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Analysing the potential of integrating wind and solar power in Europe using spatial optimisation under various scenarios

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ABSTRACT

The integration of more variable renewable energy sources (vRES) like wind and solar photovoltaics (PV) is expected to play a significant role in reducing carbon dioxide emissions from the power sector. However, unlike conventional thermal generators, the generation patterns of vRES are spatially dependent, and the spatial distributions of wind and PV capacity can help or hinder their integration into the power system. After reviewing existing approaches for spatially distributing vRES, we present a new method to optimise the mix and spatial distribution of wind and PV capacity in Europe based on minimising residual demand. We test the potential of this method by modelling several scenarios exploring the effects of vRES penetration, alternative demand profiles, access to wind sites located far offshore, and alternative PV configurations. Assuming a copper-plate Europe without storage, we find an optimum vRES penetration rate of 82% from minimising residual demand, with an optimum capacity mix of 74% wind and 26% PV. We find that expanding offshore wind capacity in the North Sea is a 'no regret' option, though correlated generation patterns with onshore wind farms in neighbouring countries at high vRES penetration rates may lead to significant surplus generation. The presented method can be used to build detailed vRES spatial distributions and generation profiles for power system modelling studies, incorporating different optimisation objectives, spatial and technological constraints. However, even under the ideal case of a copper-plate Europe, we find that neither peak residual demand nor total residual demand can be significantly reduced through the spatial optimisation of vRES.

1. Introduction

Decarbonisation of the electric power sector is one of the key transitions which must take place as part of Europe's commitment to reducing CO_2 emissions in order to avoid dangerous climate change [1,2]. This will be achieved mainly through the integration of more renewable energy sources (RES) such as onshore wind, offshore wind, solar photovoltaics (PV), hydro and biomass into the power system. Many studies have presented scenarios of what such a low-carbon European power system could look like in the long term, typically by 2050 [3–7]. These scenarios must employ nearly 100% RES, or a combination of RES and other low-carbon technologies such as nuclear power, bioenergy, or fossil fuels with carbon capture and storage (CCS). However, with several countries aiming to reduce nuclear power capacity and slow development of the European CCS industry [8], a heavier dependence on RES may be more likely.[1] This will pose a challenge as, without significant development in nuclear or CCS capacity, comparing the current installed wind and PV capacities with those in several high-RES scenarios (Table 1) suggests that an additional 300–700 GW of wind capacity and 720–870 GW of PV capacity would need to be installed by 2050 [2,3,9–11]. The question then arises, where should all this capacity be built?

Abbreviations: CCS, Carbon capture and storage; CDDA, Common Database on Designated Areas; CLC, Corine Land Cover; CSP, Concentrating solar power; CV, Coefficient of variation; ECF, European Climate Foundation; ECMWF, European Centre for Medium-Range Weather Forecasts; EEA, European Environment Agency; EEZ, Exclusive Economic Zone; ERA-I, European Reanalysis Interim Dataset; EU, European Union; EV, Electric vehicle; ENTSO-E, European Network of Transmission System Operators for Electricity; FLH, Full load operating hours; HDH, Heating degree hour; HP, Heat pump; IEC, International Electrotechnical Commission; IPCC, Intergovernmental Panel on Climate Change; JRC, European Union Joint Research Centre; LLSQ, Linear least squares; OECD, Organisation for Economic Co-operation and Development; PSM, Power system model; PR, Performance ratio; PV, Photovoltaic; RES, Renewable energy source; vRES, Variable renewable energy source

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[1] In 2014, Germany, Belgium and Switzerland operated 21 nuclear reactors between them, but plan to phase out nuclear power by 2022, 2025 and 2034 respectively [109]. France also aims to reduce its share of nuclear generation from nearly 74% to 50% by 2025 [110]. Despite these contractions in nuclear capacity, only seven new reactors are currently planned or under construction in Europe.

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Symbols

A	Left-hand-side constraint coefficient matrix
B	Right-hand-side constraint value matrix
c	Installed generation capacity (MW)
C	Vector containing values of c
CC	Capacity credit (%)
d	Electricity demand (MW, MWh h^{-1})
f	Capacity factor (-)
F	Matrix containing values of f (-)
g	Generation (MW, MWh h^{-1})
r	Residual demand (MW, MWh h^{-1})
R	Total residual demand (MWh)
T	number of generation technologies

Subscripts

c	country
eq	equality
i	vRES generation technology
ieq	inequality
LT	long-term
ST	short-term
t	time step
x	grid cell
y	year

Table 1
Comparison of current (2015) installed power generation capacity in Europe with installed capacity from several (nearly) 100% RES scenarios for Europe in 2050.

Generation Type	Current (2015) installed capacity (GW)		Installed capacity in selected high-RES scenarios(GW)		
	EWEA [9]	ENTSO-E [10] (EU28 + CH + NO)	Roadmap 2050 [2][a]	Energy Revolution [3][b]	Re-thinking 2050 [11][c]
Onshore wind	130.6 (14%)	136.0 (13%)	245 (12%)	594 (23%)	462 (24%)
Offshore wind	11.0 (1%)		190 (9%)	237 (9%)	
Photovoltaic (PV)	95.4 (10%)	94.6 (9%)	815 (41%)	926 (36%)	962 (49%)
Ocean (Wave and Tidal)	0.3 (0.03%)	–	–	53 (2%)	65 (3%)
CSP	5.0 (0.6%)	–	203 (10%)	208 (8%)[g]	96 (5%)
Biomass (including waste)	16.7 (1.8%)	25.4 (3%)	85 (4%)	108 (4%)	100 (5%)
Geothermal	0.82 (0.1%)	–	47 (2%)	52 (2%)	77 (4%)
Hydro	141.1 (16%)	193.9[d] (19%)	205 (10%)	223 (9%)	194 (10%)
Natural Gas	192 (21%)	216.8 (21%)	215 (11%)	–	–
Coal	161 (18%)	187.0 (18%)[e]	–	–	–
Oil	33.7 (4%)	31.8 (3%)	–	–	–
Nuclear	120.2 (13%)	124.6 (12%)	–	–	–
Other	–	2.3 (0.2%)	–	181 (7%)[h]	–
Total RES	401.0 (44%)	403.9 (40%)	1790 (89%)	2401 (93%)	1956 (100%)
of which vRES[f]	237.3 (26%)	230.6 (23%)	*1250 (62%)*	1810 (70%)	*1489 (76%)*
Total Non-RES	506.9 (56%)	608.4 (60%)	215 (11%)	181 (7%)	–
Total	908	1012	2005	2582[f]	1956

[a] 100% RES scenario, 20% demand side management scenario, included EU27 + NO + CH.
[b] 5th edition, Advanced Scenario, included OECD Europe (EU27 – Baltic Countries + Turkey).
[c] Included EU27.
[d] ENTSO-E report 'renewable' (145.6 GW) and 'other' (48.3 GW) hydro, with the former including run-of-river and hydro plants with storage, 'other' being pumped storage plants with no natural inflow. Only renewable counted in renewable total.
[e] Including anthracite, peat and other non-RES fuels.
[f] Excluding run-of-river hydro.
[g] Total installed capacity (2460 GW) and generation (5764 TWh) reported in original study for OECD Europe did not include assumed import of 620 TWh y^{-1} from North African CSP, thus CSP capacity increased to compensate for this by assuming the same capacity factor for North African CSP as for European CSP in the study (55%).
[h] Hydrogen.

As generation from variable renewable energy sources (vRES) such as PV and wind is intermittent, the challenge is even greater as any residual demand[2] – the difference between the total demand and vRES generation – must be provided by dispatchable fossil (e.g. coal, oil, gas), renewable (e.g. hydro, biomass, concentrating solar power (CSP)) or nuclear backup generation capacity [12]. Given that vRES generation profiles depend on both the type of technology and weather regime where they are installed, optimising the mix and spatial distribution of vRES has been suggested as one way of helping to integrate vRES into the power system [13,14].

Steps have been taken in this direction in the literature; however, most existing studies have shortcomings in that they: (i) consider complementarity between vRES generation profiles but do not consider demand [15–24]; (ii) allocate, rather than optimise the spatial distribution of vRES[3] [5,25–30]; (iii) consider only a limited number of vRES technologies [31–34], (iv) are limited in geographical scale [17,19,20,22,23,35–39]; or (v) optimise capacity, but do not examine the robustness of the resulting distributions to different weather years [36,40–42]. For example, the first group of studies investigate how different vRES generation patterns can be used to complement or balance each other, in order to achieve more constant overall generation. This

[2] The terms load and demand are often used synonymously, however this study adopts the ENTSO-E definition of *load* as 'an end-use device or customer that receives power from the electric system' with *demand* defined as 'the measure of power that a load receives or requires' [111].

[3] We use the term *allocation* to refer to those studies which exogenously assume or weight vRES capacities per region based on parameters such as capacity factor, vRES potential, land suitability or population. This is also the approach taken in most high-level power system modelling studies. We use the term *optimisation* to indicate studies which actually formulate the spatial distribution as an optimisation problem with an objective function (e.g. maximum capacity factor, minimum residual demand, minimum cost etc.).