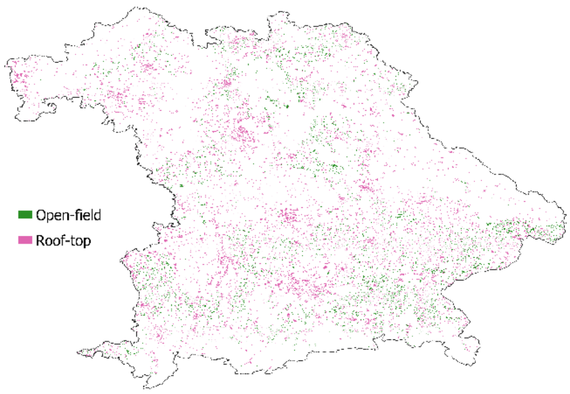

Figure 2: Available areas for open-field and Roof-top PV

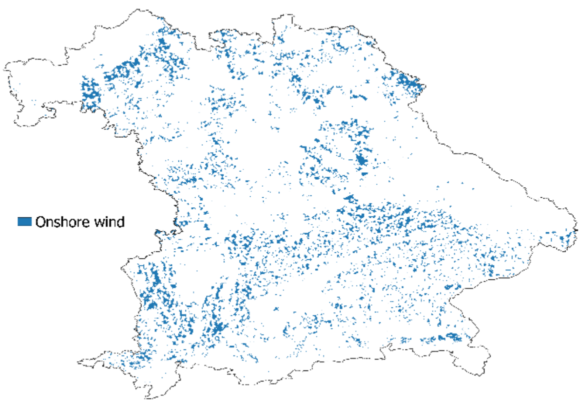

Figure 3: Available areas for onshore wind

3 Potential and Generation Profiles

The total power potential of each technology is then calculated by taking the resulting available area and maximum possible capacity at each available pixel. The shadowing effects of the PV panels on one another and the optimum spacing between individual wind turbines for recovery of wake are considered while calculating the maximum possible capacity. Further analysis using Historical weather data and technical parameters of the technologies is required to calculate the hourly capacity factors and Full load hours at each pixel. The theory behind such calculations is given in detail in the documentation of the tool [10].

For PV, the historical weather data corresponding to Global Horizontal Irradiance (GHI) and Top of the Atmosphere Irradiance (TOA) is taken from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), which is the latest atmospheric reanalysis of the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO) [11]. The MERRA-2 data has a lower spatial resolution of 5/8° longitude and 1/2° latitude but a very high temporal resolution of one hour. The bias errors in MERRA data that are raised in the clearness index and due to elevation have been corrected using the methods suggested by Zhao et. al [14]. The hourly capacity factors and FLH have been calculated at this resolution for fixed modules at optimal tilt angle for the year 2021 which can be seen in Figure 4.

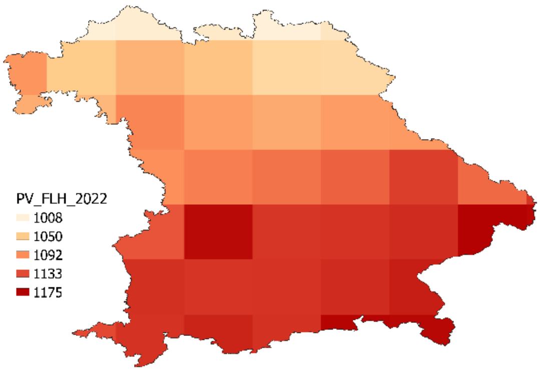

Figure 4: FLH for Photovoltaics

The potential analysis for onshore wind potentials also uses historical weather data from MERRA-2 [12] but a further redistribution of wind speed has been carried out to increase the spatial resolution to the standard pixel size of the tool. Long-term average wind speed from Global Wind Atlas [13] is taken as the weighting factor during redistribution. The FLH varies significantly depending on what kind of turbine is used for the analysis. The FLH map of the onshore wind using 99m and 155m high turbines can be seen in Figure 5 and Figure 6 respectively.

Figure 5: FLH for onshore Wind using 99m high turbine

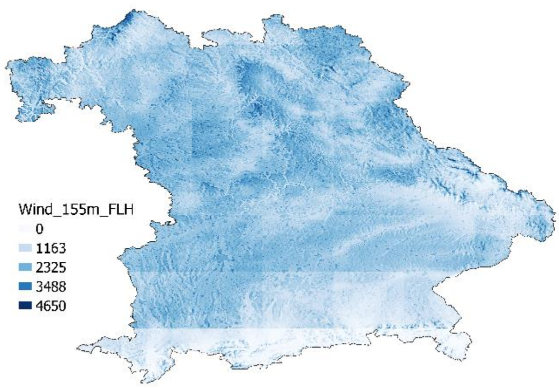

Figure 6: FLH for onshore wind using 155m high turbine

FLH along with the available power potential will give the annual generation potential for each technology. All the potential results of PV and wind for Bavaria are summarized in Table 1 below.

Table 1: Potentials of PV and onshore wind in Bavaria

Technology	Type	% Land Available	Power Potential (GW)	Annual Energy Potential (TWh)
Open-field PV	Fixed at optimal tilt	1.67	93.25	109.32
Roof-top PV	Fixed at optimal tilt	1.76	97.62	108.80
Onshore Wind	99m high turbine	7.74	47.49	67.24
Onshore Wind	155m high turbine	7.74	33.84	60.45

In addition to the maps and the potentials, the tool gives the hourly capacity factor time series, which is another important input for any energy system model. These time series can be generated for a few representative locations such as the top 10%, median, lower 20%, etc. Figure 7 shows the sorted curves of the same.

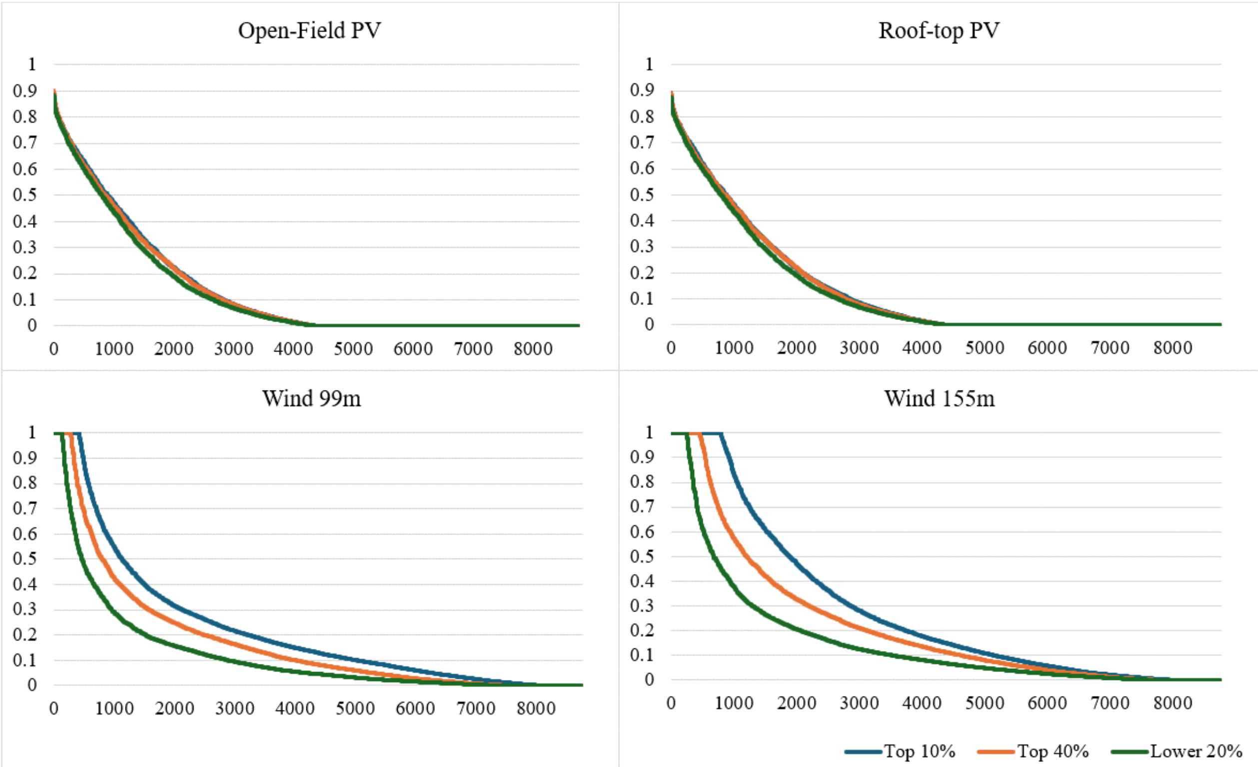

Figure 7: Sorted capacity factor time series for various technologies in Bavaria

The difference in these curves in PV is very low because of a similar amount of solar irradiance throughout Bavaria. However, this is not true for wind due to the high variability of wind speed from one pixel to another. This is also evident from the FLH maps. The gap between the time series also increased with the height of the wind turbine.

4 Biomass potential

The tool pyGRETA is modeled to use a different approach for biomass as it is not directly weather dependent. The methodology is taken from a study on Southeast Asia biomass potential [15]. The input data taken for this analysis comes from the Food and Agriculture Organization of the United Nations (FAO). Only three types of biomasses are considered: agricultural crop residues, forestry industrial wood logging residues, and livestock manure. For agricultural crop residues, country-wide annual crop production data is taken from which the amount of available residue is estimated using mass-to-mass ratios and availability factors. The availability factor is taken to accommodate for only the remaining mass after fulfilling the other existing uses such as natural fertilizers, animal feed, etc. Energy crops are not considered here. The amount of available forestry logging residue is also estimated similarly using the annual industrial wood production data from FAO.

These biomass amounts are then allocated to relevant pixels by the tool. The crop residues are given to agricultural areas and natural vegetation mosaic whereas the logging residues are allocated to forest areas. In doing so, the protected areas are not allocated. The amount of available manure is calculated from livestock density raster data which is already available at high resolution from Geo-Wiki.

As the input data is available at the country level, after allocation to relevant areas, it is possible to see the potential of one region such as Bavaria. The cropped Bavarian maps of biomass densities can be seen in Figure 8 and Figure 9. The available energy from the biomass is then calculated by using the Lower Heating Value (LHV) of each type of biomass. The available energy density map is shown in Figure 10. The possible emissions while burning the biomass are also estimated similarly.

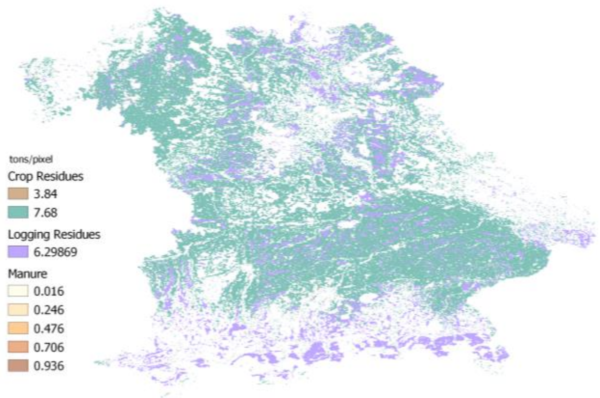

Figure 8: Biomass density map of Bavaria

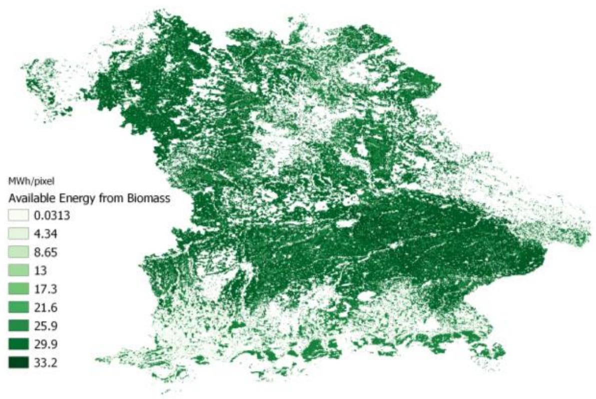

Figure 10: Available bio energy density map of Bavaria

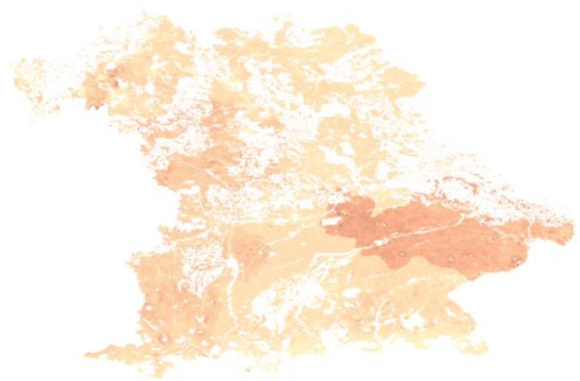

Figure 9: Manure density map of Bavaria

Table 2: Biomass Potential in Bavaria

Quantity (Million tons)			Potential
Crop Residues	Logging Residues	Manure	Available Energy (TWh)
4.25	1.04	0.19	21.85

These estimations suggest that the potentials from the tool are low compared to the literature. It is worth mentioning here that pyGRETA was initially developed for a country or bigger level analyses, so the data sources were selected based on their worldwide data availability. FAO production data is one such source where country-level aggregates are available for most of the countries in the world. While using the tool for a local analysis such as this one, the shortcomings of the tool are identified. Further work and effort will go into using more detailed local production data in the tool to generate such high-resolution allocations.

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