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Natural resource endowment is not a strong driver of wind or PV development

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Natural resources have previously been included in analyses explaining differences between renewable energy deployment across countries or subnational regions. Most previous analyses used resource volumes, or rough proxies for these, and results have been inconclusive. This study uses panel data analysis, with indicators of both the quality and quantity of natural resources, and analyses effects on wind and PV development by comparing countries of the world, and provinces or states of China, Germany, and the US. Either measure of natural resources has limited explanatory power on differences in wind or PV development between countries. Resource quality, not quantity, has a more consistent, positive effect when comparing states or provinces of China, Germany and the US. Still, plenty of countries, states or provinces with relatively poor quality natural resources have managed relatively high levels of wind or PV development, and vice versa. The only exceptions are the US wind power market and the Chinese PV market, where development is more strongly correlated with natural resources. The conclusion is that natural resources are a small part in a larger set of drivers, and that low quality natural resources do not preclude developing relatively high market shares of wind or PV power.

1. Introduction

Much research has been devoted to the preconditions and drivers of renewable energy development. One of the factors considered is natural resource endowment. This refers to the abundance and/or quality of natural resources required for the generation of renewable energy; rivers, biomass, wind or solar irradiation. Unlike fossil energy resources, these cannot be transported, and countries or states/provinces are therefore limited to the utilization of locally available resources [1] (with the exception of biofuels and solid biomass [2]).

There is a voluminous body of literature that has sought to assess the abundance of such natural resources. Such assessments translate e.g., prevailing wind speeds or solar irradiance into an upper limit, or maximum potential, of MW of installations or MWh of power generation form these sources. Such assessments fall into different categories depending on the restrictions of the resources that are included. The widest scope of assessment, which is referred to as the resource potential or theoretical potential, reflects the total energy content of e.g., the wind within the area of study. Other categories narrow this scope, and exclude resources e.g., in areas with difficult terrain conditions for construction, or areas where natural resources are too low for economically viable deployment of wind or PV power, etc. [3,4]. Each additional exclusion results in a smaller potential; see Fig. 1. Studies of the maximum potential for different renewable energy technologies have been done at the global level, national level, as well as subnational divisions [e.g., [3,5–7]].

Other studies have focused on the quality, rather than the abundance, of natural resources. Natural resource quality is, for example, a key point in feasibility or economic performance studies of e.g., wind or PV projects in specific locations or areas [8–10]. Projects at sites with resources with higher energy density, i.e., stronger wind speeds or solar irradiation, result in a higher productivity. Such projects result in more electricity generated, with the same equipment, than would have been the case in an area with lesser quality natural resources (see e.g., Fig. 2). This increases revenue and therefore the economic value, measured for instance as Net Present Value, of the project. Such feasibility studies consider a list of further items, including costs for land, grid connection and access roads, but the quality of the

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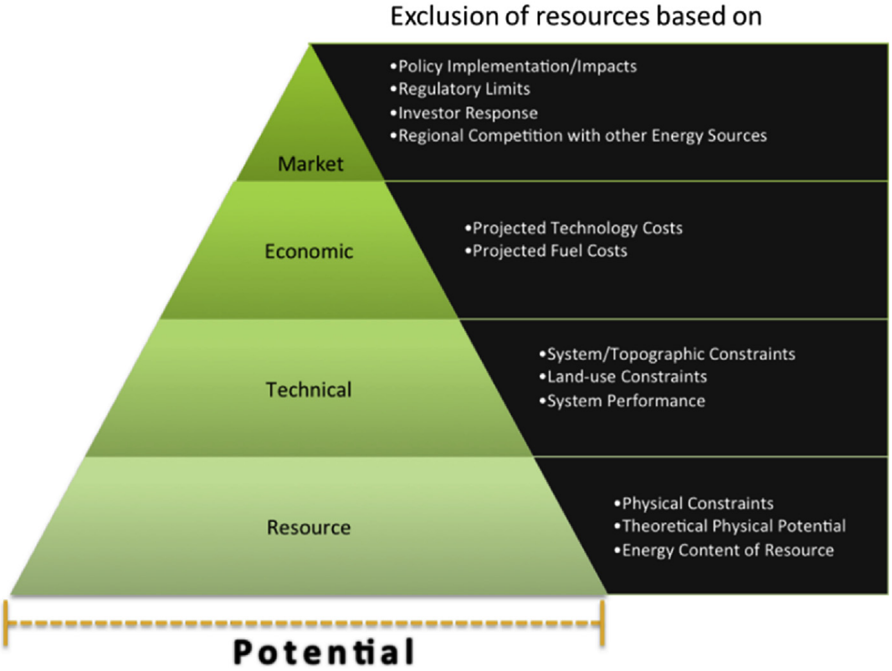

Fig. 1. Categories of natural resource potential and assumptions with which they are derived.
Source: reproduced from [3].

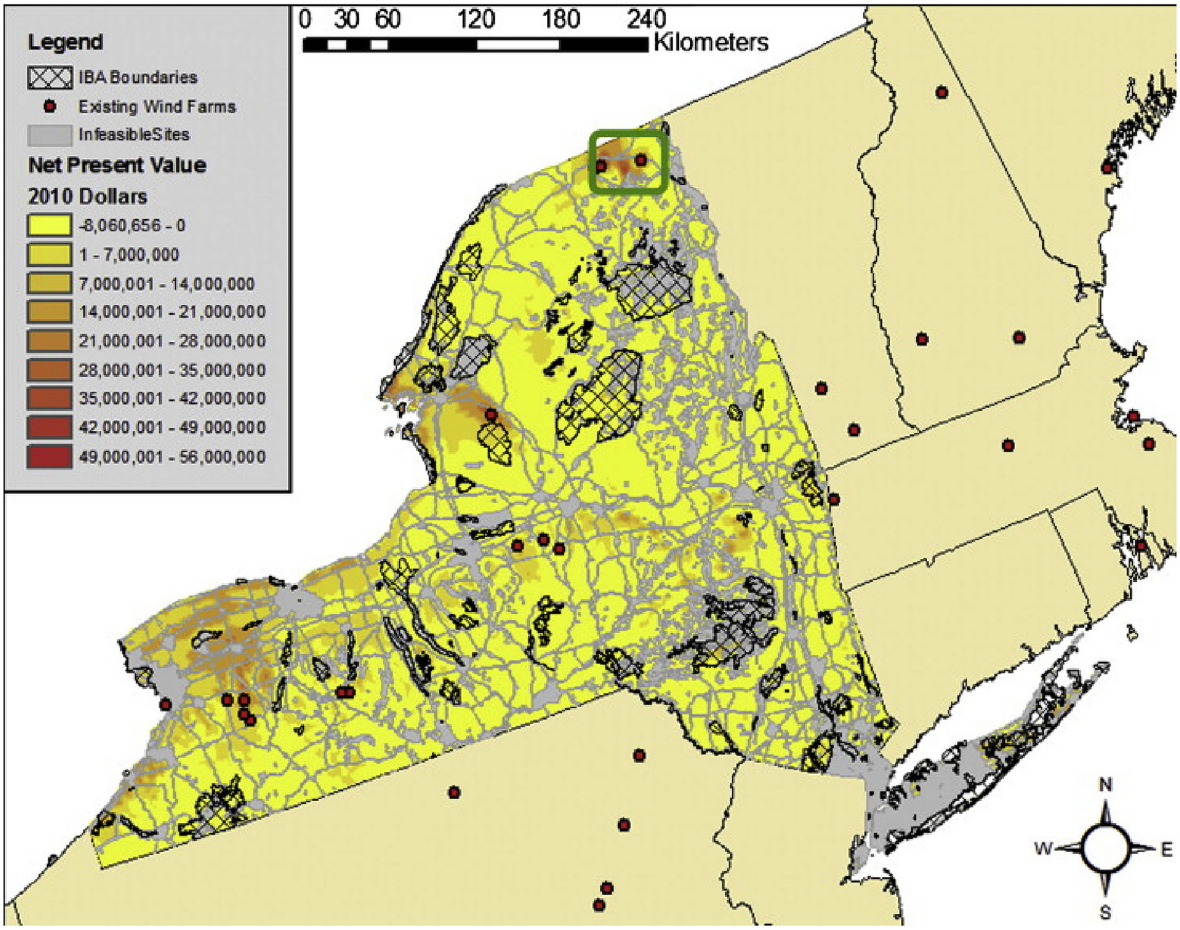

Fig. 2. Wind resource quality and resulting Net Present Value of wind farm development: map of the state of New York.
Reproduced from [8].

local natural resources is the single most important item in determining a project's profitability [8].

Third, and the focus of this paper, differences in natural resource endowment have been considered in explaining the large variation in the use of different renewable energy technologies between countries, or between states or provinces within countries. One common approach for explaining such variation is with panel data analysis, in which a selection of variables is tested for their relationship with the use of renewable energy [e.g., [1,11–20]]. The number of this type of analyses that includes reference to natural resource endowment is still limited, however, and results so far have been mixed. Different studies have identified either positive, negative, or insignificant effects from natural resource endowment on different indicators of renewable energy development, with little consistency in the sign of effects for comparable outcome variables or technologies (see a sample in Table 1). One of the few consistencies is that a number of studies reported negative effects from wind resource endowment. Carley [1] offers an explanation, arguing that US states with good wind resources may feel less need for adopting support policies, whilst in reality, both resources and policy incentives are needed to ensure wind power development. This contracts with results from Delmas and Montes-Sancho [21], who find that US states with good wind or PV resources were actually more likely to adopt RES incentive policies, but who find no effect on installed RES capacity, and conclude that the relationship is a complex mix of natural and institutional factors.

Another explanation for the inconclusive results may be the measure of natural resource endowment used. Most studies have used measures of the maximum technical potential, i.e., the total volume of natural resources. To illustrate why this may be a problem, consider that the NREL has estimated the maximum technical potential in the US to be 32.7 PWh for onshore wind, and 283 PWh for PV [3]. Actual generation in 2015 was 191 TWh from wind, or 0.9% of the maximum potential, and 21.3 TWh from PV, or less than 0.01% of the maximum potential [22]. As these resources are still so very far from exhausted, it is not very clear why it should be expected that their (lack of) availability should have an effect on current development of wind or PV power. A further issue is that a number of studies have used rather indirect measures of the maximum potential, particularly in earlier studies on wind power. Some have used total surface area (km^2) of windy areas (typically including areas in wind classes 3 or above) [1,17,21], or even total surface area [13], as a proxy for generation potential. Such rough proxies may have made it more difficult to identify a, potentially limited, causal relationship with renewable energy deployment.

There is a much clearer causal relationship between natural resource quality, i.e., the energy density of the local wind or PV resources, and subsequent deployment of these technologies. As the studies on economic performance of renewable energy projects clarify, developers consider multiple locations in an effort to identify the location which will yield the best return on investment. There is no reason to assume that, ceteris paribus, they would not cross state lines in order to utilize better quality natural resources there. Similarly, in countries with high quality wind or PV resources, these technologies would yield better returns, making these, ceteris paribus, more financially competitive alternatives. This may be expected to drive stronger growth of RES deployment in countries with better quality natural resources. Such measures of natural resource quality have been used, but only in a more limited number of comparative studies, focused on comparisons of RES development between states of the US [16,19,21,23] (See also Table 1).

Lastly, earlier analysis have regularly used outcome variables that combined all RES technologies. Some studies, for example,

Table 1
Sample of studies on effects of natural resource endowment on renewable energy development.

Study	Geography	Outcome variable	Measure of natural resource endowment	Result
[13]	EU countries	Contribution of all RES (%) to total power consumption	Total surface area of each country (km^2)	Positive or negative depending on estimation method
[17]	EU, OECD & BRICS countries	Contribution of all RES (%) to total power consumption	• Wind areas (km^2) class 3–7 at 50 m; • Solar resources in total MWh per year;	• Negative for wind resources; • Positive for solar resources
[21]	US states	1) Likelihood of RES support policy adoption; 2) Market size (MW), all RES combined	• Land available in windy areas (km^2), all wind power classes, some geographic exclusions; • Solar potential as average daily total radiation[a]	• Positive effect on policy adoption from both wind and solar resources; • No effect on market size from either wind or solar resources
[1]	US states	1) Logged share of RES in total power consumption 2) Total MWh from RES	• Available land area (km^2) in wind class 3 or higher, excluding land with zoning restrictions; • Solar potential in total volume of MWh	• Negative effect for wind resources; • Positive effect for solar resources;
[16]	US states	Total number of RES support policies adopted	• Percentage of U.S. electricity consumption that could be produced by state wind generation ('high-quality wind' at '25% efficiency') • Solar potential as average radiation (kWh/m^2·d)[a]	No effect of either wind or solar resources
[24]	US states	Likelihood of adoption of 4 different RES support policies	Percent of electricity sales that can be provided from renewable sources	No effect on adoption of any of the 4 policy categories
[20]	US states	1) Market size (MW of wind power); 2) Market growth (MW increase over x yrs); 3) No. of large wind power projects	Availability of high quality wind resources. Exclusion for land use limitations and proximity of transmission lines	Positive effect on all three indicators
[19]	US states	1) Likelihood of having any wind turbine installations; 2) Log of annual additions (MW of wind power)	State average wind power class	• Marginally significant positive effect on likelihood ($p < 0.10$); • Positive effect on annual additions
[23]	US states	Total number of solar support policies	Annual average sunny days	Positive effect

Note: a number of studies also included reference to biomass resources; the overview presented here is focused on wind and PV.

[a] From the description it is not entirely clear whether this referred to total volume of potential, calculated on the basis of kWh/m^2·day, or intensity of solar irradiation as kWh/m^2·day.

have used the sum of electricity produced by all RES technologies as the outcome variable, and included wind, solar, and biomass generation potentials as explanatory variables in a single regression, rather than using separate regressions to find effects of wind power potential on wind power development, or PV potential on PV development in different states or countries [1,13,16,17,21,24]. In some cases, the outcome variable was a sum of all RES, including hydropower, whilst hydropower resources were not included as an explanatory variable [13,17], further reducing the potential causal relationship. Admittedly, many of these studies include this resource potential as a control variable, with the analysts indicating the limits of the (operationalization of the) variable themselves [e.g., [13,17]]. The quality of the operationalization of the natural resource variable in earlier work is of course strongly tied to the quality of the data available at the time, but improved measures are currently available.

This study uses indicators of both the quality and quantity of natural resources, and analyses their effects on the deployment of wind and PV. Separate analyses compare wind and PV development between countries of the world, and between provinces or states of China, Germany, and the US.

2. Method and data

There are a number of different ways that natural resource endowment might spur wind power or solar PV deployment. Three different relationships will be considered here, corresponding to different lines of inquiry found in earlier literature (see also Table 1). First, countries (or provinces or states within a country) with good natural resources may be more likely to deploy wind power or solar PV. Second, they may tend to have higher levels of deployment of either technology. Third, they may tend to see more rapid deployment. The latter is not exactly the same thing as having higher levels of deployment. Different countries (or provinces, states) have started to use wind or PV technologies at different moments in time. It has long been established that renewable energy technologies tend to follow logistic growth patterns, with increasingly rapid growth of deployment at higher levels of deployment [25–27]. Regarding growth speeds rather than absolute levels of deployment may correct for bias with regard to the maturity of the sector between individual countries.

There are also several different measures of natural resource endowment that might matter. First, a high density of wind or solar resources might better enable deployment of wind and PV, as high wind speeds or solar irradiation levels yield high capacity factors, and therefore higher profitability, for wind or PV projects. Second, high total volumes of generation potential might better enable the deployment of wind or PV, as these imply less of a restriction on the total amount of wind or PV projects that may be deployed. Although most countries are likely very far removed from exhausting their total wind or PV potential (as argued in the introduction), this measure of natural resources is included here because many previous analyses have used such measures (Table 1). Third, high per capita volumes of generation potential might matter, in particular when the outcome variable regards market shares of wind or PV. Such outcome variables correct for country size (roughly speaking), and it therefore makes sense to do the same with the explanatory variables.

2.1. National level comparison

The national level dataset includes all countries of the world. Limitations on data availability for a number of control variables restricted the number of countries included in regression analyses to 132. The time period covered is 1980–2014.

2.1.1. Outcome variables

This study will analyse effects of natural resource endowment on 1) likelihood of a country installing wind or PV; 2) wind and PV's market share; and 3) the speed with which this market share grows. The first variable is a binary outcome; the country has or does not have any wind or PV. Market share is defined as wind or PV power production (MWh), as a percentage of power consumption from all sources. Market growth speed is defined as annual increases in market share (i.e., market share$_t$-market share$_{t-1}$). The latter two variables are natural log transformed. As implied by the logistic growth of new energy technologies, the original values of market size and annual growth were highly skewed (and heteroskedastic, with larger variation at larger values).

Data on power generation from wind and PV was collected from Eurostat for EU countries, UN data for the rest of the world, and from BP's statistical review of world energy for countries or from the Earth Policy Institute where these sources had more complete time-series [28–31].

2.1.2. Natural resource endowment variables

Data on natural resources is from datasets from the National Renewable Energy Laboratory [6,7]. For every country, these datasets provide 1) the total area in each class of wind or solar resources, and 2) the resulting production potential (MWh) for the area in each of those classes. This is calculated using a model wind turbine (class IEC II), or a model PV panel (10% conversion efficiency). The calculation for wind power output builds on measurements of hourly wind velocities in 40 km grids, and further considers outages and wake losses for individual turbines in a model farm setup. The calculation for PV uses the average annual solar irradiation; further details are provided in the datasets themselves [6,7]. Terrain types unsuited for building wind or PV farms are excluded in these datasets (see also Table 2). In this study, only the potential in wind classes 3 or higher are included, in line with previous analyses [1,17,21]. This is equivalent to a capacity factor of 22% or above [7]. Offshore resources are also excluded, as are areas more than 100 km from large electrical load centres. For PV, fewer studies have specified a threshold in minimal resource quality. This study follows He and Kammen [32], who suggest average irradiance of 160 Wh/m^2·hour, roughly equivalent to solar class 7 and above (>3.5 kWh/m^2·day) in NREL's database (each class is an 0.5 kWh/m^2·day in this database). The NREL dataset for solar resources does not separate by distance to load centres, and simply assumes 1.5% of all surface area is available for PV deployment.

These selection criteria (summarized in Table 2) help create a variable of readily available, or relatively high quality, natural resources (somewhere between technical and economic potential in Fig. 1). This potential is closer to the amount that could practically be harvested for electricity generation, and prevents bias against countries with vast areas with low quality resources and/or are sparsely populated, or have long coastlines (offshore wind makes up a fraction of global installations, whilst resources are substantial).

From this data, three different indicators of natural resource endowment are derived. First, a resource quality indicator; calculated as total generation potential (no thresholds), divided by total surface area. The resulting value is in GWh/km^2, indicating the national average wind or solar resource density. Second, the total volume of high quality resources; as total generation potential (GWh; with minimum quality thresholds as listed in Table 2). Third, a per capita volume of high quality resources (GWh/capita; with thresholds).

Table 2
Natural resource endowment: exclusions and thresholds used in this study.

Tech	Used to compare	Exclusions	Quality threshold	Source
Used in national level analysis				
Wind	Countries of the world	'Protected, urban, and high-elevation areas are fully excluded, and certain land cover types are fractionally excluded'. Onshore only.	Classes c3 and up, 'distance to nearest large load' of <100 km	[7]
PV	Countries of the world	'5% of land available for PV installation, of which 30% could be covered with panels'	Class 7 or up, i.e., more than 3.5 $kWh/m^2 \cdot day$	[6]
Used in sub-national level analysis (separate regressions for each country)				
Wind	Provinces of China	Elevation >3000 m, slopes >20%; forestry, cropland, wetland, urban built-up, water, snow and glacial, and protected lands	Wind speeds exceeding 6 m/s	[33]
	States of Germany	Areas in forests, protected areas, national parks, nature reserves, built-up areas, water bodies, glaciers and permanently snow covered areas	At least 1600 full-load hours	[34]
	States of the US	Urban areas, federally protected lands, water bodies, areas with slopes greater than 20%	Modelled capacity factor exceeding 25.5% (net)	[35]
PV	Provinces of China	Elevation >3500 m; slopes >3%; forestry, cropland, wetland, water, snow and glacial, and protected lands; separate assumptions for rooftop PV in urban areas	At least $/m^2 \cdot h$ Global Horizontal Irradiance	[32]
	States of Germany	Unclear, separate assessments of rooftop and utility PV	Undefined minimum yield value	[36]
	States of the US	Water, wetlands, forests and national parks, areas with slopes >3%; separate land use exclusions for urban and rural utility scale, and for rooftop PV.	None, or not specified	[35]

2.1.3. *Further explanatory and control variables*

Higher levels of per capita GDP result in a better ability to afford modern renewables, which are relatively costly alternatives in early development phases in particular [e.g., [11–15,37]]. High income countries also have better technological capabilities to develop and deploy modern renewables [18,38].

The development of the global industry is expected to accelerate renewable energy development in individual countries. This is measured in cumulative MW of installations (natural log), as is usual in analyses of technological experience curves [24,25].

In analyses with outcome variable 'market growth speed', the market share of wind or PV in the previous year is included. The logistic growth curve implies that such higher market shares enable greater annual market share increases [25–27].

A further minimal list of control variables is included, with its selection following earlier analyses using panel data techniques to identify factors that affect the development of renewable energies.

High levels of per capita electricity consumption, or total national volumes of electricity consumption, may make it more difficult to attain large market shares of renewables, as there may be limiting factors to the pace of growth of the industries required to deploy renewables [39,40]. Growing power demand may create a larger market for additions with wind or PV installations, although Pfeiffer and Mulder [41] hold that countries with rapidly growing power demand tend to concentrate efforts on the construction of fossil and hydropower plants, rather than renewables.

Individual market shares of electricity generation are included for most important alternative technologies (coal, hydro, and nuclear), following e.g., [11–14,37]. These different energy types may affect the drive for renewables as they may make it easier or more difficult to integrate substantial shares of renewables into the electricity mix [42]. They may also affect energy import dependency [41]; this is controlled for separately with energy imports as a percentage of primary energy consumption. Concern over local air pollution from electricity generation is further controlled for with per capita emissions of SO_2.

Data for control variables is mostly collected from the World Bank's World development indicators [43]. Details on operationalization and sources for all variables are provided in Table A.1.

2.2. *Sub-national level comparison*

China, Germany and the US were selected for the subnational analyses. Each has substantial markets for both wind and PV, is large enough to expect considerable variation in natural resource endowment between provinces or states, and has relatively easily accessible statistics at province or state level. The three make for an interesting selection as they have strikingly different economic and political systems, including in the way that authority (in energy policy making) is distributed between national and provincial or state levels [cf. [44–47]].

2.2.1. *Outcome variables*

It was not possible to accurately determine market shares of electricity generation from wind or PV (as in the national comparison; section 2.1.1), because of a lack of provincial/state level data on electricity generation from these technologies. This could have been estimated using data on installed capacity and capacity factors (from natural resource assessments, section 2.2.2). This would create strong endogeneity in our model, however, as this capacity factor is also included in the set of explanatory variables.

As an approximation of market share, the dependent variables will be Watt of installations of wind or PV, divided by MWh of electricity consumption from all sources. This is still an indication of whether or not development of wind or PV is more concentrated in certain provincial or state level markets.

The range of data is 2001–2015. The exception is PV in China; for which provincial level installation data was available only for years 2012–2015. Data was collected from national statistics bureaus; details on operationalization and data sources are provided in Table A.2.

2.2.2. *Natural resource endowment variables*

Data on provincial or state level natural resource endowment is derived from different sources for each country [32–36]. As in the national comparison, these sources exclude areas unsuited to construction of wind or PV projects, and have thresholds for minimal resource quality (Table 2). It was not possible to determine resource volumes at exactly the same threshold and exclusion levels for all three countries; these are determined by the authors of the assessment studies, and differ somewhat over different sources. The sub-national analyses for China, Germany and the US are done in three separate regressions, however, so individual regressions will not mix measures of resource quality with different threshold and exclusion levels. Comparing the size of coefficients for resource quality found in these separate regressions could be debatable because of the differences in measurement, but that will not be attempted here. The analysis will focus on whether or not the coefficient in each separate regressions is significantly different from zero.

Each of the studies reports average capacity factor for a model turbine or PV panel in each province or state, as well as total volume of generation potential. This average capacity factor will be used as the resource quality indicator. Total and per capita volume of high quality resources are determined as in the national comparison (section 2.1.2).

2.2.3. Control variables

The set of control variables is the same as for the national comparison (section 2.1.3), except that it does not include energy imports or emissions of SO_2, because of limited data availability for such indicators at the sub-national level. Details provided in Table A.2.

2.3. Estimation method

Our data is time-series cross-sectional data. The dataset for the national level comparison contains observations for 132 countries for which data for all explanatory variables was available, for the period 1980–2014. The sub-national dataset contains observations for all states/provinces of China, Germany or the US for the period 2001–2015. Because quite a portion of the between country (or state/province) variation is not accounted for very well with our (limited) set of control variables, panel-data methods are more suited than pooled OLS [48]. For the outcome variable on the likelihood that countries (or states/provinces) have deployed any wind turbines or PV panels, a binary logit model is used. Our models for market share and market growth speed include correction for (first-order) autocorrelation, which was found to be present (Table A.3). Each estimation was a random effects model; the use of fixed effects is excluded by the fact that our key explanatory variable, natural resource endowment, is time-invariant and would be dropped in such a model.

3. Results

3.1. National level comparison

Results of the regression analysis are presented in Table 3. The key result is that volumes of natural resources, either as per capita or national totals, have no relation with any of the three measures of development of wind or PV. The three different measures of resource endowment are collinear, as higher average resource quality makes for larger volumes of high quality resources. This could result in explanatory power from one of the measures being drawn away by the inclusion of another measure [49,50]. Separate regressions, one for each measure of resource endowment, did not lead to different results (Table A.4).

Countries with high resource quality are more likely to have deployed wind turbines or PV panels; this is likely due to the better profitability of these technologies in such countries (note that deployment here means having more than just demonstration projects (i.e., >100 MW of installations), for more explanation see the last paragraph of this section). Because the dataset used for this analysis is time-series data, this result is equivalent to countries with high quality natural resources deploying these technologies earlier than countries with lesser quality natural resources do. This too, matches expectations: wind and PV equipment costs have fallen over time, and countries with higher quality natural resources will get to a point where these technologies are considered affordable enough, sooner than countries with lesser natural resources will do. Graphs of this likelihood versus the quality of natural resources reveal that this relationship, although statistically significant, is not one of the stronger drivers of these odds (Fig. 3). For wind, countries in the two groups with highest wind resource quality are most likely to have deployed wind turbines, but throughout, the graph is rather flat. For PV, the relationship is even less obvious, suggesting that other factors are at least as important determinants for the odds of deploying PV.

Countries with better quality wind resources also tend to have larger shares of electricity generation from wind. This too, can be linked to the better profitability and/or decreased cost for policy stimulus measures. No such relationship could be identified for PV (more on this below). Higher quality solar resources were not linked with more rapidly growing PV market shares.

More consistently positive effects were found with global technological experience, measured as global installed capacity. As cumulative installations have grown over time, technological costs have fallen [24,25], which has made these technologies more financially competitive. This has not only made it more likely that countries adopted the technologies, but also spurred larger, and faster growing markets for wind and PV. Per capita GDP has a

Table 3
Natural resource endowment and wind and PV deployment: national level comparison.

	Wind			PV		
	Market exceeds 100 MW	Market share	Market growth speed	Market exceeds 100 MW	Market share	Market growth speed
Resource quality (GWh/km^2)	1.917***	0.1827**	0.03366	3.873**	-0.2591	-0.4215
	(0.000)	(0.012)	(0.534)	(0.015)	(0.464)	(0.209)
Per capita volume HQ resources (GWh/cap)	−5.107	−2.824	0.3955	4.637	1.089	-0.07722
	(0.120)	(0.153)	(0.767)	(0.524)	(0.393)	(0.950)
Total volume HQ resources (GWh)	6.4e-09	6.0e-08	−3.4e-09	1.2e-07	1.2e-08	−3.7e-08
	(0.974)	(0.169)	(0.875)	(0.617)	(0.695)	(0.153)
Per capita GDP (2010 USD, ln)	5.423***	0.5583***	0.6294***	2.704	0.7599**	0.8056**
	(0.000)	(0.000)	(0.003)	(0.123)	(0.018)	(0.021)
Global installed capacity (MW, ln)	7.865***	1.007***	0.301***	4.838***	1.07***	0.6511***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Market share wind/PV (%, lag 1)[a]			0.3607***			0.187***
			(0.000)			(0.004)
Control variables	Included, see Table A.5 for results			Included, see Table A.5 for results		
Observations	4118	534	486	3795	187	172
Groups (countries)	132	51	51	131	34	33

p-values in parentheses. *p*-values: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

[a] Refers to market share of wind in the previous period in the wind model, and PV for the PV model.

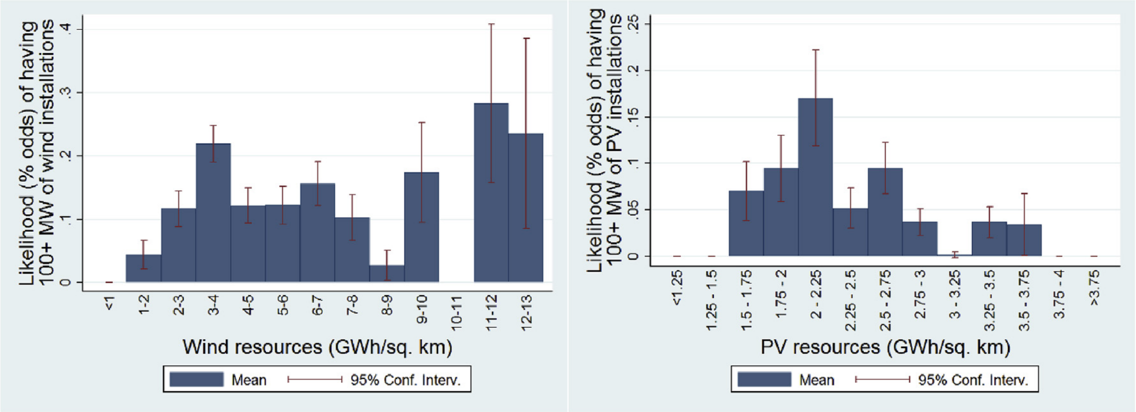

Fig. 3. Quality of natural resources versus odds of having at least 100 MW of wind (left) or PV (right) installed. Resources as GWh/km^2, national average.

similar relation with deployment. Richer nations are more likely to have deployed wind turbines, and have larger as well as faster growing wind power markets. This supports the notion that wealthier nations are better capable of affording the relatively costly renewable alternatives, and/or have higher technological capacities in the development and deployment of these novel technologies [18,38]. For PV, high per capita GPD enables larger and faster growing markets, but GDP is not related with the likelihood of having deployed more than a few demonstration projects. This may be because the utilization of PV beyond niche markets is a recent phenomenon in most countries; only 19 countries had markets exceeding 100 MW of PV installations in 2010. Results further indicate that larger markets tend to grow faster, consistent with the logistic growth pattern with which markets for novel technologies grow [25–27]. For effects of further control variables, please see the Appendix, Table A.5.

The analysis for which results are listed in Table 3 exclude observations from countries and years with less than 100 MW of installations. The motivation for doing so, is that it has previously been established that the demonstration phase is subject to very different market mechanics than the pre-commercial and supported commercial phases [51–53]. In the demonstration phase, small individual projects are developed for e.g., testing purposes or as lighthouse projects. Such projects are much more stochastic events, and much less driven by market driving forces and institutional pressure or stimulus, which are still underdeveloped in these early 'nursing markets' [53,54]. For comparison, results including all observations are provided in Table A.6. Key differences when including all observations are 1) per capita GDP has a significant effect on market share and growth speed for both wind and PV with this data filter; and 2) resource quality has a significant effect on the likelihood of having a minimal amount of wind or PV (Table A.6).

3.2. Sub-national level comparison

Results of the regression analyses for provinces or states of China, Germany and the US (separately for each country) are presented in (Tables 4 and 5).

Resource quality has a positive effect on wind power market sizes in Germany and the US, and PV market sizes in China and the US. Resource quality further has positive effects on the likelihood of

Table 4
Wind power deployment and natural resource endowment: sub-national comparison.

	Has any wind			Market size			Market growth speed		
	China	Germany[a]	USA	China	Germany	USA	China	Germany	USA
Quality of natural resources	13.8	–	237.7***	2.462	38.67***	24.07***	0.753	6.994	21.04**
(capacity factor, modelled)	(0.679)		(0.001)	(0.464)	(0.003)	(0.002)	(0.755)	(0.186)	(0.022)
Per capita volume of HQ natural resources (GWh/capita)	−1246	–	−3.903	253.6	7.064	-0.4362*	−189.9	−2.175	-0.1733
	(0.799)		(0.360)	(0.212)	(0.392)	(0.072)	(0.192)	(0.693)	(0.484)
Total volume of HQ natural resources (GWh)	0.000406**	–	3.6e-06	−7.2e-06	4.0e-06	2.7e-07	8.3e-06	2.9e-06	2.0e-09
	(0.014)		(0.517)	(0.423)	(0.383)	(0.228)	(0.190)	(0.366)	(0.993)
GDP per capita (2010 USD, ln)	0.002137***	–	0.000213	0.000021	1.7e-06	-0.000011	-0.000075***	−1.6e-06	-0.000025
	(0.000)		(0.314)	(0.264)	(0.882)	(0.501)	(0.000)	(0.892)	(0.485)
Global installed capacity (MW, ln)	−1.479	–	8.115***	1.359***	0.5244***	1.346***	1.611***	-0.2746***	0.2378
	(0.638)		(0.003)	(0.000)	(0.000)	(0.000)	(0.000)	(0.005)	(0.439)
Market share wind (%, lag 1)	–	–	–	–	–	–	0.2138***	0.549***	0.1336
							(0.002)	(0.000)	(0.235)
Control variables	Included, see Table A.10 for results			Included, see Table A.10 for results			Included, see Table A.10 for results		
Observations[b]	463	–	735	301	233	474	222	203	271
Groups (provinces or states)	31	–	49	31	16	39	30	16	38

p-values in parentheses. p-values: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Notes:
[a] No results could be obtained for Germany here as all but one state of Germany had PV installations over the entire period of data (2001–2015).
[b] Data period is 2001–2015 for all countries.

having any wind or PV, and market growth speed, for both wind and PV in the US. There are a few instances where indicators for resource volumes have negative effects, but this is due to collinearity between different measures of resource endowment. When modelled in separate regressions for each of the three measures, effects are either insignificant or positive (Table A.7). Out of the three indicators of natural resource endowment, resource quality, as modelled capacity factor, is the most consistent in having significant, positive effects. This is similar to what was found in the comparison between countries, although the superior utility of resource quality rather than volumes is more evident in the sub-national comparison.

In China, the likelihood of a province deploying wind turbines, appears more strongly connected with the province's available resource volume (total GWh of potential) rather than resource quality (average capacity factor). When using separate regressions for each of the different resource endowment measures, the market size of wind power is also more strongly connected with resource volume rather than quality (Table A.7). This is likely connected to Chinese wind power planning. For example, Chinese policy has identified seven areas for gigawatt scale ‘wind power bases’, located in sparsely populated Northern provinces “because of the availability of land”, in addition to high wind resource quality [55]. Further, Chinese feed-in-tariffs are higher for areas with poorer quality wind resources, offsetting some of the financial benefits from wind farm development in areas with higher natural resource quality [55].

In Germany, PV developments appear unaffected by any measure of natural resource endowment. This is likely because Germany is too small to have substantial differences in solar irradiation between different states. Modelled capacity factors range roughly between 10 and 11.5%, far smaller than differences between Chinese provinces (14–31%) or US states (10–26%). Note in particular the difference in spread; these capacity factors cannot really be compared across these countries, as they are derived from different studies using different modelling methods for each country (see section 2.1.2).

Scatter plots of resource quality versus market sizes of wind and PV by year end 2015 are provided in Figs. 4 and 5. These plots reveal the presence of potentially influential data points, specifically Mecklenburg-Vorpommern, which has the largest market size for wind in Germany (Fig. 4), and California, which has the largest market size for wind in the US (Fig. 5). These are not outliers, as there is nothing to indicate there was any measurement error, and therefore no reason to discard these from the analyses. The natural log transformation of the outcome variable ‘market size’ further largely reduces the issue of strong variation of these individual data points. Still, it should be mentioned that excluding California from the dataset results in no significant relationship between resource quality and PV market size in the US. Effects on likelihood and market growth speed remained (Table A.8). When excluding Mecklenburg-Vorpommern from the analysis of German wind market sizes, the relationship remains positive and significant (Table A.9). Scatter plots with these exclusions can be found in Figures A.1 & A.2.

Overall, the scatterplots in Figs. 4 and 5 reveal that resource quality is not necessarily a strong determinant of market sizes, even in some of the cases where a statistically significant relationship between the two was identified. Countries, or provinces or states, with relatively low quality natural resources regularly manage to develop relatively large wind or PV markets, whilst countries, provinces or states, with relatively high quality natural resources regularly fail to develop relatively large wind or PV markets. Exceptions are the US markets for wind power and the Chinese markets for PV, that do show a clearer trend of larger markets in provinces or states with higher resource quality.

Within the set of control variables, there are a number of similarities and differences with effects found in the national level comparison. Per capita GDP did not have the driving effect on wind or PV development, as it did in the national level comparison. This may be a combination of two reasons. First, that variation in GPD between provinces or states is not as large as it is between countries. Secondly, that financing for development of wind or PV farms, and payments for renewable power generation more easily cross province or state borders than it does national borders. The operations of power companies, too, are not as much limited by state or provincial borders as they are by national borders. Results were not affected when filtering observations of provinces or states with less

Table 5
PV deployment and natural resource endowment: sub-national comparison.

	Has any PV			Market size			Market growth speed		
	China	Germany[a]	USA	China	Germany	USA	China	Germany	USA
Quality of natural resources (capacity factor, modelled)	115.2	–	441.5***	33.27***	5.803	30.1***	0.671	0.8905	16.7**
	(0.739)		(0.000)	(0.000)	(0.851)	(0.009)	(0.910)	(0.979)	(0.016)
Per capita volume of HQ natural resources (GWh/capita)	23.56	–	−3.538***	6.153***	64.89	-0.07998	1.709	22.39	-0.05053
	(0.623)		(0.003)	(0.008)	(0.311)	(0.528)	(0.210)	(0.750)	(0.620)
Total volume of HQ natural resources (GWh)	−9.3e-07	–	−6.2e-07	−2.0e-07**	−7.3e-06	−3.1e-08	−7.3e-08	−2.2e-06	1.1e-08
	(0.608)		(0.357)	(0.043)	(0.802)	(0.614)	(0.219)	(0.948)	(0.768)
GDP per capita (2010 USD, ln)	0.000299	–	0.00045	0.000063*	-0.000025	−7.5e-06	−9.0e-06	-0.000032*	0.000019
	(0.731)		(0.196)	(0.076)	(0.114)	(0.732)	(0.723)	(0.084)	(0.455)
Global installed capacity (MW, ln)	36.92***	–	6.247**	2.302***	1.185***	1.434***	−1.763***	-0.2626	-0.004828
	(0.000)		(0.019)	(0.000)	(0.000)	(0.000)	(0.008)	(0.120)	(0.968)
Market share PV (%, lag 1)	–	–	–	–	–	–	0.4993***	0.8741***	0.6243***
							(0.000)	(0.000)	(0.000)
Control variables	Included, see Table A.11 for results			Included, see Table A.11 for results			Included, see Table A.11 for results		
Observations[b]	462	–	750	104	239	692	70	207	516
Groups (provinces or states)	31	–	50	30	16	49	29	16	48

p-values in parentheses. *p*-values: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Notes:
[a] No results could be obtained for Germany here as all but one state of Germany had PV installations over the entire period of data (2001–2015).
[b] Data period is 2001–2015 for all countries; differences in observations due to differences in no. of provinces/states. Exception is PV in China, for which data was available for 2011–2015.

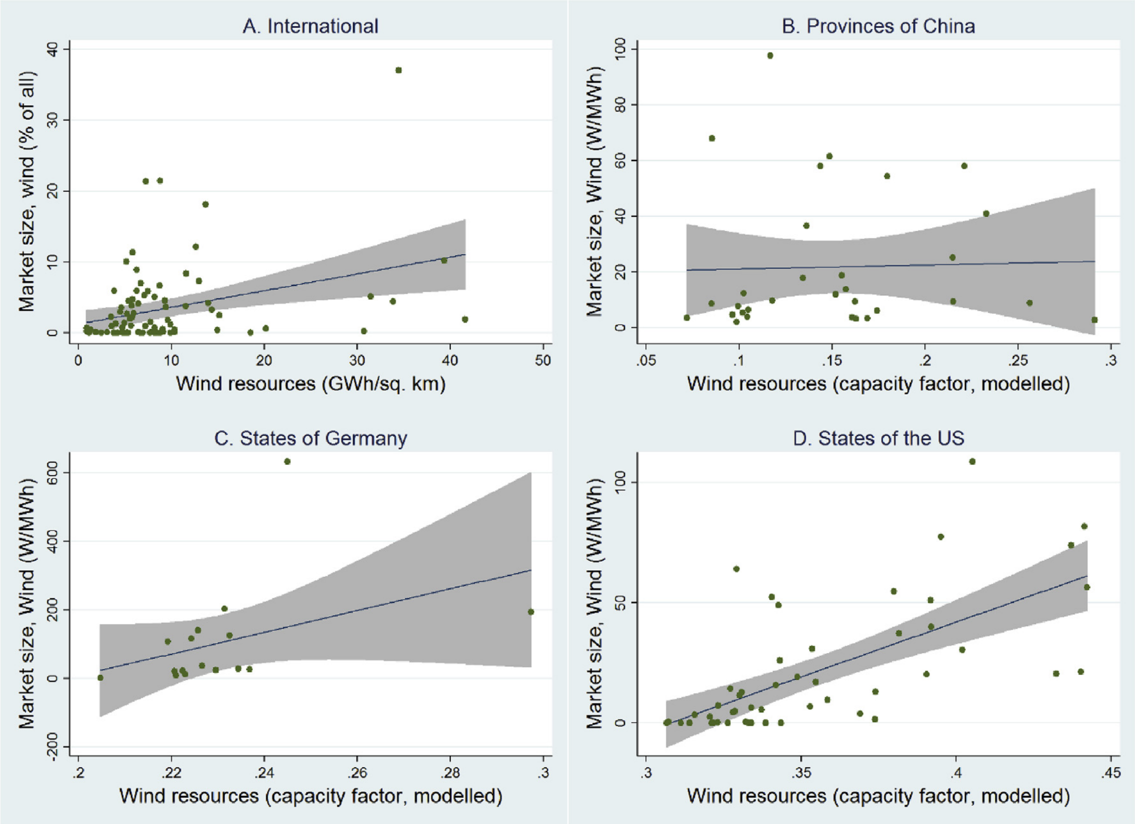

Fig. 4. Natural resources quality versus market size, wind power. Panel A: market size as wind power production (MWh), as % of electricity consumption from all sources, year-end 2014; wind resource quality as GWh/km2, national average. Panels B–D: market size as wind power installations, W of installations per MWh of electricity consumption from all sources, year-end 2015; wind resource quality as state-wide or province-wide average capacity factor. Note: lines in each panel are trend lines, shaded areas are 95% confidence intervals (for the slope of this trend line, not for the distribution of the population).

than 100 MW of installations (as was done in the national level comparison). This suggests experience from demonstration projects, too, crosses state or provincial borders more easily than it does national borders. There were positive effects from the global build-up of experience on the likelihood of deploying any wind or PV, as well as on their market sizes (but not market growth speed), likely due to falling equipment costs with increased cumulative global equipment production experience. As in the national level comparison, larger markets tended to grow faster, indicating the logistic growth pattern repeats itself at sub-national levels.

4. Discussion

Results presented here indicate that natural resource quality drives wind and PV development, although not as strongly or consistently as could have been expected.

Although the measures of resource endowment used here are arguably an improvement over those used in comparable earlier exercises (Table 1), problems likely remain. National, and even provincial or state level averages of resource quality may still not be the best indicator for readily available potential. Natural resources may be found in localized hotspots, or small areas where wind farm development would generate financially superior results, compared to development in immediate surrounding areas (see also Fig. 2). This would be less of an issue with solar resources, however, which are less subject to such localized variation. Further, the financial attractiveness of wind and PV farm development sites is a more complicated mix of expected capacity factor, distance to grid, price and availability of lands, local electricity prices, etc. [8,9].

In this study, wind and PV installations were normalized across states or provinces by dividing by total volume of electricity consumption in each state or province, as has been a usual approach in previous work. Such normalization could also have been done on the basis of surface area (i.e., as MW/km^2), to identify whether wind or PV installations were more geographically concentrated in areas with superior resources quality. This, however, did not result in substantially different conclusions. As an indication, scatterplots of the relationship are provided in Figure A.3 and A.4.

An important factor left out of the analysis here is the policy environment, which can spur renewables development with feed-in-tariffs, portfolio standards, and many other mechanisms, as has previously been studied by other analysts in more detail [1,16,17,21,23,24,41]. For example, Hitaj [19] provides maps of areas in the US, where wind farms are located just along US state lines, in areas with poorer wind resources but better support policies.

Following [17], it was attempted to account for these with variables that count the number of policies implemented, for a list of policy categories as reported on in IEA's database for “Global Renewable Energy Policies and Measures” [56] (results in Table A.12). These variables were found to have little explanatory power, as earlier analysts concluded [17]. These have been left out of the main results presented here, because of the unconvincing operationalization of policy numbers, which poorly reflects differences in policy effectiveness. Similarly, costs of competing energy sources were included, using global or regional energy prices for

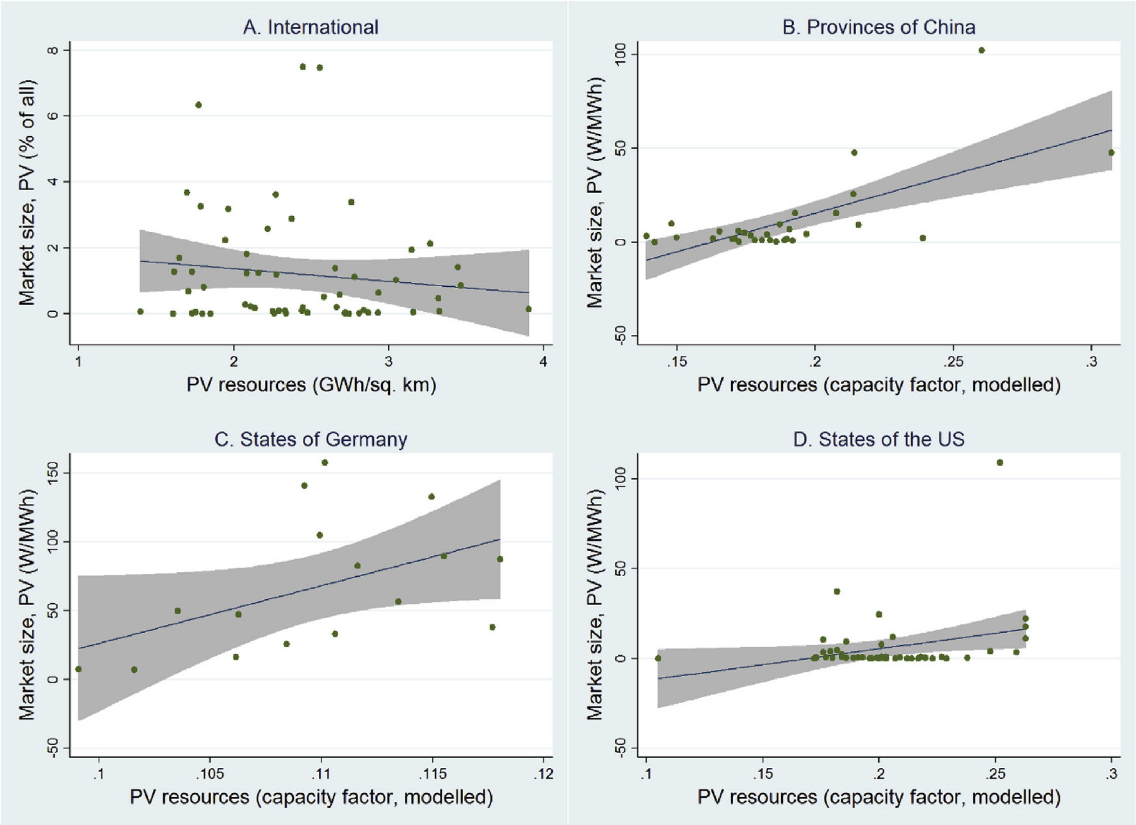

Fig. 5. Natural resources quality versus market size, PV power. Panel A: market size as PV power production (MWh), as % of electricity consumption from all sources, year-end 2014; solar resource quality as GWh/km2, national average. Panels B–D: market size as PV installations, W of installations per MWh of electricity consumption from all sources, year-end 2015; solar resource quality as state-wide or province-wide average capacity factor. Note: lines in each panel are trend lines, shaded areas are 95% confidence intervals (for the slope of this trend line, not for the distribution of the population).

coal, oil, and natural gas, following [12,13,17]. Again with little additional explanatory power; these had insignificant or a negative relationship on some indicators of wind and PV deployment; something which may be attributed to poor operationalization rather than causal effects as well. It went beyond the scope of this exercise to attempt to collect data sub-national level policy and energy prices.

Individual provinces, states, or countries, may choose to cooperate in the national or global mission for renewable energy transitions, even if their lands aren't prime locations. This makes sense from a (national) planning perspective, too. For example, in China, two provinces, Inner Mongolia and Xinjiang, account for over 90% of all high quality wind resources [33], but similar geographic concentration of wind farms would make consumption in local electricity markets even more problematic than is currently the case [57,58].

5. Conclusions

Results presented here indicate that measures of natural resource quality have more explanatory power than measures of resource volumes, on differences in wind and PV development. Natural resource quality was found to have a statistically significant, positive effect on wind and PV development in a number of markets. High natural resource quality, however, is not a necessary, nor a sufficient condition for strong market development. Plenty of countries, states or provinces with relatively poor quality natural resources have managed relatively strong wind or PV development, and vice versa. The only clear examples of natural resources being an important driver of deployment are the wind power market in the US and the PV market in China.

The conclusion is that natural resources are a small part in a larger set of drivers. Renewables stimulus polices, in particular, should be expected to play an important role. Differences in their design across countries, or provinces or states, may well account for differences in natural resource quality, with more generous stimulus in areas with poorer natural resources. Such differences in policy design may also be an explanation why resource quality appears as an (important) driver of renewables development in some markets, but not in others. An expanded set of country case studies would help identify whether natural resource quality is a driver of renewable energy development in a majority of markets, or not.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2017.06.062.

References

[1] S. Carley, State renewable energy electricity policies: an empirical evaluation of effectiveness, Energy Policy 37 (8) (2009) 3071–3081.

[2] P. Lamers, et al., International bioenergy trade—a review of past developments in the liquid biofuel market, Renew. Sustain. Energy Rev. 15 (6) (2011) 2655–2676.

[3] A. Lopez, et al., U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis, National Renewable Energy Laboratory Technical Report NREL/TP-6A20-51946, 2012.

[4] M. Hoogwijk, B. de Vries, W. Turkenburg, Assessment of the global and regional geographical, technical and economic potential of onshore wind energy, Energy Econ. 26 (5) (2004) 889–919.

[5] M.Z. Jacobson, M.A. Delucchi, Providing all global energy with wind, water, and solar power, Part I: technologies, energy resources, quantities and areas of infrastructure, and materials, Energy Policy 39 (3) (2011) 1154–1169.

[6] NREL, Solar Resources by Class and Country, online database avaliable via, 2008, en.openei.org/datasets/dataset/solar-resources-by-class-and-country.

[7] NREL, Global CFDDA-based Onshore and Offshore Wind Potential Supply Curves by Country, Class, and Depth (Quantities in GW and PWh), online database available via, 2013, en.openei.org/datasets/dataset/global-cfdda-based-onshore-and-offshore-wind-potential-supply-curves-by-country-class-and-depth-q.

[8] R. van Haaren, V. Fthenakis, GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State, Renew. Sustain. Energy Rev. 15 (7) (2011) 3332–3340.

[9] J.R. San Cristóbal, Multi-criteria decision-making in the selection of a renewable energy project in Spain: the Vikor method, Renew. Energy 36 (2) (2011) 498–502.

[10] J.R. Janke, Multicriteria GIS modeling of wind and solar farms in Colorado, Renew. Energy 35 (10) (2010) 2228–2234.

[11] G. Bölük, M. Mert, Fossil & renewable energy consumption, GHGs (greenhouse gases) and economic growth: evidence from a panel of EU (European Union) countries, Energy 74 (0) (2014) 439–446.

[12] A.C. Marques, J.A. Fuinhas, Drivers promoting renewable energy: a dynamic panel approach, Renew. Sustain. Energy Rev. 15 (3) (2011) 1601–1608.

[13] A.C. Marques, J.A. Fuinhas, J. Pires Manso, Motivations driving renewable energy in European countries: a panel data approach, Energy Policy 38 (11) (2010) 6877–6885.

[14] N. Apergis, J.E. Payne, Renewable energy consumption and economic growth: evidence from a panel of OECD countries, Energy Policy 38 (1) (2010) 656–660.

[15] P. Sadorsky, Renewable energy consumption, CO2 emissions and oil prices in the G7 countries, Energy Econ. 31 (3) (2009) 456–462.

[16] D.C. Matisoff, The adoption of state climate change policies and renewable portfolio standards: regional diffusion or internal determinants? Rev. Policy Res. 25 (6) (2008) 527–546.

[17] M. Aguirre, G. Ibikunle, Determinants of renewable energy growth: a global sample analysis, Energy Policy 69 (2014) 374–384.

[18] D. Popp, I. Hascic, N. Medhi, Technology and the diffusion of renewable energy, Energy Econ. 33 (4) (2011) 648–662.

[19] C. Hitaj, Wind power development in the United States, J. Environ. Econ. Manag. 65 (3) (2013) 394–410.

[20] F.C. Menz, S. Vachon, The effectiveness of different policy regimes for promoting wind power: experiences from the states, Energy Policy 34 (14) (2006) 1786–1796.

[21] M.A. Delmas, M.J. Montes-Sancho, U.S. state policies for renewable energy: Context and effectiveness, Energy Policy 39 (5) (2011) 2273–2288.

[22] USEIA, Electric Power Monthly - Online Statistics Table 1.1.A. Net Generation from Renewable Sources: Total (All Sectors), 2006-May 2016. 2016.

[23] P. Taggart, Why Do States Adopt Energy-driven Tax Incentives?, 2016.

[24] S. Vachon, F.C. Menz, The role of social, political, and economic interests in promoting state green electricity policies, Environ. Sci. Policy 9 (7) (2006) 652–662.

[25] T.J. Foxon, et al., UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures, Energy Policy 33 (16) (2005) 2123–2137.

[26] C. Wilson, Up-scaling, formative phases, and learning in the historical diffusion of energy technologies, Energy Policy 50 (0) (2012) 81–94.

[27] C. Marchetti, N. Nakićenović, The Dynamics of Energy Systems and the Logistic Substitution Model, PRE-24360, 1979.

[28] EC, Eurostat Database; Tables nrg_107a (Electrical Capacity, Main Activity Producers & Autoproducers) and nrg_113a (Supply, Transformation and Consumption of Renewable Energies - Annual Data), 2015. http://ec.europa.eu/eurostat/en/web/products-datasets/-/NRG_107A. http://ec.europa.eu/eurostat/en/web/products-datasets/-/NRG_113A.

[29] United Nations, UN Data; Energy Statistics Database; Tables 'Electricity - Total Net Installed Capacity of Electric Power Plants, Wind/solar', 'Electricity - Total Wind Production', and 'Electricity - Total Solar Production', 2015. http://data.un.org/Explorer.aspx?d=EDATA.

[30] BP, Statistical Review of World Energy 2015, available via, 2015. last accessed Jan. 3rd, 2017, http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[31] Earth Policy Institute, Cumulative Installed Wind Power Capacity in Top Ten Countries and the World, 1980-2014, online database available via, 2015, earth-policy.org/data_center/C23.

[32] G. He, D.M. Kammen, Where, when and how much solar is available? A provincial-scale solar resource assessment for China, Renew. Energy 85 (2016) 74–82.

[33] G. He, D.M. Kammen, Where, when and how much wind is available? A provincial-scale wind resource assessment for China, Energy Policy 74 (2014) 116–122.

[34] WindEnergie eV B, G.W.E. Association, Studie zum Potenzial der Windenergienutzung an Land. Executive summary, BWE, Berlin, 2011.

[35] A. Lopez, et al., US Renewable Energy Technical Potentials: a GIS-based Analysis, NREL, 2012.

[36] AEE, Overview of Renewable Energies by Bundesländ, From, 2016. last accessed Jan. 4th, 2017, https://www.foederal-erneuerbar.de.

[37] A.N. Menegaki, Growth and renewable energy in Europe: a random effect model with evidence for neutrality hypothesis, Energy Econ. 33 (2) (2011) 257–263.

[38] A. Dechezleprêtre, et al., Invention and transfer of climate change–mitigation technologies: a global analysis, Rev. Environ. Econ. Policy 5 (1) (2011) 109–130.

[39] S. Jacobsson, K. Karltorp, Formation of competences to realize the potential of offshore wind power in the European Union, Energy Policy 44 (0) (2012) 374–384.

[40] G.J. Kramer, M. Haigh, No quick switch to low-carbon energy, Nature 462 (7273) (2009) 568–569.

[41] B. Pfeiffer, P. Mulder, Explaining the diffusion of renewable energy technology in developing countries, Energy Econ. 40 (0) (2013) 285–296.

[42] B.K. Sovacool, The intermittency of wind, solar, and renewable electricity generators: technical barrier or rhetorical excuse? Util. Policy 17 (3–4) (2009) 288–296.

[43] World Bank, World Development Indicators, online dataset accessible via, 2016, databank.worldbank.org/data/.

[44] R. Saidur, et al., A review on global wind energy policy, Renew. Sustain. Energy Rev. 14 (7) (2010) 1744–1762.

[45] J. Peck, J. Zhang, A variety of capitalism … with Chinese characteristics? J. Econ. Geogr. 13 (3) (2013) 357–396.

[46] E. Orban, C. Xiaoyuan, P.H. Koehn, Great-power Decentralization and the Management of global/local economic Policy and relations: Lessons in Fluidity from the People's Republic of China, Int. Rev. Adm. Sci. 69 (2) (2003) 235–258.

[47] B. Kong, China's energy decision-making: becoming more like the United States? J. Contemp. China 18 (62) (2009) 789–812.

[48] D. Hoechle, Robust standard errors for panel regressions with cross-sectional dependence, Stata J. 7 (3) (2007) 281.

[49] B. Knaeble, S. Dutter, Reversals of least-squares Estimates and model-invariant Estimation for Directions of unique effects, Am. Stat. (2016), http://dx.doi.org/10.1080/00031305.2016.1226951.

[50] K.A. Frank, Impact of a confounding variable on a regression coefficient. Sociological Methods & Research 29 (2) (2000) 147–194.

[51] N. Rosenberg, Exploring the Black Box: Technology, Economics, and History, Cambridge University Press, 1994.

[52] J.M. Utterback, W.J. Abernathy, A dynamic model of process and product innovation, Omega 3 (6) (1975) 639–656.

[53] N. Bento, C. Wilson, Measuring the duration of formative phases for energy technologies, Environ. Innovat. Soc. Transit. (2016) 95–112.

[54] A. Bergek, M. Hekkert, S. Jacobsson, Functions in innovation systems: a framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policymakers, in: T.J. Foxon, J. Köhler, C. Oughton (Eds.), Innovation for a Low Carbon Economy - Economical, Institutional and Management Approaches, 2008, pp. 79–111. Edward Elgar: Cheltenham and Northampton.

[55] IEA/ERI, China Wind Energy Development Roadmap 2050. Report by the International Energy Agency and the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC) of P.R. China, 2012.

[56] IEA/IRENA, Global Renewable Energy Policies and Measures Database, online dataset accessible via, 2016, http://www.iea.org/policiesandmeasures/.

[57] X. Zhao, et al., Constraints on the effective utilization of wind power in China: an illustration from the northeast China grid, Renew. Sustain. Energy Rev. 16 (7) (2012) 4508–4514.

[58] M.R. Davidson, et al., Modelling the potential for wind energy integration on China's coal-heavy electricity grid, Nat. Energy 1 (2016) 16086.

References included in Appendix A

[59] JRC, Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2, Available online via, 2012, edgar.jrc.ec.europa.eu/overview.php?v=42.

[60] IEA, Coal Information (2014 Edition) PART III; Table 4.9: Steam Coal Prices for Electricity Generation (Current USD/tce), 2014.

[61] World Bank, World Bank Commodity Price Data (The Pink Sheet), 2015. http://databank.worldbank.org/data/reports.aspx%3fsource=global-economic-monitor-%28gem%29-commodities.

[62] CWEA, China wind Power Industry Map by the Chinese Wind Energy Association, Several Years Used (In Chinese), 2016.

[63] NEA, 2015 wind Power Installations and Production by Province, 2016.

[64] EIA, Electricity, Detailed State Data, Available via, 2016. last accessed Jan. 4th 2017, https://www.eia.gov/electricity/data/state/.
[65] AWEA, AWEA U.S. Wind Industry Annual Market Report 2015, 2016.
[66] NEA, 2015 PV Installations Utility and Distributed by Province, 2016.
[67] SEIA, Major Solar Projects in the United States Operating, under Construction or under Development Updated: April 4, 2016, Available via, 2016. last accessed Jan. 4th, 2017, http://www.seia.org/research-resources/major-solar-projects-list.
[68] NREL, The Open PV Project, Available via, 2016. last accessed Jan. 4th, 2017, https://openpv.nrel.gov/.
[69] National Bureau of Statistics of China, Online Statistics Database, Available via, 2016. last accessed Jan 4th, 2017, http://data.stats.gov.cn/easyquery.htm?cn=C01.
[70] DEStatis, Online Statistics Database, Available via, 2016. last accessed Jan. 4th, 2017, https://www.destatis.de/DE/ZahlenFakten/ZahlenFakten.html.
[71] Bureau of Economic Analysis, Regional Data, available via, 2016. last accessed Jan. 4th, 2017, https://www.bea.gov/itable/.