Critique of Miller and Keith (2018) on the power density method for assessing renewables potentials

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Introduction

This critique examines the following paper:

- Miller, Lee M and David W Keith (2018). "Observation-based solar and wind power capacity factors and power densities". *Environmental Research Letters*. **13** (10): 104008. ISSN 1748-9326. doi:10.1088/1748-9326/aae102. Open access.

Miller and Keith describe how national renewables potentials might be assessed using output power densities. Their uncharacteristically low estimates for wind and photovoltaic generation lead to large requirements for land and challenge the technical feasibility of fully renewable electricity generation. Elsewhere, Miller and Keith (2018c) claim that technology-specific values of this metric correlate with aggregate environmental impact — although the authors use the less common term "environmental consequences" instead. If indeed so, representative power densities can and should be used to rank technologies for public policy purposes.

The terms "model" and "scenario" are not distinguished in this critique beyond noting that a scenario needs to be encapsulated as a model instance, provisioned with suitable data, and then executed to create results.

Issues

Power density

The power density of a technology is the average or peak output of that technology divided by some characteristic area associated with that technology. Power densities are therefore normalized against either output or installed capacity, the latter also known as capacity density. Miller and Keith adopt the former convention. The metric is often reported and deployed in spatially averaged form.

In the case of Miller and Keith (2018), the focus is wind and photovoltaic generation across the continental United States and the authors provide spatially-aggregated estimates. Defining and quantifying characteristic areas for individual technologies is proving to be both difficult and controversial.

Power density is an example of a scale-independent intensity metric. Such metrics, more generally, can play a role in regulation by defining performance bounds within which new installations should fall (Dean 2017:89).

Germany as a representative example

Miller and Keith (2018:9) provide a rough analysis of German renewables potentials using this metric:

> As an example of the implications of these results, consider Germany and its ambitious energy transformation policy (Energiewende). Germany's primary energy consumption rate is 1.28 $\mathrm{W m^{-2}}$ (BP 2018). If our US wind power density of 0.50 $\mathrm{W_e m^{-2}}$ [e = electrical] was applicable to Germany, then devoting all German land to wind power would meet about 40% of Germany's total primary energy consumption, while if German wind power performs like the best 10% of US wind (0.80 $\mathrm{W_e m^{-2}}$), then generation would be 62% of Germany's consumption. Finally, if Germany's goal was to generate the most wind power without economic constraints, very high capacity densities (e.g. 10 $\mathrm{MW_i km^{-2}}$ [i = installed] could be deployed, reducing capacity factors but possibly raising the power density to 1.0 $\mathrm{W_e m^{-2}}$ and meeting 80% of consumption. Whereas for solar at 5.4 $\mathrm{W_e m^{-2}}$, 24% of Germany's land area would need to be devoted to commercial-scale solar to meet total primary energy consumption.
>
> Of course, no such single-technology scenario is plausible. A mix of energy sources and storage is essential to addressing temporal and seasonal variability. Note that the amount of

> primary energy required to supply the same amount of final energy will fall with electrification and battery storage-reducing requirements, but using electricity to make gas or other synthetic fuels has the opposing tendency. Yet, we hope this example illustrates the relevance of power density when planning for deep decarbonization.

Harvard University videos

Miller and Keith (2018c) is a promotional video produced by Harvard University in which Miller states that (starting 01:57, emphasis added):

> solar PV ... its climatic impacts are about **ten times lower** than wind power for the same generation rate

There appears to be no published basis for this statement. Neither of two 2018 papers Miller co-authored traverses the issue (the webpage embedding this video describes Miller and Keith 2018b and not the paper under discussion here). It makes little sense to favor photovoltaics over wind generation on these grounds. Each technology compliments and both technologies are required for a rational system.

Miller further states in relation to 100% renewable generation (Miller and Keith 2018e) (starting 02:32, emphasis added):

> If you are a city, state, or country now implementing plans to becoming 100% renewable, you may need to devote **5 to 20 times more land** to wind or solar than your original plans indicated in order to meet your renewable energy targets.

And in relation to Germany, Miller continues (starting 02:38, emphasis added):

> If you are an energy innovator, like Germany, then simply due to the physical constraints, it is **extremely unlikely** that even converting your entire country to wind power could meet your country's total energy demands.

This last statement is presumably supported by the back-of-the-envelope calculation quoted above. While noting to that no one is advocationg shifting solely to wind generation in order to achieve a decarbonized electricity system.

Lines of argument

This critique contends that scale-independent metrics can be useful for model interpretation, for checking the integrity of input data and results, and for setting minimum performance bounds for regulatory purposes — but not as a calculation tool to inform policy development and particularly not when more sophisticated methods are both available and reported. Germany is therefore offered as a case-study to highlight the benefits of sophisticated numerical modeling.

With regard to the analysis for Germany (quoted above), the lines of argument to be presented and developed comprise:

- use of primary energy demand to inform future analysis is inappropriate
- the matching of current levels of primary energy demand is even more inappropriate
- single technology analysis is inappropriate
- the land availability assumptions deployed are inappropriate
- the uncritical use of wind yield metrics calibrated using US data is inappropriate
- the "environmental consequences" of different renewable technologies are alluded to but never specified nor investigated
- correlations between yield metrics and environmental impacts are also implied but not substantiated or quantified
- more generally, sophisticated state-of-the-art techniques are not reviewed despite a range of credible published studies
- the underlying study cannot be replicated because the datasets are not open
- due to the above, the conclusions offered are not warranted but will no doubt be cited and used

Low-carbon scenario studies for Germany to 2050

A range of sophisticated studies have assessed low to zero-carbon, high renewables share scenarios for Germany. This section lists several to provide background and context. More studies can be added in due course.

Table 13 from Ausfelder *et al* (2017:118) is translated and reproduced in part below. The six external studies cited are described from page 110 onward. Ausfelder *et al* also presents their own numerical analysis. Scenario #3 with 100% renewable electricity generation is from German Federal Environment Agency (UBA) and reported as Werner *et al* (2013). The other five scenarios are not carbon neutral or fully renewable in 2050 but that future state is clearly the goal. An attached PDF (release 01) contains table 13 in full in original and translated form for reference.

	Scenario	Primary energy	Final energy	RES share of final energy	Gross electricity generation	CO_2 reduction	Installed PV • onshore wind • offshore wind
	Units	TWh	TWh	%	TWh	%	GW

1	Target scenario	1969	1527	58	472	−80	78 • 70 • 18
2	Climate protection scenario 95	1696	1157	96	769	−95	130 • 150 • 45
3	GHG-neutral Germany	3086	1651	100	3086	−100	275 • ~380 • 45
4	Scenario 85/amb/Mix/ accelerated	2114	1768	67	818	−85	166 • 168 • 33
5	Cross-sectoral target scenario 2050	—	—	—	816	−80	200 • 140 • 38
6	Scenario "100-II"	2256	1598	66	590	−83	126 • 130 (wind combined)

Table: Key scenario quantities for the year 2050 (Ausfelder *et al* 2017:27).

For comparison, the 2014 baseline is as follows:

	Historical	Primary energy	Final energy	Comment
	Units	TWh	TWh	
0	2014 data	4285	2537	final energy includes export, bunkering, and non-energy consumption

Table: Key quantities from 2014 for comparison (Ausfelder *et al* 2017:27).

The ratio of final to primary energy in 2014 is 59% — compared with a drop to 53% for scenario #3 or much improved at 78% for scenario #1. That variation (in the absence of errors) reflects major differences in the various scenarios, noting that #3 produces high quantities of power-to-liquid (P2Liquid) fuels for the transport sector.

Ausfelder *et al* provide informative Sankey diagrams for all scenarios. These diagrams are well worth studying. Some translated terms are given elsewhere to assist readers who don't speak German.

BP (2018) records the primary energy demand in 2017 as 3896 TWh (335 Mtoe) — some 9% lower than that quoted by Ausfelder *et al* (2017) for 2014. This difference is probably a definitional issue that needs pinning down — mostly likely that BP excludes non-energetic final consumption from fuel tallies. Notwithstanding, this descrepency makes no material difference to the themes being pursued in this critique. BMWi (2018) and also UBA (not cited) and JRC IDEES (not cited) also provide comprehensive national energy statistics.

Comparisons with Miller and Keith (2018)

A direct comparison from Miller and Keith (2018) to the various energiewende studies given above and elsewhere is not possible. The two approaches use such different methodologies and scenarios that there is no sensible connection between the two.

What could be undertaken to advantage though is for different numerical studies to calculate the average output power density for each technology and compare these with the values given by Miller and Keith (2018). That exercise would, of course, need a resolution on how best to estimate the areas occupied by each technology, be it onshore and offshore wind, PV, lignite-fired generation, or some other conversion process.

Critique of Miller and Keith (2018)

This section breaks down the renewables potential assessment for Germany by Miller and Keith (2018) into separate largely orthogonal lines of argument and examines each one in turn.

Wind yield

The typical average output power density for wind farming in the continental United States is estimated by Miller and Keith (2018) as 0.5 $W_e m^{-2}$ [e = electrical]. By other accounts, this is clearly low. Perhaps by a factor of 6 (Goggin 2018:4) and 16-fold (Jacobson 2018b). Readers are referred to the rebuttals by Michael Goggin and Mark Jacobson for details (listed below). More work is indeed required to understand how average power density (an intensity) and wind farm extent (an extensity) can be better estimated and utilized appropriately. The wind yield metrics used for the German cameo were calibrated using US data with no adjustment nor discussion on its appropriateness for a different geography and climate.

Nitsch (2018) uses wind turbine capacity density estimates from Austria and Denmark to assess the wind potential for the Czech Republic. Nitsch employs a 1 km × 1 km grid to calculate values for Austria (which average 4.9 $MW_i{\cdot}km^{-2}$) [i = installed] and Denmark (which average 1.8 $MW_i{\cdot}km^{-2}$). Assuming a capacity factor of 30% — for the sole purpose of exploring data integrity — the Danish value is close to that proposed by Miller and Keith, but the Austrian value is three-fold higher. Both countries reach capacity densities of 19 $MW_i{\cdot}km^{-2}$ for ideal sites, providing an indication of the resource variability involved.

Turbine spacing is obviously material. Miller makes this point in his promotional video (Miller and Keith 2018e). Enevoldsen and Valentine (2016) investigate turbine spacing and find patterns exist.

Weather data is typically available at a spatial resolution of 20 km × 20 km. Finer-grained and down-scaled datasets can also be sourced and used.

Reuter and Elsner (2016) provide a forward-looking summary of wind generation technologies in the German context.

With regard to hydroelectricity, Herath *et al* (2011) review three methods for estimating water footprint, thereby demonstrating that no one defining characteristic area is self-evident.

Land availability

It is simply nonsensical to use the entire surface area of Germany to do back-of-the-envelope assessments. Miller and Keith may well counter that this was a *Gedankenexperiment* designed to explore potentialities. While that approach could have merit in some circumstances, it is completely redundant here in light of the amount of detailed information available and the range of credible land availability studies on which to draw.

Indeed, there are several comprehensive renewables potentials studies for Germany based on high-resolution assessments and accounting for habitation, structures, protected areas, and similar. Lütkehus *et al* (2013) provide a detailed area accounting for Germany in relation to wind energy.

There are currently substantial efforts to produce a suite of comprehensive unified open datasets suitable for undertaking high-resolution renewables assessments across the European Union. These include the CORINE Land Cover (CLC) inventory (Copernicus 2018) and the Geospatial Land Availability for Energy Systems (GLAES) project (Jülich Forschungszentrum *ongoing*, Ryberg 2017, Ryberg *et al* 2017). CORINE supports a spatial resolution of 100 km × 100 m.

Wind potential

Wind potential estimates combine wind yield and land availability information. As indicated, this assessment can range from ballpark values to detailed high-resolution studies.

Miller and Keith (2018:9) suggest that the wind potential for Germany is 1560 $TWh{\cdot}a^{-1}$ premised on the idea that entire country is available for wind generation. In contrast, Purr *et al* (2015:57) estimate the wind potential for Germany at 1000 $TWh{\cdot}a^{-1}$ using spatially-resolved data and in the absence of public opposition. The clear discrepancy between these two values relates to the apparently low output power density of 0.5 $W_e m^{-2}$ employed by Miller and Keith.

Single technology assessments

It is also pointless to examine just one technology when undertaking renewables assessments. Numerical modeling can estimate the optimal mix of wind, PV, and other renewable technologies in combination with other measures, including storage, flexibility, and network reinforcement.

The authors discuss this point briefly, but they also contradict themselves by presenting highly-stylized single technology assessments and presuming that these then offer researchers, policy analysts, and the public generally, results possessing some level of validity.

Environmental impacts

Miller and Keith (2018:1) indicate that average power densities can serve as proxies for "environmental consequences" but fail to traverse the issue in detail — the term is mentioned three times in the abstract and then never discussed within the body of the paper. What exactly are those consequences, can they be quantified, and do they usefully correlate against technical metrics such as power density?

In this regard, the relationship between hydro dam head and greenhouse gas emissions and other forms of impact have been studied and this metric can offer insights (Gleick 1992). That said, hydro sitting is highly situation-specific and the blanket approach used by Miller and Keith is not remotely appropriate for this particular technology.

A recent study by Matthes *et al* (2018), supported by Dijks *et al* (2018), factored in environmental constraints which considered future renewables deployments for Germany.

If non-renewable generation technologies are included in the power density framework, then it is unlikely that any pattern between power density and environmental impact would emerge. For instance, unfiltered lignite-fired generation — assuming a definition for its footprint can be agreed — would doubtless show a higher energy density than wind or PV and is yet clearly more detrimental in terms of both local and global harms.

The environment impacts of renewable generation technologies can be both technology-specific and site-specific. Life-cycle analysis (LCA) categories that are local and relevant include: toxicity, biodiversity loss, wildlife mortality and/or displacement, land-use change, and micro-climate modification.

Most installations also downgrade amenity and landscape values and may also cause human nuisance. Both sets of issues can be included, to some degree at least, in high-resolution assessment models.

The degree to which these various LCA categories correlate with power densities across technologies is unclear at best. Nonetheless that claim is repeated in a Harvard University promotional video featuring Miller (Miller and Keith 2018c) and is also contained in press release from *Joule* (Cell Press 2018) for the related article Miller and Keith (2018b).

Recent detailed work in Germany on bird and bat strikes by turbine blades relies on both observation and theory to produce species-specific collision-risk models (CRM) (Grünkorn *et al* 2016a, 2016b). These results are currently being studied by energy system modelers and possibly also by the wind industry, regulators, and policy analysts.

Primary energy demand

It is pointless using current primary energy demand to undertake future renewable resource assessments for Germany. Under energy efficiency and consumption considerations, the German government is officially committed to reduce primary demand as follows (BMWi 2015:4):

Target	**2014**	**2020**	**2050**
Primary energy consumption (base year 2008)	−8.7%	−20%	−50%
Projected annual values for comparison [TWh]	4285	3755	2347

Table: German government targets for reduction in primary energy demand. The values shown are not official but are provided for illustrative purposes based on the 2014 value taken from Ausfelder *et al* 2017:27).

This reduction is also present in the scenarios above (see tables) where primary energy demand falls from 4285 TWh in 2014 to somewhere between 3086 and 1696 TWh in 2050 for the various studies cited.

Much of this reduction is expected to be due to the displacement of thermal generation by renewable electricity and the displacement of end-use thermal processes, including mobility, by electrification. In 2017, around 80% of primary energy demand was thermal in nature (BP 2018:00). It is an analytical error of about magnitude two to continue to cover current levels of dumped waste heat (technically anergy) from thermal generation and internal combustion engines when migrating to systems with 100% renewable generation.

Miller and Keith (2018:9) do remark on this limitation but the more correct approach would be to include the very significant effect in calculations and not as some unquantified afterthought. The Miller and Keith assessment was, after all, predicated on 100% renewable generation.

Sophistication

Ball-park metrics and first-cut analyses can play useful roles. David McKay (2009) employed such methods to good advantage to scope energy sustainability options for the United Kingdom in the absence of accepted nation energy models for that country (albeit not without suggestions of bias, see Hickey 2010). Least developed countries with poor national information are also candidates for estimates based on power densities and related metrics.

The integrated assessment of current and future systems has a significant history, including projects such as MARKAL and MESSAGE, both of which now stretch back several decades. More latterly, these and other models have been developed to cater for systems with high renewables shares through support for high temporal, topological, and spatial resolutions (Ringkjøb *et al* 2018). Improvements to these models to better support technology-specific and site-specific environmental impacts was noted earlier and this effort should continue.

Ausfelder *et al* (2017) review six studies plus their own that use sophisticated software and examine potential German energy systems out to 2050. Other studies from a range of research institutes are not cited here (but probably should be). As the Sankey diagrams in Ausfelder *et al* show, once a scenario is developed, populated with data, and run, rich insights can be obtained that are not possible with back-of-the-envelope estimates.

Outlook

Single-year "waypoint" scenarios derived from the results of multi-decade models just discussed are now being examined by a new generation of very-high-resolution energy system models that support sophisticated AC load flow (Wienholt *et al*, in preparation). This soft-coupling also means that lessons from waypoint models can be to inform and refine their originating multi-decade models. This waypoint/multi-decade modeling synergy is expected to steadily develop over the next years.

Unwarranted conclusions

There appears to be an implication in the German example by Miller and Keith that the current German energiewende might be somehow flawed because their back-of-the-envelope estimate using a simplistic methodology and questionable assumptions fails to produce a sufficiently 'credible' answer. In contrast, a good number of numerical studies show the German energiewende is entirely feasible on technical grounds and likely to be achieved, particularly if public acceptance prevails.

However articles in the mainstream press that suggest that wind energy should be deprioritized on the basis of incomplete, questionable, or even flawed work do little to assist with public acceptance. For example, quoting from Grolle (2018), as published in *Der Spiegel*, a widely-read German daily (translated):

> According to a new study, the expansion of wind energy reaches its limits, because the rotors impede each other. And worse, at least at the local level, the plants could even contribute to warming.

That story admittedly stems mostly from Miller and Keith (2018b). But comments by Miller in a Harvard

University promotional video (Miller and Keith 2018c) also suggest that the authors prefer photovoltaics over wind for reasons that are not disclosed in the literature.

Non-reproducible science

The QGIS dataset and post-GIS analysis by Miller and Keith (2018) are not available nor open and cannot be inspected and run by independent researchers to check their veracity. This is a serious shortcoming, particularly as the authors strongly criticize another researcher for running analysis using an unexaminable "private model without deep public documentation" (Jacobson 6 October 2018:7).

Discussion

One has to ask why energy researchers would apply such simplistic analysis to Germany when the state-of-the-art is so much more sophisticated? Miller is aware of German energy policy, having gained his PhD at the Max Planck Institute in Jena, undertaken post-doc research at that same institution, and published highly-technical wind potential estimates for Germany as Miller *et al* (2013). How then too could the Miller and Keith analysis pass peer review, particularly without providing a comparison to the state-of-the-art?

With regard to power densities, it may well be that the practice of normalizing the performance of dissimilar generating technologies against characteristic areas is so fraught that the technique is not worth pursuing. Unlike dimensional analysis, there appears to be no natural definition of characteristic areas and the resulting metrics become so open to interpretation that they cease to be informative.

The German example in Miller and Keith (2018) will doubtless continue to be cited in the future as evidence that the German energiewende is in difficulty, a conclusion that is both misleading and damaging. This is highly regrettable.

To-do list

The following material could be usefully added:

- further coverage of the numerical studies that analyze future German energy systems
- improved treatment of environmental impacts associated with future energy systems, including wildlife protection measures and constraints
- consider broadening text to include solar assessments as well
- more numerical results, particularly useful would be power densities calculated from simulation outputs
- select one source for current energy statistics: Ausfelder *et al* (2017), BMWi (2018), BP (2018), UBA (not referenced)
- also migrate from markdown to LaTeX

References

acatech, Leopoldina, Akademienunion (editors) (August 2018). *Coupling the different energy sectors: options for the next phase of the energy transition — Position paper*. Germany: acatech, Leopoldina, Akademienunion. ISBN 978-3-8047-3673-3. English translation.

acatech, Leopoldina, Akademienunion (editors) (November 2017). *Sektorkopplung: Optionen für die nächste Phase der Energiewende — Stellungnahme* [*Sector-coupling: options for the next phase of the Energiewende — Position paper*] (in German). Germany: acatech, Leopoldina, Akademienunion. ISBN 978-3-8047-3672-6.

Ausfelder, Florian, Frank-Detlef Drake, Berit Erlach, Manfred Fischedick, Hans-Martin Henning, Christoph Kost, Wolfram Münch, Karen Pittel, Christian Rehtanz, Jörg Sauer, Katharina Schätzler, Cyril Stephanos, Michael Themann, Eberhard Umbach, Kurt Wagemann, Hermann-Josef Wagner, and Ulrich Wagner (November 2017). *Sektorkopplung: Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems* [*Sector-coupling: investigations and considerations for the development of an integrated energy system*] (in German). München, Germany: acatech, Leopoldina, Akademienunion. ISBN 978-3-9817048-9-1.

BMVI (August 2015). *Räumlich differenzierte Flächen-potentiale für erneuerbare Energien in Deutschland — BMVI-Online-Publikation 08/2015* [*Spatially-differentiated land potentials for renewable energy in Germany — BMVI-Online-Publication 08/2015*] (in German). Berlin, Germany: Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). ISSN 2364-6020.

BMWi (August 2018). *Energiedaten: Gesamtausgabe*. Berlin, Germany: Bundesministerium für Wirtschaft und Energie (BMWi). SI units.

BP (June 2018). *BP statistical review of world energy 2018* (67th ed). London, United Kingdom: BP.

Copernicus (22 October 2018). CORINE Land Cover (CLC) — Copernicus Land Monitoring Service. *Copernicus Programme*. Europe.

Cell Press (4 October 2018). Large-scale US wind power would cause warming that would take roughly a century to offset. *Science Daily*. USA.

Deane, Paul (19 April 2017). "Chapter 13: Energy supply: a changing environment: conclusions and outlook". In Welsch, Manuel, Steve Pye, Dogan Keles, Aurélie Faure-Schuyer, Audrey Dobbins, Abhishek Shivakumar, Paul Deane, and Mark Howells (editors) (19 April 2017). *Europe's energy transition: insights for policy making*. London, United Kingdom: Academic Press. ISBN 978-0-12-809806-6. doi:10.1016/B978-0-12-809806-6.00013-4.

Federal Ministry for Economic Affairs and Energy (November 2015). *The energy of the future: fourth "energy transition" monitoring report — Summary*. Berlin, Germany: Federal Ministry for Economic Affairs and Energy (BMWi).

Dijks, Sebastian, Miron Thylmann, and Wolfgang Peters (October 2018). *Regionale Auswirkungen des Windenergieausbaus auf die Vogelwelt: Eine exemplarische Untersuchung von sechs bundesdeutschen Landkreisen* [*Regional effects of wind energy expansion on bird life: a showcase study of six German rural districts*] (in German). Berlin, Germany: WWF Deutschland. ISBN 978-3-946211-24-2.

Enevoldsen, Peter and Scott Victor Valentine (1 December 2016). "Do onshore and offshore wind farm development patterns differ?". *Energy for Sustainable Development*. **35**: 41–51. ISSN 0973-0826. doi:10.1016/j.esd.2016.10.002.

Enevoldsen, Peter and Mark Z Jacobson (*under review*). "Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide".

Jülich Forschungszentrum (*ongoing*). Geospatial Land Availability for Energy Systems (GLAES). *Jülich Forschungszentrum (FZJ)*. Jülich, Germany.

Gleick, Peter H (1992). "Environmental consequences of hydroelectric development: the role of facility size and type". *Energy*. **17** (8): 735–747. ISSN 0360-5442. doi:10.1016/0360-5442(92)90116-H.

Goggin, Michael (5 October 2018). *New studies cause confusion about benefits of renewable energy*. Washington DC, USA: Grid Strategies LLC.

Grolle, Johann (9 October 2018). Windenergie: Droht das Ende der Wind-Ernte? [Wind energy: the end of the wind harvest threatened?] (in German). *Spiegel Online*. Hamburg, Germany. Paywalled.

Grünkorn, Thomas, Jan Blew, Timothy Coppack, Oliver Krüger, Georg Nehls, Astrid Potiek, Marc Reichenbach, Jan von Rönn, Hanna Timmermann, and Sabrina Weitekamp (2016a). *Ermittlung der Kollisionsraten von (Greif-)Vögeln und Schaffung planungsbezogener Grundlagen für die Prognose und Bewertung des Kollisionsrisikos durch Windenergieanlagen (PROGRESS)* [*Determination of collision rates of birds (of prey) and creation of planning-based principles for forecasting and assessment of the collision risk of wind turbines (PROGRESS)*] (in German). Husum, Germany: BioConsult SH.

Grünkorn, Thomas, Jan Blew, Timothy Coppack, Oliver Krüger, Georg Nehls, Astrid Potiek, Marc Reichenbach, Jan von Rönn, Hanna Timmermann, and Sabrina Weitekamp (2016b). *Prognosis and assessment of bird collision risks at wind turbines in northern Germany (PROGRESS) — Summary and conclusions*. Husum, Germany: BioConsult SH.

Herath, Indika, Markus Deurer, David Horne, Ranvir Singh, and Brent Clothier (2011). "The water footprint of hydroelectricity: a methodological comparison from a case study in New Zealand". *Journal of Cleaner Production*. **19** (14): 1582–1589. doi:10.1016/j.jclepro.2011.05.007.

Hickey, Jim (18 August 2010). 'No hot air' about renewable energy while blowing smoke: David Mackay plays 'Brutus' to the Sun's 'Caesar'. *Justmeans*. Northampton, Massachusetts, USA.

Jacobson, Mark Z (3 October 2018a). *Response to Miller and Keith "Observation-based solar and wind power capacity factors and power densities" (Environmental Research Letters, 2018)*.

Jacobson, Mark Z (6 October 2018b). *Response to reply of Miller and Keith*.

Jacobson, Mark Z (2 October 2018c). *Response to Miller and Keith "Climatic Impacts of Windpower" (Joule, 2018)*.

Lütkehus, Insa, Hanno Salecker, and Kirsten Adlunger (June 2013). *Potenzial der Windenergie an Land: Studie zur Ermittlung des bundesweiten Flächen- und Leistungspotenzials der Windenergienutzung an Land* [*Potential of wind energy on land: study to determine the nationwide area and performance potential of wind energy use on land*] (in German). Dessau-Roßlau, Germany: Umweltbundesamt (UBA).

Matthes, Felix Chr, Franziska Flachsbarth, Charlotte Loreck, Hauke Hermann, Hanno Falkenberg, and Vanessa Cook (October 2018). *Zukunft Stromsystem II: Regionalisierung der erneuerbaren Stromerzeugung : Vom Ziel her denken* [*Future electricity system II: regionalization of renewable electricity generation: thinking on the goal*] (in German). Berlin, Germany: WWF Deutschland. ISBN 978-3-946211-22-8.

Miller, Lee M and David W Keith (2018). "Observation-based solar and wind power capacity factors and power densities". *Environmental Research Letters*. **13** (10): 104008. ISSN 1748-9326. doi:10.1088/1748-9326/aae102. Open access.

Miller, Lee M and David W Keith (4 October 2018b). "Climatic impacts of wind power". *Joule*. ISSN 2542-4351. doi:10.1016/j.joule.2018.09.009. Closed access.

Miller, Lee M and David W Keith (2018c). Climatic impacts of wind power. Cambridge, Massachusetts, USA: Harvard University Center for the Environment. Video 02:39.

Miller, Lee M and David W Keith (2018d). Observation-based solar and wind power capacity factors and power densities. Cambridge, Massachusetts, USA: Harvard University Center for the Environment. Video

03:48.

Miller, Lee M and David W Keith (October 2018e). *Supplemental information for 'Observation-based solar and wind power capacity factors and power densities'*.

Miller, Lee M and Axel Kleidon (29 November 2016). "Wind speed reductions by large-scale wind turbine deployments lower turbine efficiencies and set low generation limits". *Proceedings of the National Academy of Sciences (PNAS)*. **113** (48): 13570–13575. ISSN 0027-8424. doi:10.1073/pnas.1602253113. Supporting information.

Miller, Lee M, Fabian Gans, and Axel Kleidon (June 2013). *A new estimate of Germany's wind energy potential which includes the effect of turbines on the flow*. 2nd International Conference on Energy and Meteorology. 25-28 June 2013, Toulouse, France.

Nitsch, Felix Johann (July 2018). *Wind power potential assessment for the Czech Republic based on Austrian and Danish site characteristics*. Vienna, Austria: University of Natural Resources and Life Sciences. Master thesis.

Page, Michael Le (13 October 2018). "Wind power's warming effect is overblown". *New Scientist*. (3199): 25. ISSN 0262-4079. Online title: "Wind farms do affect climate — but they don't cause global warming". Paywalled.

Purr, Katja, Ulla Strenge, Kathrin Werner, Diana Nissler, Manuela Will, Guido Knoche, and Annette Volkens (editors) (January 2015). *Germany in 2050: a greenhouse gas-neutral country*. Dessau-Roßlau, Germany: Umweltbundesamt (UBA). ISSN 1862-4359. Translation of 2014 report.

QGIS Development Team (ongoing). QGIS geographic information system Open Source Geospatial Foundation Project.

Reuter, Andreas and Peter Elsner (editors) (February 2016). *Windkraftanlagen: Technologiesteckbrief zur Analyse "Flexibilitätskonzepte für die Stromversorgung 2050"* [*Wind turbines: technology fact-sheet for analysis of* "*Flexibility concepts for the power supply 2050*"] (in German). Germany: acatech, Leopoldina, Akademienunion.

Ringkjøb, Hans-Kristian, Peter M Haugan, and Ida Marie Solbrekke (1 November 2018). "A review of modelling tools for energy and electricity systems with large shares of variable renewables". *Renewable and Sustainable Energy Reviews*. **96**: 440–459. ISSN 1364-0321. doi:10.1016/j.rser.2018.08.002. Creative Commons CC-BY-NC-ND-4.0 license.

Ryberg, David Severin (21 December 2017). FZJ-IEK3-VSA/glaes: GLAES launch. Zenodo.

Ryberg, David Severin, Martin Robinius, and Detlef Stolten (21 December 2017). "Methodological framework for determining the land eligibility of renewable energy sources". Preprint arXiv:1712.07840.

Werner, Kathrin, Diana Nissler, and Katja Purr (editors) (October 2013). *Treibhausgasneutrales Deutschland im Jahr 2050 — Hintergrund* [*Greenhouse gas-neutral Germany in 2050 — Background*] (in German). Dessau-Roßlau, Germany: Umweltbundesamt (UBA).

Wienholt, Lukas *et al* (*in preparation*). Optimal sizing and siting of storage units in a high-resolution power system model.

`file: miller-and-keith-2018-posting.md|pdf`

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