Energy Conversion and Management 156 (2018) 403–415

Contents lists available at ScienceDirect

Energy Conversion and Management

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

National and global wind resource assessment under six wind turbine installation scenarios

Christopher Jung*, Dirk Schindler, Jessica Laible

Environmental Meteorology, Albert-Ludwigs-University of Freiburg, Werthmannstrasse 10, D-79085 Freiburg, Germany

ARTICLE INFO

Keywords:
Wind resource
Wind energy yield
Capacity factor
Electricity consumption
ERA-20C

ABSTRACT

Based on ERA-20C data available for the period 2008–2010, the potential of six onshore wind turbine installation scenarios to cover current electricity consumption at the national and global scale was studied. The technical wind energy potential was estimated using the recently developed, highly accurate Burr-Generalized Extreme Value mixture distribution. The installation scenarios were evaluated by varying wind farm efficiency, the concentration of wind turbines, and wind turbine siting strategy for wind turbine densities of 1–25% of the land area. With the systematic installation of wind turbines at the national scale and international coordination of energy distribution, wind energy production could match current electricity consumption in the 2030s assuming a tenfold increase in current expansion rate. However, the results greatly differ from country to country mainly because of the meteorological potential, the total area available for wind turbine installation, and the population size. In industrialized countries such as China, France, Germany, and Japan, either low average annual wind energy yield or the large population prevents complete coverage of electricity consumption by wind energy at low and moderate wind turbine density. In developing countries including Ethiopia, Sudan or Kenia, where wind energy potential is high and electricity consumption is low, expansion of wind energy could greatly improve electricity supply. It was found that 98 countries could cover their current electricity consumption by an installed capacity of 0.0734 MW/km^2. This installed capacity enables 73 countries to cover even a 100% increase of the current electricity consumption. Based on the range of evaluated scenarios, it is possible to estimate the upper and lower bounds of the technical potential predefined by the applied wind turbine densities.

1. Introduction

Along with economic development, electricity consumption has steadily increased over the last decades [1]. In 1980, globally consumed electricity was 7,319 TW h/yr. Until 2014, global electricity consumption increased by 283%, reaching 20,715 TW h/yr [2]. The countries with the highest electricity consumption in 2014 were China (5,113 TW h/yr, including Hong Kong and Macau) and the USA (3,913 TW h/yr) (Fig. 1).

Currently, conventional fuels are predominately used to cover electricity consumption [3]. However, the utilization of conventional fuels is connected with greenhouse gas emissions, which drive climate change [4]. Furthermore, emissions of air pollutants pose human health risks [5]. In addition, anticipated peaking of fossil fuels requires finding appropriate substitutes such as renewable energies [6]. Renewable energies are vital sources of future energy helping to mitigate climate change [7]. They are clean, environmentally friendly, and health-compatible alternatives to fossil fuels [8].

Wind turbines convert kinetic energy contained in the wind first into mechanical and then into electrical energy [9]. Nowadays, wind turbine technology is considered to be matured and the costs of wind energy are low [10]. The current expansion rate of installed wind energy capacity (*IC*) is enormous. From 2001 to 2016, *IC* increased by 2,037% from 23,900 MW to 486,790 MW. In 2016, the highest wind energy capacity was installed in China (168,690 MW), the USA (82,184 MW), and Germany (50,018 MW). The corresponding installed capacities per area were 0.018 MW/km^2 in China, 0.009 MW/km^2 in the USA, and 0.1435 MW/km^2 in Germany [11].

The wind energy potential is typically divided into five categories which are hierarchically structured [12]: (1) the meteorological potential, which is the available wind resource, (2) the site potential, which excludes geographical unsuitable areas from the meteorological potential, (3) the technical potential, which takes the available wind energy technology into account, (4) the economic potential, which is defined as the technical potential that can be realized, and (5) the implementation potential which considers constraints and incentives

* Corresponding author.
E-mail address: christopher.jung@mail.unr.uni-freiburg.de (C. Jung).

https://doi.org/10.1016/j.enconman.2017.11.059
Received 30 August 2017; Received in revised form 17 November 2017; Accepted 19 November 2017

Nomenclature

Acronyms

a.g.l.	above ground level
B-GEV	Burr-Generalized Extreme Value distribution
CanadaSC5	scenario 5 estimations for Canada
cdf	cumulative distribution function
epdf	empirical probability density function
pdf	probability density function
RussiaSC5	scenario 5 estimations for Russia
SC1-SC6	wind turbine installation scenario 1–6

Symbols

$\bar{P}$	mean wind power density (W/m^2)
$\bar{x}$	mean wind speed (m/s)
μ	location parameter of Generalized Extreme Value distribution
AEY	annual average wind energy yield (GW h/yr)
AEYC	annual average wind energy yield per country (TW h/yr)
AEYG	global annual average wind energy yield (TW h/yr)
APR	atmospheric pressure (Pa)
CF	capacity factor
EC	electricity consumption (TW h/yr)
f	probability density function
F	cumulative distribution function
G	atmospheric gas constant (J/kg K)
IC	installed wind energy capacity (MW)
K	total number of countries
k	country
MAPE	mean absolute percentage error (%)
n	number of hours in a year (h)
P	power (W)
R^2	coefficient of determination
S	share of wind energy covering electricity consumption of 2014
SR	scenario ratio *AEYC*(SC1)/*AEYC*(SC6)
T	temperature (K)
u	zonal wind vector component (m/s)
v	meridional wind vector component (m/s)
WFE	wind farm efficiency
WTAC	wind turbine area per country (km^2)
WTD	wind turbine density per country (%)
WTN	number of wind turbines at *WTAC* grid cells (wind turbines/km^2)
WTT	wind turbine availability
x	wind speed (m/s)
z	grid cell (1 km^2)
η	scale parameter of Generalized Extreme Value distribution
ι	shape parameter of Generalized Extreme Value distribution
o	first shape parameter of Burr distribution
ρ	air density (kg/m^3)
σ	scale parameter of Burr distribution
χ	second shape parameter of Burr distribution
ω	mixing parameter of Burr-Generalized Extreme Value distribution

Subscripts

0	average conditions
a	air
B	Burr
emp	empirical
GEV	Generalized Extreme Value
W	wind turbine
z	grid cell

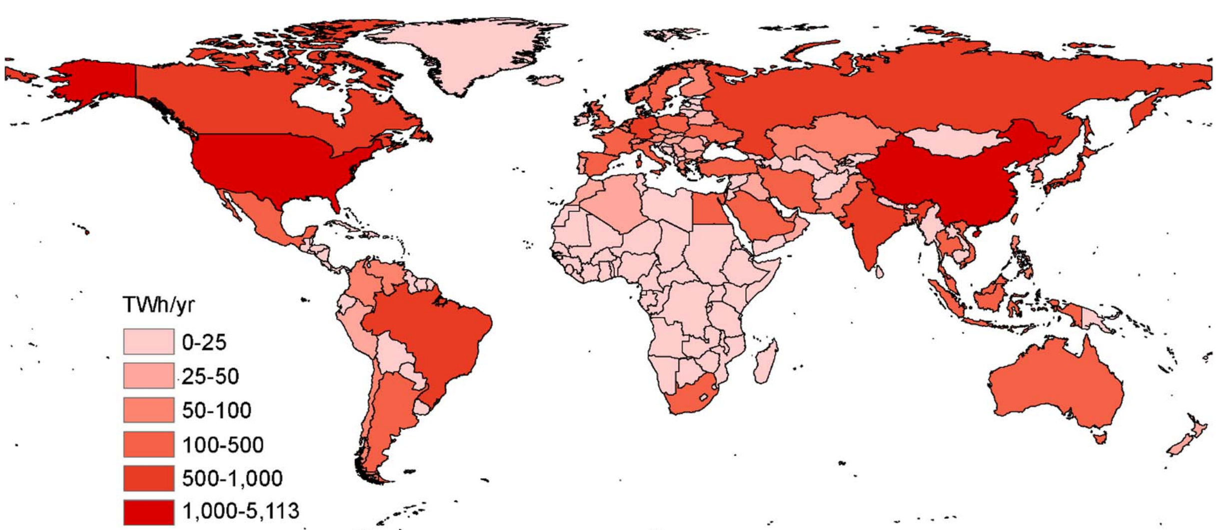

Fig. 1. Electricity consumption in 2014 [2].

that determine the time required to install wind turbines.

The global technical potential of wind energy has been investigated in several previous studies. Based on approach and applied specifications, the obtained results vary greatly among these studies. For instance, in a bottom-up study, it was estimated that a dense network of 2.5 MW onshore wind turbines could generate 1,100 PW h/yr electrical energy [13]. In a top-down study, the estimated electricity generation was lower amounting to 158–596 PW h/yr [14]. In that study, it was argued that each wind turbine extracts kinetic energy from the atmosphere, which reduces the overall extractability of kinetic energy and wind speed (x) on a large scale [15]. However, it has been demonstrated that this effect becomes important only at magnitudes that clearly surpass current electricity consumption or even primary energy consumption [16].

Previous studies mainly focused on the total extractable wind energy. However, real-world expansion of wind energy utilization is