Integrated analysis of regional energetic demand and renewable energy potentials at the example of Ludwigsburg county, Germany

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Abstract. This work compares heating and electricity demands with local renewable energy potentials at the example of Ludwigsburg county, a mostly suburban region in South-Western Germany. Bottom-up analyses of the energetic potentials are performed within an established regional energy simulation platform and are thus based on a consistent set of geoinformatic data. This approach has two advantages compared to a top-down analysis or using multiple specialized tools: it allows assessing energetic potentials in high spatial resolution and relates it to heating and electricity demands on a single-building scale. Secondly, it is transferable to other regions due to the widespread availability of most input data. Our results show that exploiting technical potentials for bioenergy, rooftop PV, wind onshore, and hydropower can cover 68% of electricity demand 7% of heat demand in 2019, indicating that energy autonomy is difficult to achieve for densely populated regions in Europe.

1. Introduction

To address climate change, Germany has reduced its total greenhouse gas (GHG) emissions output by 42% between 1990 and 2020 and increased its share of electricity from renewable sources to 46% (2020)[1]. To reduce 2030 GHG emission by 65% (compared to 1990) and become climate neutral by 2045 [2, 3], further measures need to be implemented soon.

About 35% of Germany’s end energy consumption in Germany is related to buildings, with 22% stemming from private households [4]. Correspondingly, most building-related GHG emissions are linked to the provision of heat and domestic hot water. Ambitious and effective energy savings and renewable heat and electricity generation measures in the building sector are therefore essential to achieve climate goals. For this, a detailed understanding of regional energetic demands and potentials is of great importance. A wide range of papers, e.g. Sola et al. [5] or Ferrando et al. [6], showcased the importance of building energy modeling for successful implementation of an energy transition recently. Most of the tools however focus on only one of many aspects, e.g. heating demand of buildings or electricity generation. Furthermore, some of the tools require large amounts of input data to calculate scenarios or enable an optimization, which is often not available, or a complex, manual task. Integrated tools that allow to gain a
holistic view on building energy demands and local renewable energy potential with high spatial and temporal resolution and that are based on a consistent and readily available data basis, thus close an important research gap. This paper uses heating and electricity demands in the building stock and sets it in context to local renewable energy potentials at the example of Ludwigsburg county, a mostly suburban region in South-Western Germany.

2. Methodology

This section describes the case study county of Ludwigsburg and the framework of methods and models applied to it.

2.1. Ludwigsburg county

The county of Ludwigsburg is part of the metropolitan area of Stuttgart in South-Western Germany. It comprises the city of Ludwigsburg itself and a further 38 municipalities. The county’s total area is 687.2 km$^2$, it hosts 545,423 inhabitants and a total of 112,306 residential buildings$^1$. Its population density of 774 persons per km$^2$ is the 7th highest of Germany’s 400 counties (excluding city districts or district-free cities)[7]. Total heat demand in 2019 (scaled from 2016 data based on the energy consumption trends, with correction factors for weather applied) was 4.85 TWh$_{th}$, while total electricity consumption was 2.06 GWh$_{el}$. 2016 billing data for electricity, gas and district heating and electricity generation from renewable sources was provided by the Sub-department of the Environment of Ludwigsburg District Office.

A digital model of the county that includes all buildings and its landscape in the CityGML format is used for subsequent analysis. The CityGML standard developed by the OGC (Open Geospatial Consortium) is increasingly used by urban planners and environmental engineers [8] to study regional development options. In addition to geometric information, metadata such as building functions or years of construction for the building stock, and the type of land use, e.g., traffic areas, forests, lakes, or main agricultural land uses for land polygons, can be included in the format. For the building part, the used model was in Level of Detail 2, LoD 2, i.e. containing the building geometry with its roof shapes [9]. Both the landscape and 3D building models were obtained from the State Office for Geoinformation and Land Development, Baden-Württemberg.

2.2. SimStadt simulation platform

SimStadt is a simulation platform that can assess regional renewable energy potentials and calculate heating, cooling and electricity demands on a building level for cities and regions based on above-mentioned geoinformatic data. The methods and applications have been described in various publications[10, 11, 12, 13, 14]. SimStadt is in constant development and further workflows, notably on onshore wind potential and free-field PV free space are under development. Due to the use of geoinformatic data, results can be visualized in a web-browser[15].

Rooftop PV potentials were calculated for all buildings. The workflow takes into account the building’s spatial orientation and the inclination of each roof surface [16, 17]. Adjustable parameters include module efficiency, preset at 15%, and the ratio of module to roof area, preset at 40% for tilted roofs and 30% at flat roof, to account for windows or rooftop installations. While higher ratios of up to 100% are mentioned in some studies [18], these typically consider selected roof areas, e.g. with south-facing orientation. In contrast, this study considers all roof surfaces. Average module to roof ratios of 30% to 40% thus seem a sensible choice for county-wide assessments and if all roof orientations are taken into account. While shadowing effects can be considered in SimStadt, this calculation-intensive feature was not taken into account here due to the high number of buildings to be considered (more than 110,000) and correspondingly long computation times. To the authors’ knowledge, no study exists that quantifies the impact of

$^1$ Data from the German census 2011 (statistik-bw.de), projected to 2019.
shadowing effects on different types of city quarters; thus, no standard correction values can be applied. At least in a first order, however, shadowing effects are expected to be small on a county-scale in this case: given its suburban nature, less than a third of all buildings in Ludwigsburg have more than three stories, and almost 40% of residential buildings are single-family homes, which usually have a garden. Both effects reduce shadowing from neighboring buildings. Furthermore, the county’s landscape is dominated by rolling hills, but is not mountainous. Shadowing from natural obstacles is thus limited as well. As a next step, above-mentioned correction factors for different archetypes of city quarters shall be examined. Generally, a technical potential is calculated, i.e. it is assumed that all roofs are eligible for the installation of PV modules. This however restricts the use of solar thermal panels. Studies found that net-zero energy buildings can be reached by favoring PV over solar thermal [19, 20].

The biomass potential is calculated by the agriculturally usable areas in Ludwigsburg county. Using the area sizes from the digital landscape model and the statistically cultivated plants (fourteen different plant types, mainly grass, winter and spring cereals and maize), a dynamic yield model is applied to assess the conversion of crops into biomass at different percentages for energy production or food production. For forested areas, static data on sustainable yields per area are applied. About 55% of the county’s land area is used agriculturally, which corresponds to about 378 km², while 18% is forested, corresponding to about 124 km². The method is described in detail in [14].

Since hydropower potentials are largely exploited and onshore wind potentials severely restricted due to restrictive zoning laws and a high population density in Ludwigsburg county, 2016 electricity generation for wind and hydro was considered as set in this work. These assumptions seem plausible, as there has been no significant hydropower expansion in Germany since at least 1990 [21], and future extension of this form of renewable energy do not play a role in the discussions on future energy systems, and there is only one wind turbine installed in Ludwigsburg county to date.

3. Results
Based on above-mentioned parameters and assumptions, Ludwigsburg county can generate 1,062 GWh of electricity from rooftop PV annually. Furthermore, 647 GWh of secondary energy can sustainably be produced from local bioenergy sources. If this amount of energy was used locally in combined heat and power plants, 226 GWh of electrical and 356 GWh of thermal energy could be produced (assuming typical conversion efficiencies of 55% thermal and 35% electrical for CHP plants [14]). On top of this, hydro and wind power can provide 113 GWh_{el} and 3 GWh_{el} of electricity annually, respectively. To put this into perspective, existing PV plants produced 115 GWh_{el} in 2016, while 501 GWh of thermal and electrical energy were produced from biomass in 2016.

Table 1 summarizes all renewable energy potentials and compares these to existing electricity generation.

On the demand side, residential buildings account for 851 GWh_{el} and 3,028 GWh_{th}, while non-residential consumers account for 1,204 GWh_{el} and 1,822 GWh_{th}, respectively. A comparison of demand and renewable energy potentials thus shows that locally available renewable energy generation could cover 68% of the county’s annual electricity demand of 2,055 GWh_{el} in 2019. Furthermore, bioenergy-based heat potentials of 356 GWh_{th} can cover 7.3% of existing heat demand, preferably within existing district heating networks that supplied 266 GWh_{th} of heat in Ludwigsburg county in 2019.

4. Discussion and Conclusion
The presented result show that high shares of locally produced renewable energy are difficult to achieve for Ludwigsburg, even if full technical potentials were exploited for key technologies.
Table 1. Calculated renewable energy potentials, existing generation in 2019, additional potentials, and current electricity and heat demands.

| Calculated in SimStadt | Existing | Additional potential |
|------------------------|----------|----------------------|
| [GWh]                  | [GWh]    | [GWh]                |
| Biomass (thermal)      | 356      | 340                  | 16                    |
| Biomass (electrical)   | 226      | 161                  | 65                    |
| PV rooftop             | 1,061    | 114                  | 947                   |
| Hydro power            | -        | 113                  | -                     |
| Wind power             | -        | 3                    | -                     |
| Demand (electric)      |          |                      | 2,055                 |
| Demand (thermal)       |          |                      | 4,850                 |

Figure 1. Comparison of local renewable electricity potentials and local electricity demand.

Figure 2. Comparison of local renewable heat potentials and local heat demand.

Generally, these results are not surprising, given Ludwigsburg’s high population density and strong industrial and commercial base as part of the Stuttgart metropolitan region. Thus, energy autarchy should not be a primary goal of such regions. Rather, a well-balanced mix of local measures and energy imports from less populated regions with Germany or abroad is required to achieve climate neutrality in a cost-efficient and socially acceptable way until 2045. Besides exploiting technical potentials as far as viable, e.g. in rooftop PV, where almost 90% of potential are still left untapped, local efforts should focus on reducing demands, in particular in the heating sector through increased refurbishments rates.

As all suitable land areas were assumed to be used for producing either food or biomass-based energy carriers, free-field PV systems were not considered in the analysis. The authors...
note, however, that free-field PV can substantially increase local renewable electricity generation potentials. Future work will thus focus on establishing a free-field PV workflow in SimStadt. On the demand side, improved modelling of buildings’ heating and cooling demands and refurbishment scenarios is a further priority. In sum, these efforts will enable an integrated assessment of most local electricity and heat demands and renewable potentials within one tool.

The approaches and methods applied to Ludwigsburg can be transferred to other regions where CityGML models are available. Performing similar analyses for other archetypal counties in Germany, scaling these results to a national level and combining them with information on the economics of specific solutions is a next step that allows to assess optimal split between local and national renewable energy supplies.

References
[1] Agora Energiewende. Die Energiewende im Corona-Jahr: Stand der Dinge 2020. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2021., 2021.
[2] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal, 2019.
[3] Bundesministerium fuer Umwelt Naturschutz und nukleare Sicherheit (BMU). Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050, 2019.
[4] Bundesministerium für Wirtschaft und Energie. Die Energie der Zukunft. Zweiter Fortschrittsbericht zur Energiewende. Technical report, 2019.
[5] Alaia Sola, Cristina Corchero, and Jaume Salom. Simulation Tools to Build Urban-Scale Energy Models : A Review. 2018.
[6] Martina Ferrando, Francesco Causone, Tianzhen Hong, and Yixing Chen. Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches. Sustainable Cities and Society, 62, 2020.
[7] Verwaltungsgliederung am 31.03.2021 (1. Quartal) - Statistisches Bundesamt.
[8] J Bahu, A Koch, E Kremers, and S M Murshed. TOWARDS A 3D SPATIAL URBAN ENERGY MODELLING APPROACH. II(November):27–29, 2013.
[9] Filip Biljecki, Hugo Ledoux, Jantien Stoter, and George Vosselman. The variants of an LOD of a 3D building model and their influence on spatial analyses. ISPRS Journal of Photogrammetry and Remote Sensing, 116:42–54, 2016.
[10] Verena Weiler, Jonas Stave, and Ursula Eicker. Renewable energy generation scenarios using 3D urban modeling tools—methodology for heat pump and co-generation systems with case study application. Energies, 12(3), 2019.
[11] Sally Koehler, Matthias Betz, and Ursula Eicker. 15-MINUTE RESOLUTION ON BUILDING LEVEL FOR WHOLE CITY QUARTERS. In 16th IAEE Conference Ljubljana, 2019.
[12] Ivan Dochev, Philip Gorzalka, Verena Weiler, Jacob Estevam Schmiedt, Magdalena Linkiewicz, Ursula Eicker, Bernhard Hoffschmidt, Irene Peters, and Bastian Schröter. Calculating urban heat demands: An analysis of two modelling approaches and remote sensing for input data and validation. Energy and Buildings, 226, 11 2020.
[13] Ursula Eicker, Verena Weiler, Jürgen Schumacher, and Reiner Braun. On the design of an urban data and modeling platform and its application to urban district analyses. Energy and Buildings, 217, 2020.
[14] Keyu Bao, Rushikesh Padsala, Volker Coors, Daniela Thrän, and Bastian Schröter. A Method for Assessing Regional Bioenergy Potentials Based on GIS Data and a Dynamic Yield Simulation Model. Energies, 13(24):6488, 2020.

[15] Christoph Bahret and Sally Köhler. A case study on energy system optimization at neighborhood level based on simulated data: a building-specific approach. Energy and Buildings, 238:110785, 2 2021.

[16] Ursula Eicker, Romain Nouvel, Eric Duminil, and Volker Coors. Assessing passive and active solar energy resources in cities using 3D city models. Energy Procedia, 57:896–905, 2014.

[17] Laura Romero, Eric Duminil, José Sánchez, and Ursula Eicker. Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach. Solar Energy, 146:264–275, 2017.

[18] Joseph Bergner, Bernhard Siegel, K Mainzer, and R McKenna. „städtische solarpotenzial-karten im vergleich“. In PV-Symposium 2018, page 10, 2018.

[19] Clara Good, Inger Andresen, and Anne Grete Hestnes. Solar energy for net zero energy buildings - A comparison between solar thermal, PV and photovoltaic-thermal (PV/T) systems. Solar Energy, 122:986–996, 12 2015.

[20] María Herrando, Antonio M. Pantaleo, Kai Wang, and Christos N. Markides. Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. Renewable Energy, 143:637–647, 12 2019.

[21] Nutzung von Flüssen: Wasserkraft — Umweltbundesamt.

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