Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The spatial dimension of the power system: Investigating hot spots of Smart Renewable Power Provision

Sebastian Rauner [a,*], Marcus Eichhorn [a], Daniela Thrän [a,b]

[a] Helmholtz Centre for Environmental Research – UFZ, Permoserstraße 15, 04318 Leipzig, Germany
[b] German Biomass Research Centre, Torgauerstraße 116, 04347 Leipzig, Germany

HIGHLIGHTS

- Spatially highly explicit analysis of the German power system.
- Spatial dissonance between power demand and renewable power supply.
- Introduction of Smart Renewable Power Provision analysis.
- Evaluation of socioeconomic and land use factors.
- Development of trajectory pathways towards Smart Renewable Power Provision.

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 24 June 2016
Accepted 10 July 2016
Available online xxxx

Keywords:
Smart renewable energy
Hot spot analysis
Renewable energy integration
Land use
Resource complementarities

ABSTRACT

The spatial dimension of the transition to a decarbonized power system becomes increasingly apparent with more than 1.5 million renewable energy sources of electricity (RESE) plants operating all over Germany. The information regarding the spatial distribution of RES-E generation and power demand is still divers and not yet systematically used for the strategic planning of the energy transition and energy system modelling. The objective of this study is therefore to analyse the current power demand and RES-E supply spatially highly explicit with regard to their local interplay, annual balances and the share of volatile to flexible RES-E. This is achieved through the development and implementation of a general framework to analyse spatial patterns of the power system at different scales. The area of study is the Federal State of Germany, with the assessment of different spatial resolution ranging from federal state to community level. The resulting patterns are evaluated for their statistical significance through a hot spot analysis, followed by a correlation analysis to find possible reasons for their formation. The study shows a spatial dissonance between power demand and RES-E supply. This suggests that the design of the policy framework, focused on the levelized cost of electricity, led to a spatial distribution not oriented on local power demand but rather on economic optimality for the single power plant owner. By additionally differentiating between the RES-E technologies in terms of their intermittency characteristics, conclusions on the ability of regions at different scales for Smart Renewable Power Provision are drawn, measured by a set of proposed low carbon indicators. The spatially most detailed level reveals the diverse state of the regions with, on the one hand, already around 10% fulfilling the indicator limit of Smart Renewable Power Provision and, on the other hand, regions with no RES-E capacity installed. An algorithm for finding desirable trajectory pathways to a decentralized energy system is introduced, build on the knowledge of the current state of the local power system. Finally, the correlation analysis indicates that for the RES-E extension not only socioeconomic but also land use characteristics are important factors to consider.

1. Introduction

The decarbonisation of the energy sector is one of the most important tasks of the global society in the 21st century. An unchecked climate change will impair life conditions of a large fraction of the world's population [1]. As one option to face these challenges, the German government implemented the "energy transition". This process already started in 1991 with the enforcement of the electricity feed-in act [2], continued with the German renewable energies act (EEG) [3] and gained momentum after the Fukushima accident in 2011 with the "energy concept" [4,5]. The

* Corresponding author.
E-mail address: sebastian.rauner@ufz.de (S. Rauner).

http://dx.doi.org/10.1016/j.apenergy.2016.07.031
0306-2619/

Nomenclature

C_{1-3}	density clusters
CEM	carbon emission mitigation
CEM_r	carbon emission mitigation indicator of region r
$CEM_r^{requ.}$	required carbon emission mitigation indicator of region r
CORINE	coordination of information on the environment
DSM	demand side management
EEG	German renewable energies act
FLH	full load hours
GDP	gross domestic product
GHG	greenhouse gas
G_i^*	general G-statistic value of feature i
Gi-Bin	confidence level
i	feature i
$I_{LAU\ 2}$	number of inhabitants on LAU 2 level
$I_{NUTS\ 1}$	number of inhabitants on NUTS 1 level
j	feature j
LAU	local administrative unit
n	total number of features
NUTS	nomenclature of territorial units for statistics
$P_r^{RES\text{-}E}$	produced power of RES-E in region r
$P_r^{RES\text{-}E_{flexible}}$	produced power of flexible RES-E in region r
$P_r^{RES\text{-}E_{volatile}}$	produced power of volatile RES-E in region r
p-value	probability
r	region
RES-E	renewable energy source of electricity
SIF	system integration friendliness
SIF_r	system integration friendliness indicator of region r
SP	secured production
SREPP	Smart Renewable Power Provision
$SREPP_r$	Smart Renewable Power Provision indicator of region r
$U_{NUTS\ 1}^{exem.\ industry}$	demand of industry enjoying special regulations in the EEG on NUTS 1 level
$U_{NUTS\ 1}^{industry}$	demand of industry on NUTS 1 level
$U_{LAU\ 2}^{household}$	demand of households on LAU 2 level
$U_{NUTS\ 1}^{household}$	demand of households on NUTS 1 level
U_r^{total}	total demand of region r
$U_{LAU\ 2}^{trade}$	demand of trade on LAU 2 level
$U_{NUTS\ 1}^{trade}$	demand of trade on NUTS 1 level
$U_{LAU\ 2}^{transport}$	demand of transport on LAU 2 level
$U_{NUTS\ 1}^{transport}$	demand of transport on NUTS 1 level
$w_{i,j}$	spatial weight between feature i and j
x_j	attribute value for feature j
z-score	standard deviations

German government aims to mitigate greenhouse gas (GHG) emissions by 80–95% until 2050, compared to 1990, respectively the renewable power generation shall increase to 80% [4].

In 2014 renewable energy sources of electricity (RES-E) have already contributed 27.4% to the overall power generation in Germany, produced by roundabout 1.5 million plants. In comparison, the conventional power plant park generated 72.76% of the power consumption with 770 plants (>10 MW nominal capacity). The current power demand on the other side is relatively constant with a slight increase of 2.9% from 2000 to 509,167 GW h in 2014.

These numbers illustrate that a power system, based on RES-E like wind, photovoltaic, biomass or water power, is of a much more decentralized nature than one based on conventional power plants. There are many advantages of the transition, GHG emission reduction, energy security improvement and economic and industrial development, to name just a few [6–9]. However, with the increasing numbers of power plants and the corresponding increase in land use change, the energy generation infrastructure becomes visible and audible to great fraction of the society, to name just the most obvious impacts. Now one of the major challenges is to coordinate the expansion and the spatial allocation of those plants for a renewable power supply in accordance with the energy policy target triangle of security of supply, cost effectiveness and environmental soundness [10]. Within this debate, spatial aspects play an increasing role due to the fact that RES-E are much more spread over the landscape than conventional power plants and their very different intermittency characteristics. Both factors need to be considered when aiming for local, regional and transregional supply concepts.

Studies performing an analysis of the German power system spatially highly explicit are lacking until today. The spatial resolution of the corresponding energy system models is mostly country level or even world regions [11–19] with only a few spatially more detailed models [7,20,21]. Renewable energy sources however are site dependent on at least five dimensions: (1) natural energy potential, (2) distributed power demand (3) system integration and sector interconnection, (4) ecological impacts and (5) socioeconomic effects [22–32].

The dramatic increase in the number of RES-E plants results in the rise of required land. Space however is already a limited resource in Germany due to the demand for land use from different directions, e.g. building and construction land, agriculture production, recreation [33]. These more spatial related effects have not been reflected in national energy strategies and energy planning so far [34–37].

Furthermore, the dimension of intermittency of the RES-E is not yet spatially explicitly considered [38]. The intermittent nature of the major RES-E generation however necessitates increasing amounts of balancing mechanisms and flexible power [9,39,40]. Consequently, the relevance of the integration of demand side management (DSM) into the power system modelling to foster accuracy is increasing [41]. With a distributed power system, the spatial dimension of these mechanisms becomes increasingly relevant. The potential for DSM as well as the required amount for the balancing of the power system depend on the location. The future relevance of these site-specific mechanisms highlights the need for a spatially explicit analysis of the power system.

As a starting point for a more spatial explicit strategy and planning process, information on the spatial patterns of already existing RES-E plants are necessary. To understand the role of those plants for the current and future power supply system it is obligatory to know (1) what share of the local demand could be supplied (2) how the different RES-E volatility characteristics may interact with regard to a secure supply.

In this study, regions with an efficient spatial connection of RES-E supply and power demand patterns in combination with a high share of flexible to volatile RES-E are referred to as regions of Smart Renewable Power Provision. They combine a low carbon emission based power generation with a RES-E technology mix resulting in potential complementary generation patterns, fostering security of supply [42]. Besides the achieved carbon mitigation these regions are beneficial for the power system in many ways, a few examples are: The spatial proximity of supply and demand avoids the massive extension of the transmission grid while the potential complementary generation patterns reduce curtailment, grid bot-