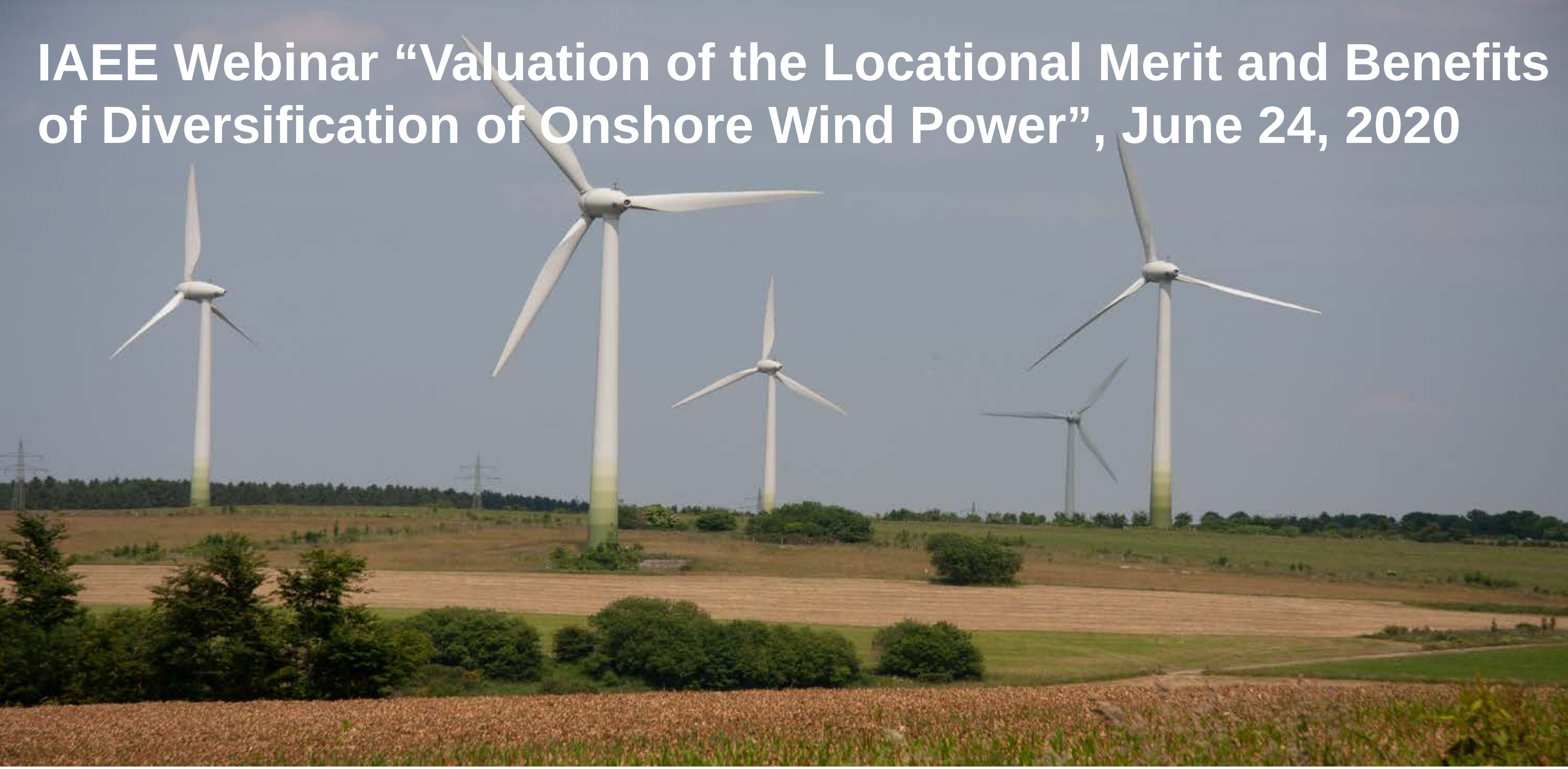

IAEE Webinar “Valuation of the Locational Merit and Benefits of Diversification of Onshore Wind Power”, June 24, 2020

Optimal Configuration and Diversification fo Wind Turbines: A Hybrid Approach to Improve the Penetration of Wind Power

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Introduction: E.ON ERC / FCN etc.

FCN – Institute for Future Energy Consumer Needs and Behavior

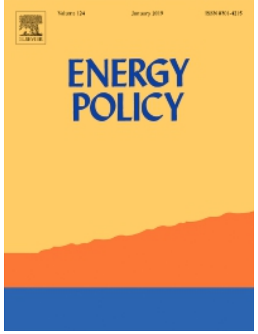
Prof. Dr. rer. soc. oec. Reinhard Madlener

Chair of Energy Economics and Management, RWTH Aachen University

- Established in June 2007 (Staff ~20-25)
- 1 Jun.-Prof. **Dr. Aaron Praktiknjo***
- 13 Junior Researchers (PhD cand.)
- 3 Post-doc Researchers
- 2 Administrative Assistants
- 2 External Junior Researchers (PhD cand.)
- Several research / teaching assistants

* JARA ENERGY Professorship in
“Energy Resources and Innovation Economics”

Co-Director, E.ON Energy Research Center



Senior Editor, Energy Policy

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Vice-President, SAEE

Introduction: Sustainable Energy Transition (*Energiewende*)

Outline

1. Motivation
2. Conceptual framework, model and data
3. Analysis and results
4. Summary and conclusions

1. Motivation

- **Wind power** plays a crucial role in decarbonizing electricity supply
- Increasing market penetration of wind power leads to decline in **market value**
- **Subsidies** are closely linked to market-based profitability
- Possible solutions to mitigate **market value** drop:
  1. System-friendly turbines
  2. Geographical diversification

System-optimal level ambiguous, as advanced turbines have higher upfront costs and diversified sites have potentially less favorable wind conditions

→ Introduction of a **hybrid approach** that helps (1) to improve market value, (2) to reduce total system costs, and (3) to reduce overall subsidy needs

- Research questions:
  1. Can the hybrid approach mitigate the **value drop** of wind power?
  2. Can the hybrid approach close the **profitability gap** between market value and LCOE?
  3. Can the hybrid approach reduce **total system costs**?
- Analysis for the case of Germany (2018-2030)

1. Motivation

- Advantageousness of the hybrid approach can be expected to depend on both a country‘s wind and power system characteristics.

- Related literature
  - Many studies analyzing competitiveness of variable renewable energy (VRE) and conventional technologies follow a **pure cost-based (LCOE) approach**
  - **Combined application** of the two strategies (system-friendly turbines, spatial diversification) for high penetration rates is missing, at least for Germany

- Hirth (2013), Hirth and Muller (2016)
- Mills and Wiser (2015)
- Tveten et al. (2016)
- Johansson et al. (2017)
- Dalla Riva et al. (2017)

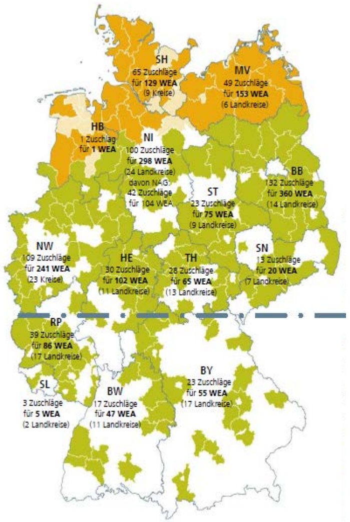
Becker and Thrän (2018)
Obermüller (2017)
Engelhorn and Müsgens (2018)
Pfluger et al. (2017ab)
Eising et al. (2020)

and more…!

2. Conceptual framework, model and data

Two Goals: (a) Identify promising **diversification areas**,
(b) Select **optimal system-friendly turbine configurations**

BAU development



BAU and div. areas

BAU and div. sensitivities

Purpose:

Show the total system cost and market value development at high penetration (up to 65%) for **business-as-usual**

Purpose:

Answer if and under which conditions **geographic diversification** makes sense (and how much)

Purpose:

Verify the BAU – DIV findings and derive additional insights

2. Conceptual framework, model and data

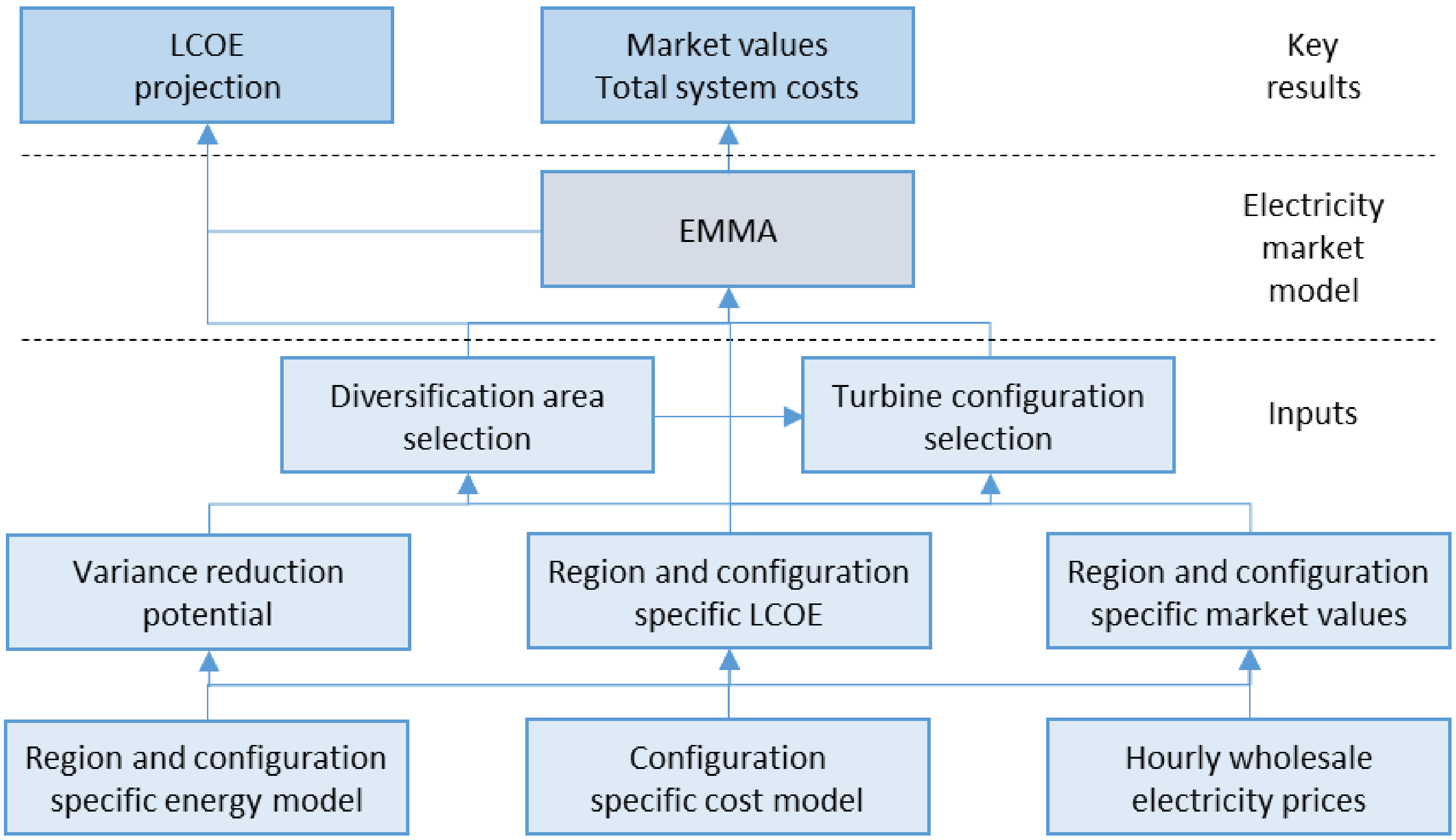
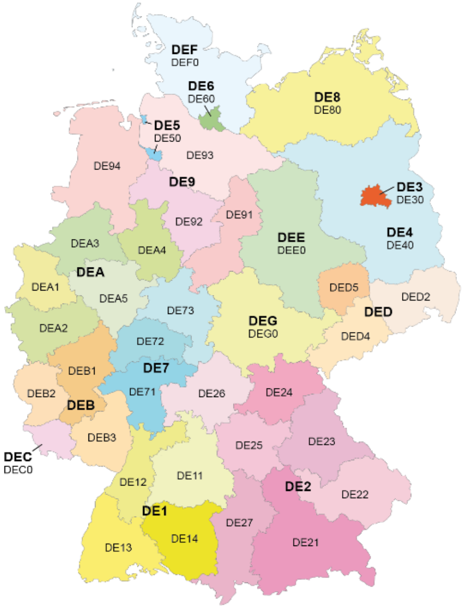
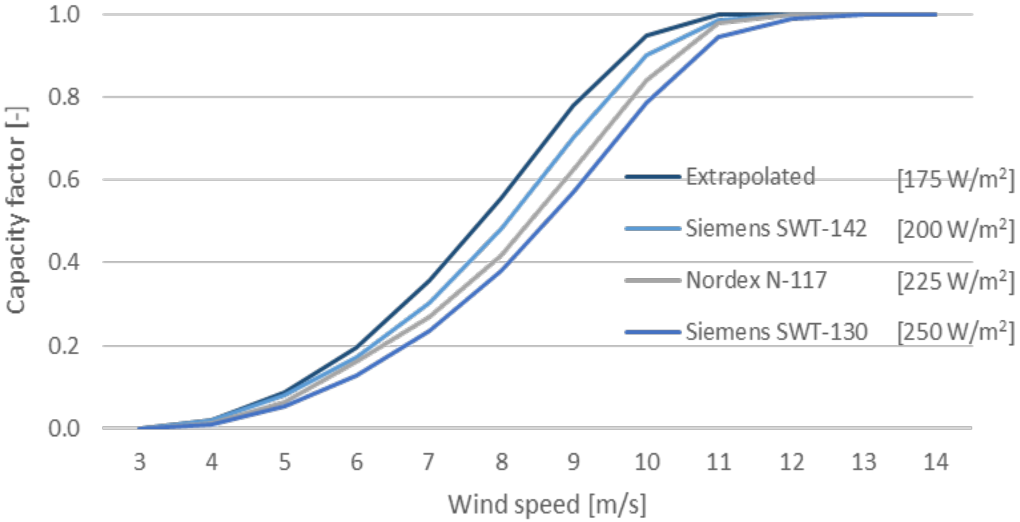


Figure 19: Top-down model architecture and components to forecast key results

2. Conceptual framework, model and data

Region and specific wind energy model (spec. focus: low wind speed turbines)





NUTS-2 wind speeds

(38 regions in Germany)

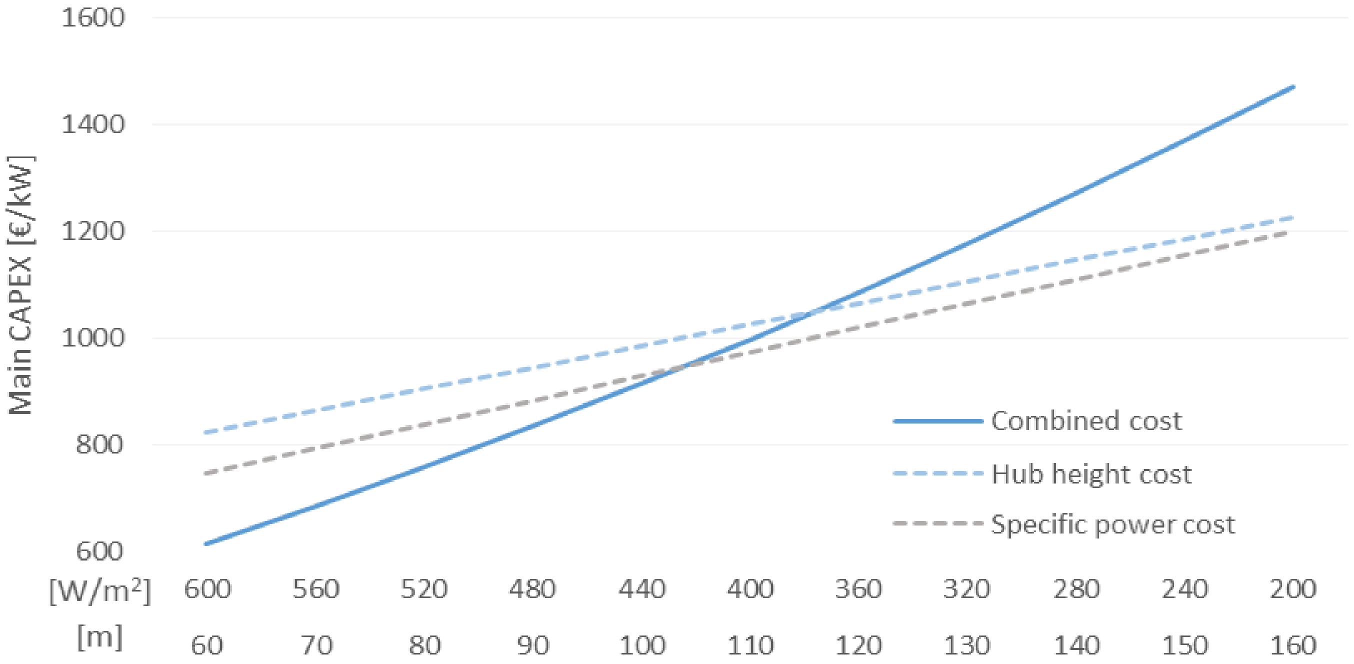
Power curves of 4 specific power turbines

(the lower the specific power, the steeper the power curve)

→ *The lower the specific power of a turbine, the steeper the power curve & the higher the electricity generation at a given wind speed*

2. Conceptual framework, model and data

Specific cost model (for a wide range of turbine configurations)



Data from WindGuard

CAPEX:

→ Turbine costs – depend largely on specific power and hub height

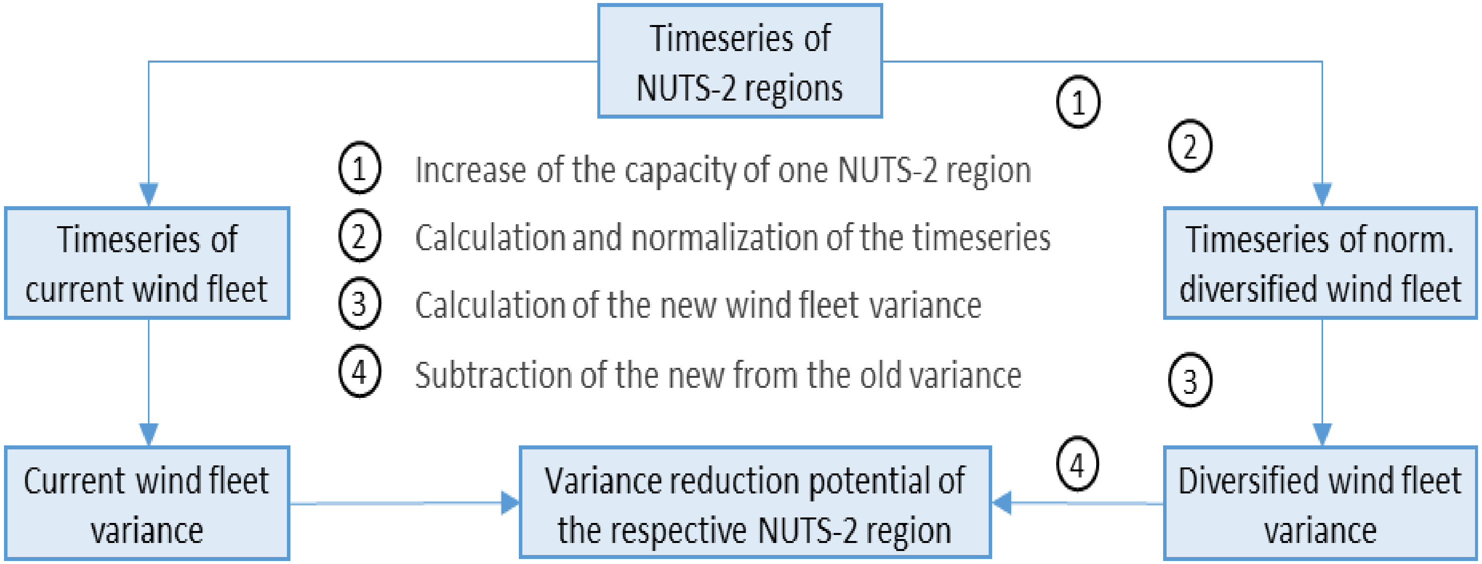
→ Site costs (foundation, infrastructure costs, other cost components)

2. Conceptual framework, model and data

Diversification area selection

Diversification areas: *can contribute to reduce the wind fleet output variance*

- Areas are chosen based on their **variance reduction** potential and **LCOE**



① Increase of the capacity of one NUTS-2 region

② Calculation and normalization of the timeseries

③ Calculation of the new wind fleet variance

④ Subtraction of the new from the old variance

Note: Due to geographic limitations of EMMA, we only investigate four exemplary, promising diversification regions

2. Conceptual framework, model and data

Turbine configuration optimization

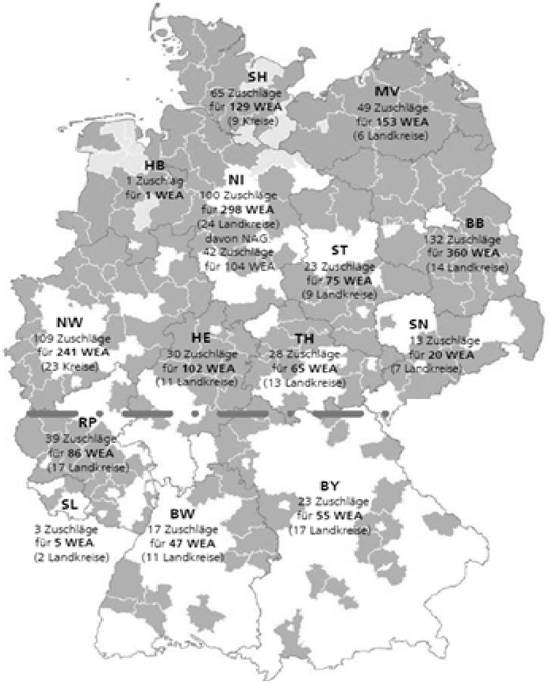
The optimal configuration ***minimizes*** *the* ***discounted difference between unit costs per kWh and expected electricity value*** (May, 2017)

→ *Choose turbine with smallest gap between MV and LCOE*

2. Conceptual framework, model and data

Modeling the current and future wind fleets

- **Benefits of hybrid approach** are assessed by comparing it with “business as usual” (BAU) turbines
- Assumed allocation of these turbines according to the **awarded bids** of the first nine auction rounds (see figure)*



State	Bid share [%]
BW	3
BY	3
BB	23
HE	6
MV	10
NI	19
NW	15
RP	5
SL	0
SN	1
SH	4
ST	8
TH	4

* Representing where new turbines in current support scheme are planned to be built

2. Conceptual framework, model and data

Electricity market model

- The **European Electricity Market Model (EMMA)** is adapted in multiple ways:
  - Four diversification regions are implemented
  - Offshore wind technologies are implemented
  - Technologies representing the current & future wind fleet are implemented
- Assumption of a **linear increase** of penetration (28% in 2018 → 65% in 2030)

Assumptions and data used

- **CO_2 price** will increase linearly (from 24 €/t in 2018 to 35 €/t in 2030)
- **Nuclear phase-out** until 2022
- Linear **coal phase-out** until 2038
- Technical potential of advanced wind turbines in Germany: **620 GW**

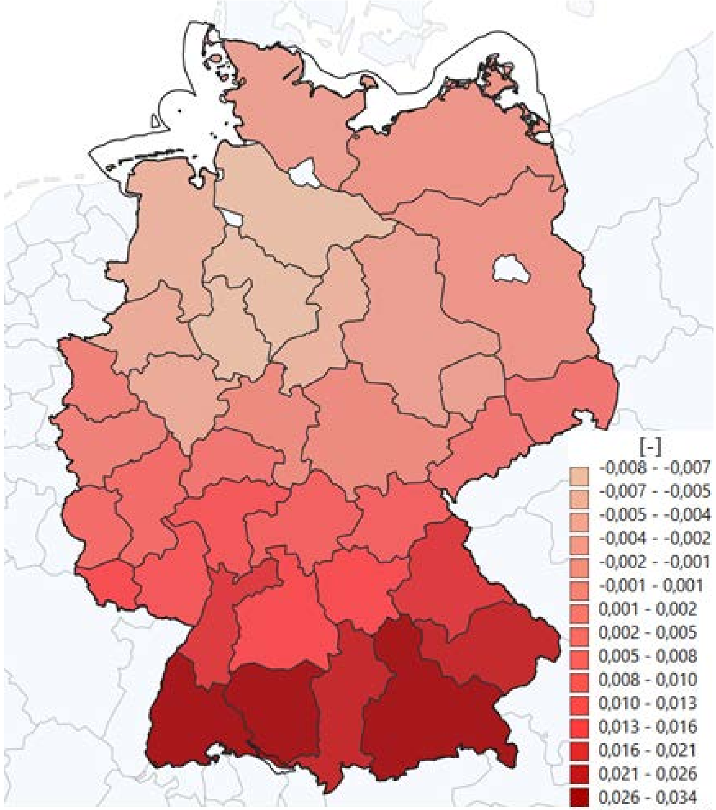
- Cost assumptions for variable renewable energy (VRE) in Germany

	CAPEX [€/kW]	OPEX [€/kW/a]	FLH [h]	Sources
Solar PV	875	15	950	Pfluger et al. (2017a, p. 56) Open Power System Data (2019)
Onshore wind	1330	53	1800	Hau (2016, 914, 919) Fraunhofer IWES (2019)
Offshore wind	2540	86	2990	Hau (2016, p. 925), DEA (2020, p. 230) Open Power System Data (2019)

3. Analysis and results

Region selection results

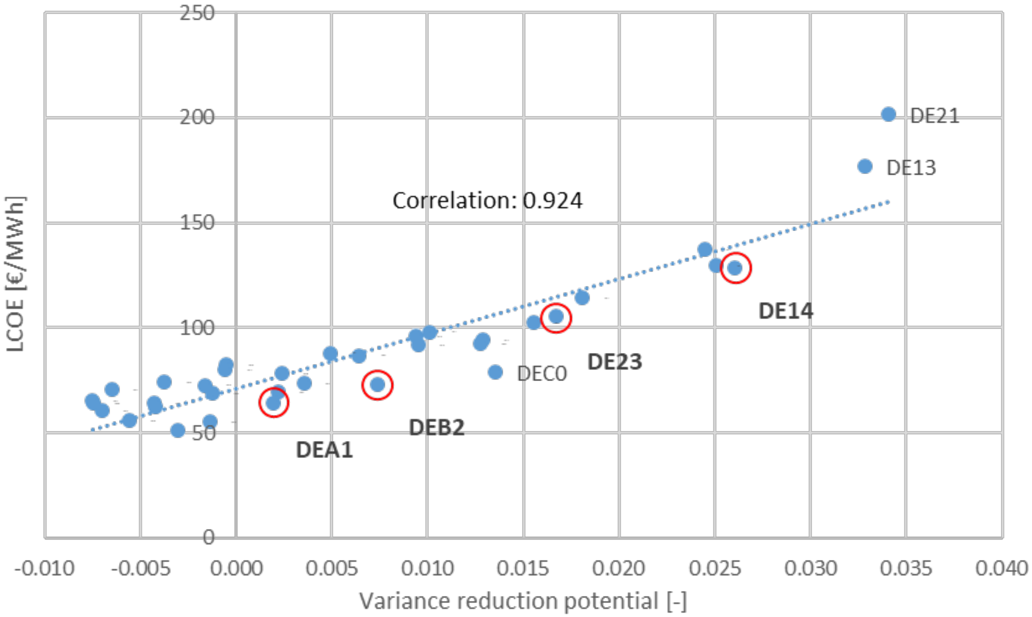
Wind fleet variance reduction potential (NUTS-2 regions)



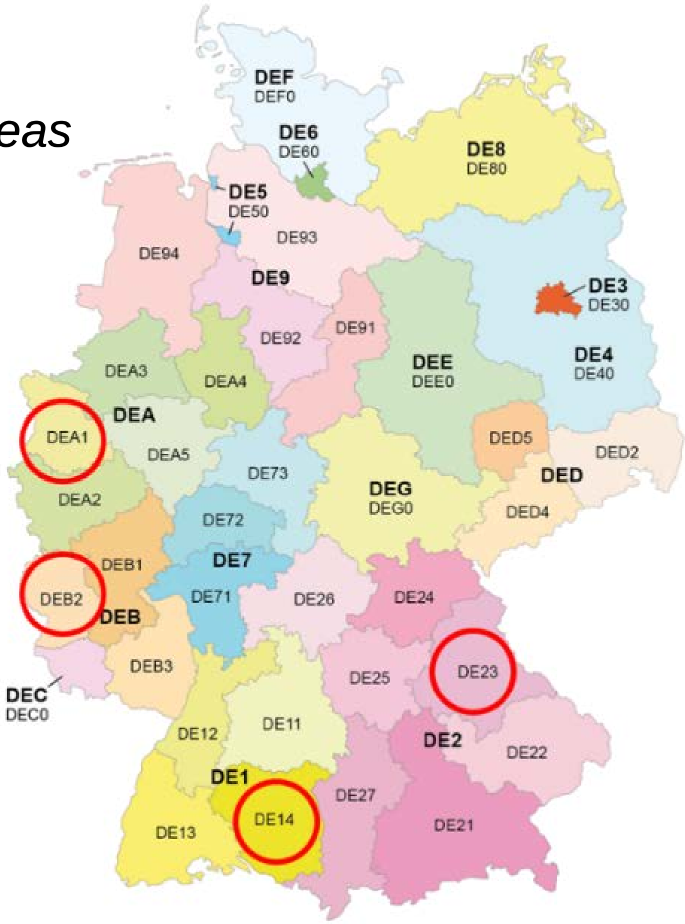
→ Low where correlation with the aggregate fleet is highest (central north)

Region selection results

Generation costs of most promising diversification areas



→ Trade-off: Higher variance reduction goes along with higher LCOE



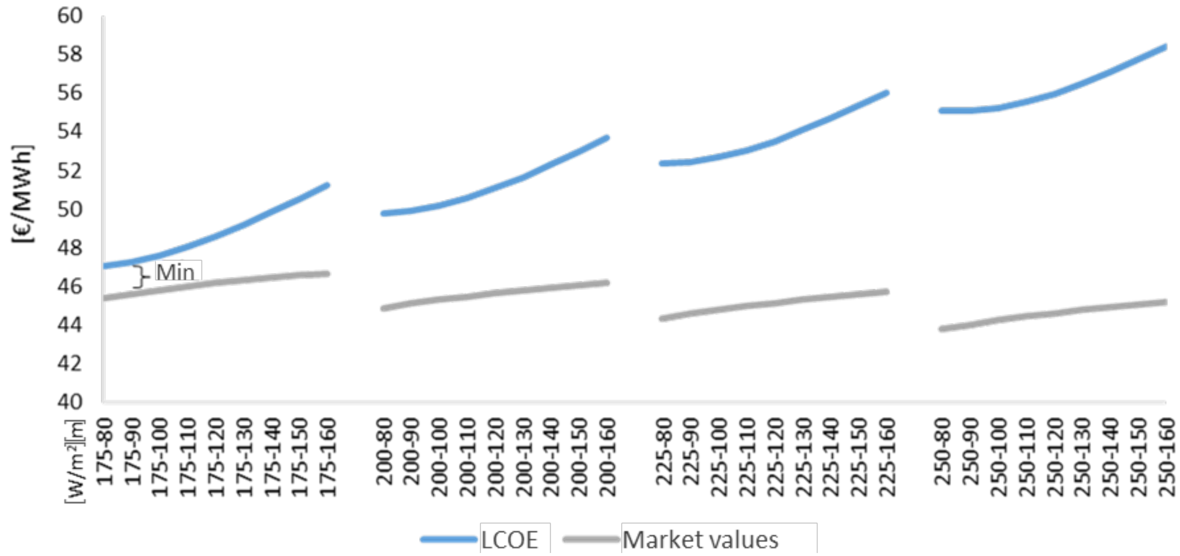
Selection of 4 areas not dominated by others with comparatively low LCOE

3. Analysis and results

Turbine optimization results

High wind speed locations

Turbine-specific market values & LCOE for Schleswig-Holstein (windiest NUTS-2 region in Germany)



LCOE:

- Increases with higher hub heights
- Decreases with lower specific power

Market value:

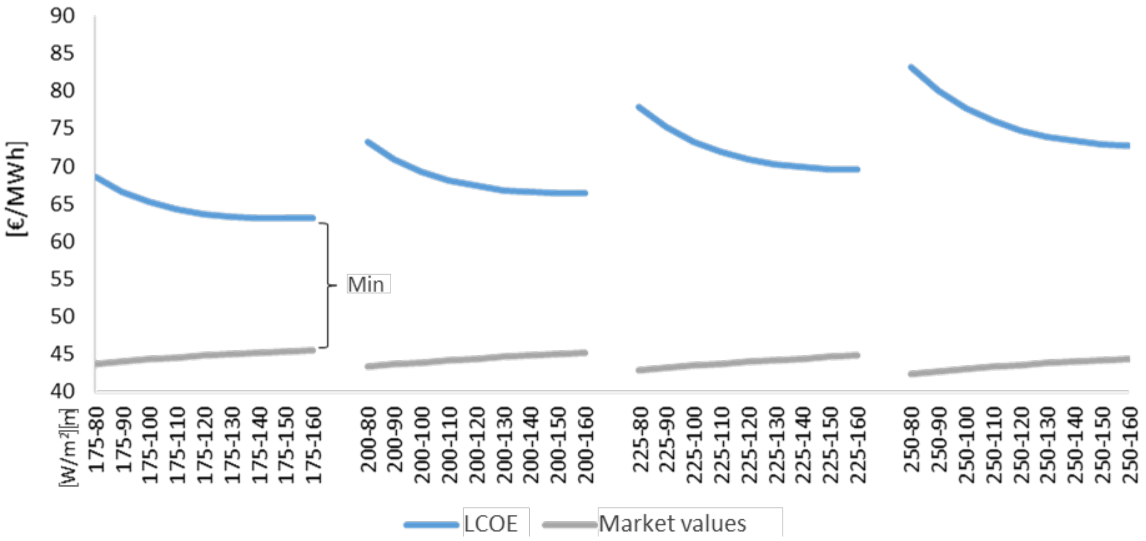
- Decreases with higher hub heights
- Increases with lower specific power

3. Analysis and results

Turbine optimization results

Moderate and low wind speed locations

Turbine specific market values & LCOE for the Rhineland-Palatinate (moderate wind quality)



LCOE:

- Decreases with higher hub heights
- Decreases with lower specific costs

Market value (lower than the windy location's)**:**

- Increases with higher hub heights
- Increases with lower specific power

→ Profitability gap is far larger than at the windy location

3. Analysis and results

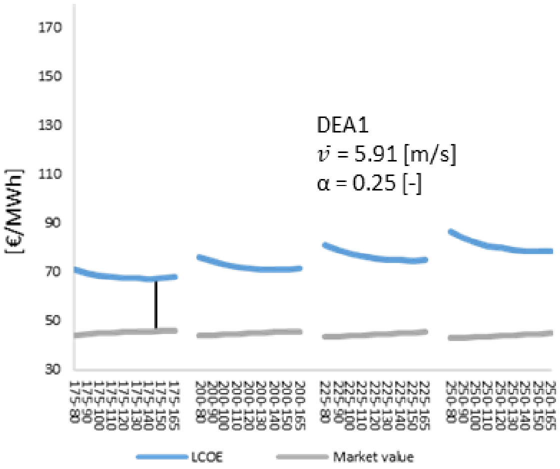
Optimal turbine configurations for selected areas:

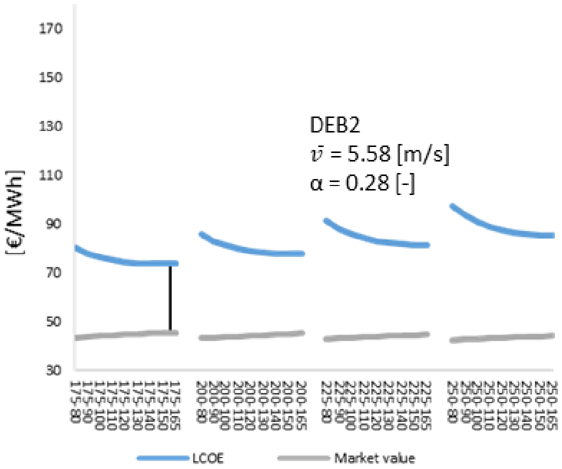
- **Lower specific power** (i.e. system-friendliness) is always better
- **Low hub heights** are optimal for high wind speed locations
- **High hub heights** are better for moderate and low wind speed locations

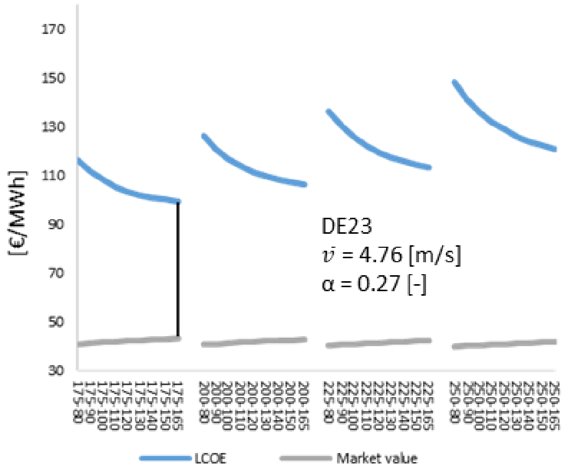
3. Analysis and results

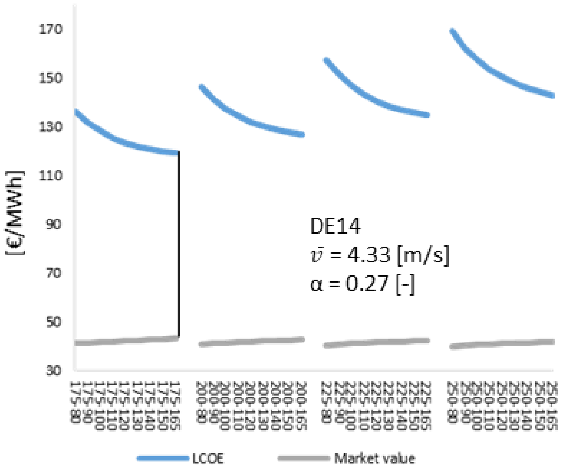
Optimal turbine configurations for selected areas:

- **Optimal configurations for all four (most promising) diversification areas (DEA1, DEB2, DE23, DE14):**
  - Specific power: 175 W/m^2
  - Hub heights: 150-165 m









Forecasted model results

Application of the hybrid approach to Germany

(comparing two EMMA model runs)

Results at 65% VRE penetration (2030)

Scenario	**MV** **[€/MWh]**	**MVF** **[-]**	**Profitability gap** **[bn €/a]**	**Total system costs** **[bn €/a]**
BAU	22.8	0.54	13.4	63.9
Hybrid approach	22.9	0.55	12.7	63.1

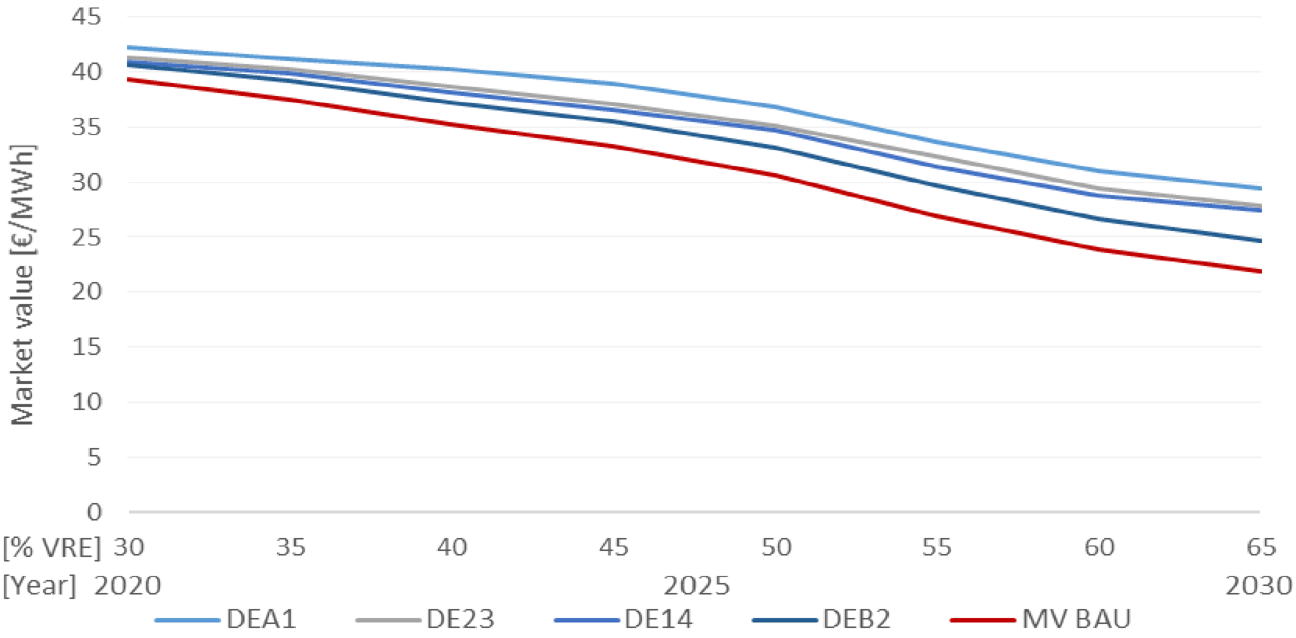
Smaller profitability gap 0.75 bn €/a → ~5% redution in overall subsidy needs compared to BAU

3. Analysis and results

Forecasted model results

Application of the hybrid approach to Germany

Market value (hybrid approach) > BAU additions (1-2 €/MWh at 30% → 2-7 €/MWh at 65%)



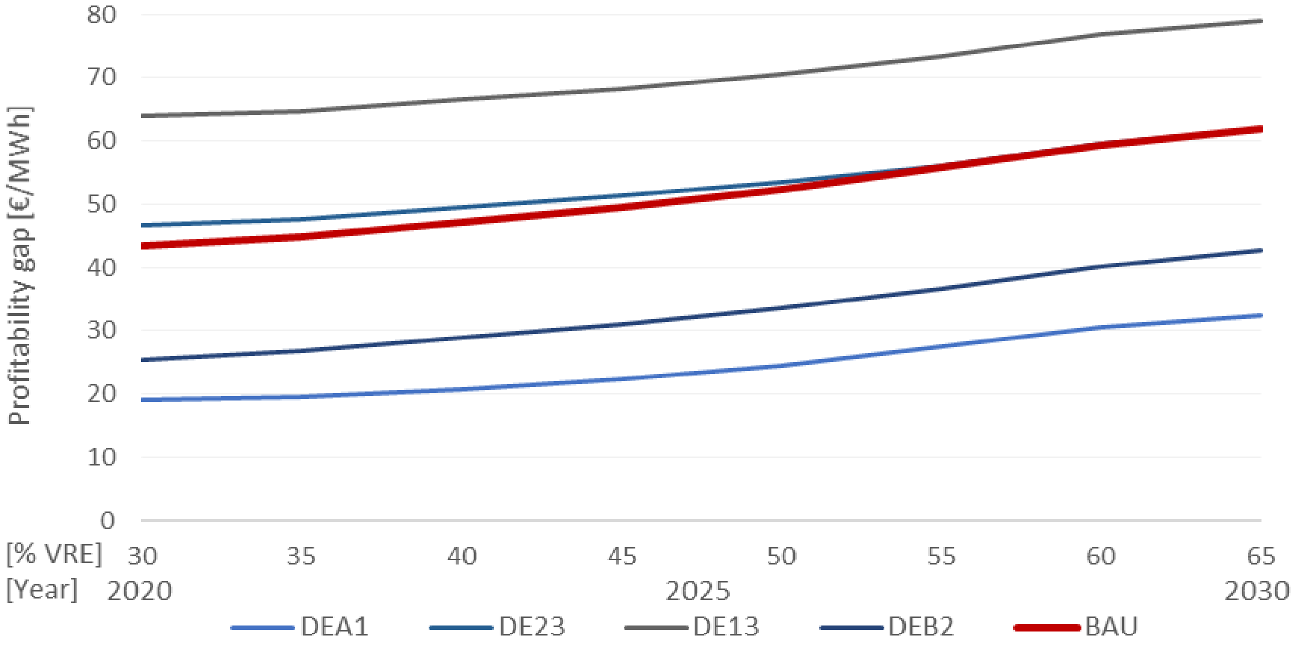
Average onshore market value factor decreases from 0.89 (30% VRE) to 0.55 (65% VRE)
Reason: increasing onshore wind farm penetration (18% → 38%)

3. Analysis and results

Forecasted model results

Application of the hybrid approach to Germany

Profitability gaps (hybrid approach)



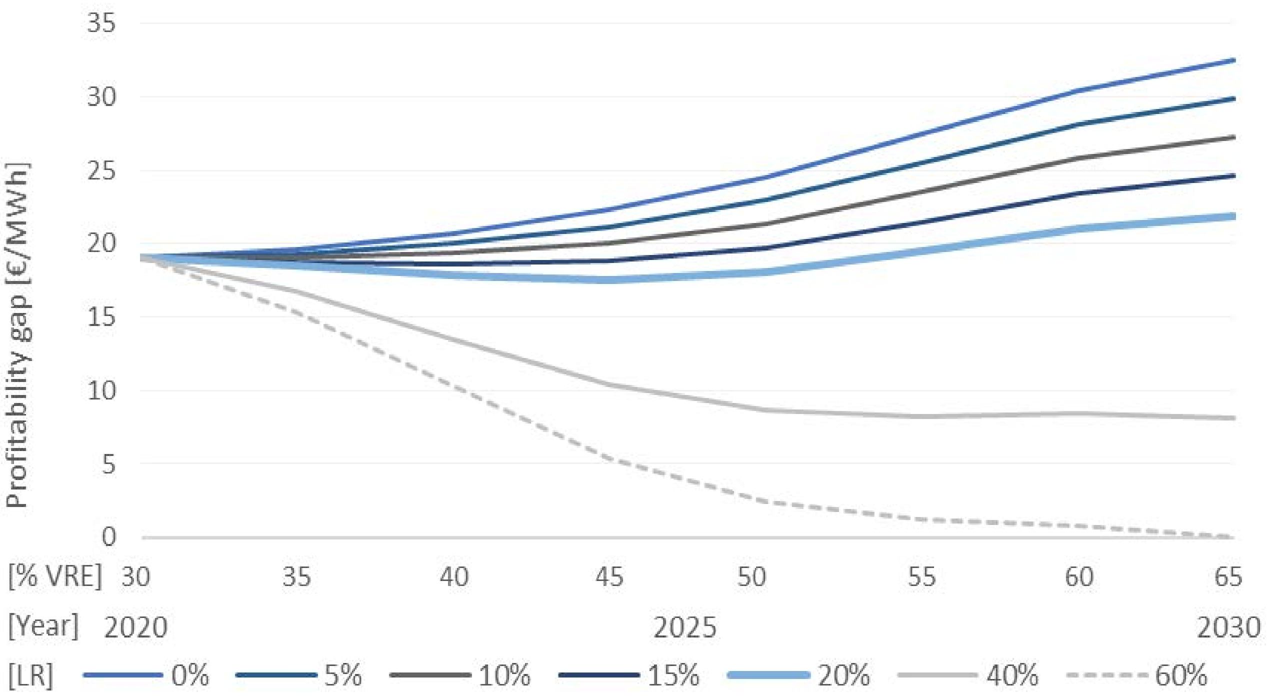
Some observations: Profitability gap increases (decrease in MV); DEA / DEB2 markedly lower (lower gen. Costs due to higher wind speeds, use of system-friendly turbines); diversification areas have high MVs (see previous slide) etc.

3. Analysis and results

Forecasted model results

Application of the hybrid approach to Germany

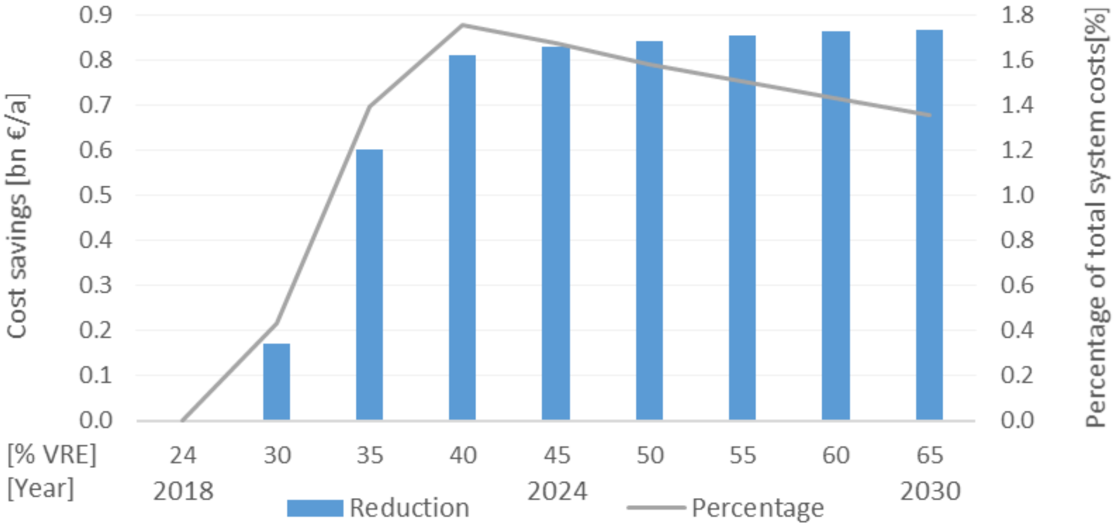
Profitability gaps (hybrid approach) DEA1 for various penetration and learning rates



Forecasted model results

Application of the hybrid approach to Germany

Total system costs and cost savings



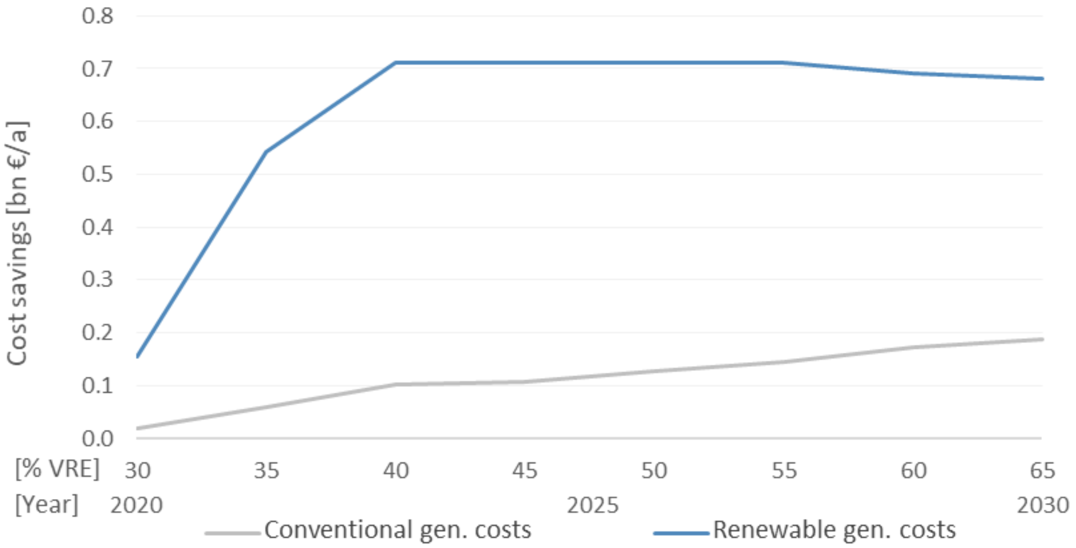
- In the modeled period total system costs of the hybrid approach model run are lower than for BAU
- Cost reductions increase steeply until ~40% VRE penetration
- Peak (percentage): energy potential of the diversification areas with lowest LCOE becomes exhausted

3. Analysis and results

Forecasted model results

Application of the hybrid approach to Germany

Savings in term of conventional and renewable generation costs (various penetration rates)



- Lower need for flexible generation in the hybrid approach → lower generation costs
- Lower LCOE in the hybrid approach → lower overall wind generation costs

Forecasted model results

Application of the hybrid approach to Germany

Results of sensitivity analysis at 65% VRE penetration compared to the original scenarios

Analysis 1 (diversification areas equipped with the same turbines as BAU wind fleet):

Change relative to	Market value factor [%]	Total system costs [%]
BAU	+0.5	-0.1
BAU-HY	-2.1	+1.3

Analysis 2 (diversification areas equipped with system-friendly turbines):

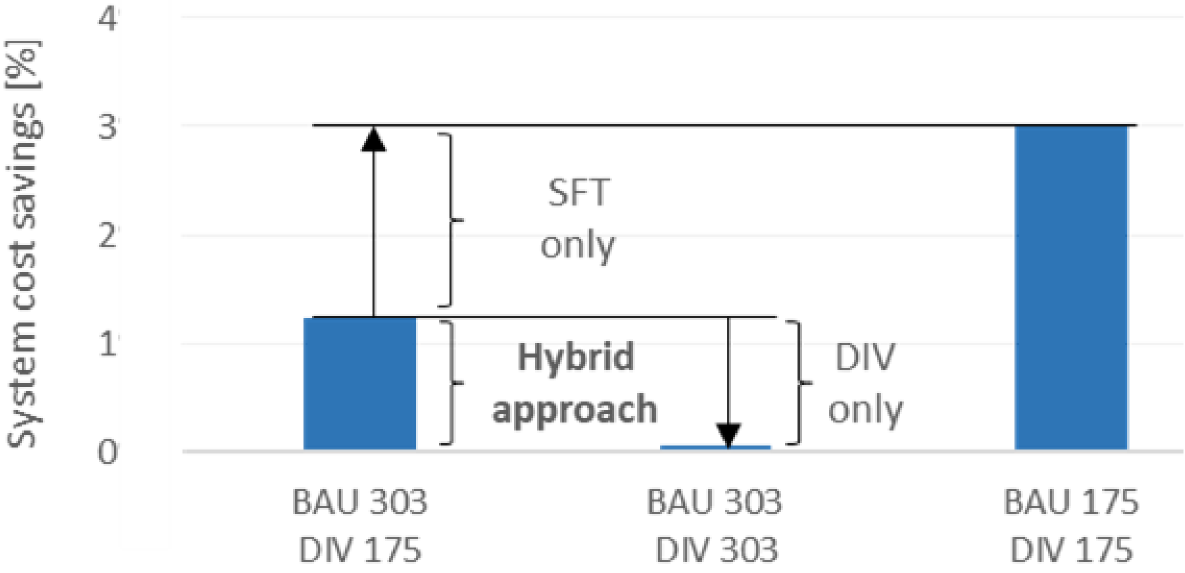
Change relative to	Market value factor [%]	Total system costs [%]
BAU	+8.4	-5.7
BAU-HY	+5.6	-4.4

4. Summary and conclusions

Summary:

- **Hybrid approach** was shown to result in *higher average market values*, *smaller overall profitability gaps*, and *lower system costs*
- Only a small share of the system benefits can be attributed to **diversification** (DIV only)
- Most system savings are due to **system-friendly turbines** (SFT only)
- Neither the BAU development nor the hybrid approach result in mainstream **merchant profitability**

  → Subsidies are likely to be necessary over the next decade



4. Summary and conclusions

- For the selected diversification areas, if equipped with system-friendly turbines, the **market value drop** is less severe (6-18% higher MV, or 2-7 €/MWh at 65% market penetration)
- **Profitability gap** (subsidy need) in diversification areas increases more slowly (gap decreases >5% at 65% VRES penetration)
- **Total system costs** decrease by 0.85 bn €/a (at 65% VRE penetration) or 1.4% of total system costs
- A large share of the benefits is attributed to system-friendly turbines, a low share to geographic diversification
- **Profitability (MV – LCOE)** can be increased by system-friendly turbines at both current and future penetration rates
- **Some diversified locations** can become increasingly profitable at higher penetration rates

Follow-up paper (in prep., FCN WP No.2/2020): system- and subsidy-optimal expansion areas; value-based support scheme to steer investment towards lower overall subsidy needs and system costs

P.S.: The paper (FCN Working Paper No. 1/2020) will be made available some time next week!!

Thank you for your kind attention. Any questions?

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References (1/7)

- Agentur für Erneuerbare Energien e.V. Der Strommix in Deutschland 2014-2018. https://www.unendlich-viel-energie.de/mediathek/grafiken/der-strommix-in-deutschland-2018 (accessed 8 August 2019).
- Aurora Energy Research, 2019. Managing merchant risk in renewables. https://www.auroraer.com/insight/managing-merchant-risk-in-renewables/ (accessed 29 January 2020).
- Becker, R., Thrän, D., 2018. Optimal Siting of Wind Farms in Wind Energy Dominated Power Systems. Energies 11 (4), 978. https://doi.org/10.3390/en11040978.
- Berkhout, V., Bisevic, A., Claußner, M., Dörenkämper, M., Durstewitz, M., Faulstich, S., Görg, P., Große, L., Hahn, B., Huneke, F., Kuhl, D., Lutz, M.-A., Mayer, J., Mergner, J., Noonan, M., Pfaffel, S., Rehwald, F., Schmidt, J., Spriestersbach, S., Stoevesandt, B., Vollmer, L., 2019. Windenergie Report Deutschland 2018. Fraunhofer Verlag, Stuttgart.
- Berkhout, V., Buchmann, E., Callies, D., Cernusko, R., Dobschinski, J., Durstewitz, M., Faulstich, S., Grashof, K., Hahn, B., Jäger, F., Keller, S., Lutz, M.-A., Meyer, J., Ortega, A., Pfaffel, S., Pfennig, M., Puchta, M., Rehwald, F., Rettenmeier, A., Dalla Riva, A., Röpnack, A., Rohrig, K., 2018. Windenergie Report Deutschland 2017. Fraunhofer Verlag, Stuttgart, 128 pp.
- Bucksteeg, M., 2019. Modelling the impact of geographical diversification of wind turbines on the required firm capacity in Germany. Applied Energy 235, 1476–1491. https://doi.org/10.1016/j.apenergy.2018.11.031.
- Bundesministerium für Wirtschaft und Energie, 2017. Powering ahead with offshore wind energy. Energiewende direkt (10).
- Bundesnetzagentur, 2018. Genehmigung des Szenariorahmens 2019-2030. https://www.netzausbau.de/2019-2030-sr (accessed 29 January 2020).
- Caglayan, D.G., 2019. Data for: The Future of European Onshore Wind Energy Potential: Detailed Distribution and Simulation of Advanced Turbine Designs.
- Capros, P., Vita, A. de, Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., 2016. EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050. European Commission.
- Dalla Riva, A., Hethey, J., Vītiņa, A., 2017. Impacts of Wind Turbine Technology on the System Value of Wind in Europe. https://www.nrel.gov/docs/fy18osti/70337.pdf (accessed 29 January 2020).

References (2/7)

- Danish Energy Agency, 2020. Technology Data for Generation of Electricity and District Heating. https://ens.dk/sites/ens.dk/files/Statistik/technology_data_catalogue_for_el_and_dh_-_0007_1.pdf (accessed 29 January 2020).
- Dansk Energi, 2018. Electricity Price Outlook 2018, 62 pp. https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2018-06/Electricity_Price_Outlook_2018.pdf (accessed 29 January 2020).
- Dörrbecker, M., 2019. Die Ebenen NUTS-1 und NUTS-2 in Deutschland. https://de.wikipedia.org/wiki/NUTS:DE#/media/Datei:Deutschland_NUTS1_und_NUTS2.png (accessed 1 May 2019).
- Drake, B., Hubacek, K., 2007. What to expect from a greater geographic dispersion of wind farms?—A risk portfolio approach. Energy Policy 35 (8), 3999–4008. https://doi.org/10.1016/j.enpol.2007.01.026.
- Eicke, A., Bensmann, A., Hanke-Rauschenbach, R., 2018. Flexibility options in power systems: A benefit analysis on the market value of variable renewable energy, in: Bachhiesl, U. (Ed.), Neue Energie für unser bewegtes Europa: 15. Symposium Energieinnovation : 14.-16. Februar 2018, TU Graz, Österreich. Verlag der Technischen Universität Graz, Graz, pp. 1–10.
- Eising, M., Hobbie, H., Möst, D., 2020. Future wind and solar power market values in Germany — Evidence of spatial and technological dependencies? Energy Economics 86, 104638. https://doi.org/10.1016/j.eneco.2019.104638.
- Elberg, C., Hagspiel, S., 2015. Spatial dependencies of wind power and interrelations with spot price dynamics. European Journal of Operational Research 241 (1), 260–272. https://doi.org/10.1016/j.ejor.2014.08.026.
- Engelhorn, T., Müsgens, F., 2018. How to estimate wind-turbine infeed with incomplete stock data: A general framework with an application to turbine-specific market values in Germany. Energy Economics 72, 542–557. https://doi.org/10.1016/j.eneco.2018.04.022.
- ENTSOE, 2019. Power Statistics. https://www.entsoe.eu/data/power-stats/ (accessed 9 August 2019).
- FA Wind, 2018. Windenergieanlagen - Was tun nach 20 Jahren? FA Wind, Berlin. https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA_Wind_Was_tun_mit_WEA_nach_20Jahren.pdf (accessed 29 January 2020).

References (3/7)

- FA Wind, 2019. Analyse der 9. Ausschreibung Wind an Land (Mai 2019). FA Wind, Berlin, 32 pp. https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/Analysen/FA_Wind_Analyse_9_Ausschreibung_Wind_an_Land.pdf (accessed 29 January 2020).
- Felice, M.D., Kavvadias, K., 2019. ERA-NUTS: time-series based on C3S ERA5 for European regions.
- FGW e.V., 2016. Leitfaden zum Referenzertragsverfahren im Erneuerbare-Energien-Gesetz 2017, Berlin. https://www.wind-fgw.de/wp-content/uploads/2017/01/Leitfaden-zum-Referenzertragsverfahren-im-EEG-2017.pdf (accessed 29 January 2020).
- Fraunhofer ISE, 2018. Levelized Cost of Electricity – Renewable Energy Technologies. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf (accessed 29 January 2020).
- Fraunhofer ISE, 2019. Energy Charts: Stromflüsse zwischen Deutschland und seinen Nachbarländern in 2018. https://www.energy-charts.de/exchange_de.htm?source=de_pf&year=2018 (accessed 10 June 2019).
- Fraunhofer IWES, 2017. Energiewirtschaftliche Bedeutung der Offshore-Windenergie. https://www.offshore-stiftung.de/sites/offshorelink.de/files/documents/Studie_Energiewirtschaftliche%20Bedeutung%20Offshore%20Wind.pdf (accessed 29 January 2020).
- Fraunhofer IWES, 2019. Windmonitor: Full-Load Hours. http://windmonitor.iee.fraunhofer.de/windmonitor_en/3_Onshore/5_betriebsergebnisse/1_volllaststunden/ (accessed 1 August 2019).
- Green, R., Léautier, T.-O., 2017. Do costs fall faster than revenues?: Dynamics of renewables entry into electricity markets.
- Grothe, O., Schnieders, J., 2011. Spatial dependence in wind and optimal wind power allocation: A copula-based analysis. Energy Policy 39 (9), 4742–4754. https://doi.org/10.1016/j.enpol.2011.06.052.
- Hand, M.M. IEA Wind TCP Task 26–Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, Sweden, the European Union, and the United States: 2008–2016. NREL/TP-6A20-71844. National Renewable Energy Laboratory, Golden, CO (US). https://www.nrel.gov/docs/fy19osti/71844.pdf (accessed 29 January 2020).
- Hau, E., 2016. Windkraftanlagen: Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, 6th ed. Springer Vieweg, Berlin, 996 pp.

References (4/7)

- Henckes, P., Knaut, A., Obermüller, F., Frank, C., 2018. The benefit of long-term high resolution wind data for electricity system analysis. Energy 143, 934–942. https://doi.org/10.1016/j.energy.2017.10.049.
- Hirth, L., 2012. Integration Costs and the Value of Wind Power. USAEE Working Paper No. 12-150. https://papers.ssrn.com/sol3/Delivery.cfm/SSRN_ID2187632_code920036.pdf?abstractid=2187632&mirid=1.
- Hirth, L., 2013. The market value of variable renewables: The effect of solar wind power variability on their relative price. Energy Economics 38, 218–236. https://doi.org/10.1016/j.eneco.2013.02.004.
- Hirth, L., 2016. The benefits of flexibility: The value of wind energy with hydropower. Applied Energy 181, 210–223. https://doi.org/10.1016/j.apenergy.2016.07.039.
- Hirth, L., 2017. The European Electricity Market Model EMMA - Model documentation. Neon Neue Energieökonomik GmbH. https://neon-energie.de/emma-documentation.pdf.
- Hirth, L., Müller, S., 2016. System-friendly wind power: How advanced wind turbine design can increase the economic value of electricity generated through wind power. Energy Economics 56, 51–63. https://doi.org/10.1016/j.eneco.2016.02.016.
- Hirth, L., Ueckerdt, F., Edenhofer, O., 2016. Why wind is not coal: on the economics of electricity generation. The Energy Journal 37 (3).
- IRENA, 2018. Renewable power generation costs in 2017. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018_summary.pdf?la=en&hash=6A74B8D3F7931DEF00AB88BD3B339CAE180D11C3 (accessed 29 January 2020).
- Johansson, V., Thorson, L., Goop, J., Göransson, L., Odenberger, M., Reichenberg, L., Taljegard, M., Johnsson, F., 2017. Value of wind power–Implications from specific power. Energy 126, 352–360. https://doi.org/10.1016/j.energy.2017.03.038.
- Joskow, P.L., 2011. Comparing the costs of intermittent and dispatchable electricity generating technologies. American Economic Review 101 (3), 238–241. https://doi.org/10.1257/aer.100.3.238.
- Kemnade, F.-J., Sperling, C., 2016. Windenergie im EEG 2017. https://www.next-kraftwerke.de/energie-blog/windenergie-eeg-2017 (accessed 2 June 2019).

References (5/7)

- Lacey, S., 2019. Merchant Solar and Wind: A Ticking Time Bomb? On The Interchange podcast this week: We explore the long-term risks of merchant renewable energy for developers. https://www.greentechmedia.com/articles/read/merchant-solar-and-wind-a-ticking-time-bomb (accessed 25 August 2019).
- May, N., 2017. The impact of wind power support schemes on technology choices. Energy Economics 65, 343–354. https://doi.org/10.1016/j.eneco.2017.05.017.
- Mills, A.D., Wiser, R.H., 2015. Strategies to mitigate declines in the economic value of wind and solar at high penetration in California. Applied Energy 147, 269–278. https://doi.org/10.1016/j.apenergy.2015.03.014.
- Obermüller, F., 2017. Build wind capacities at windy locations? Assessment of system optimal wind locations. EWI working paper No. 17/09, Köln.
- Open Power System Data, 2019. Time series: Load, wind and solar, prices in hourly resolution.
- Pfluger, B., Tersteegen, B., Franke, B., 2017a. Langfristszenarien für die Transformation des Energiesystems in Deutschland. Modul 2: Modelle und Modellverbund. Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie. BMWI, Berlin. https://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-1-hintergrund-szenarioarchitektur-und-uebergeordnete-rahmenparameter.pdf?__blob=publicationFile&v=2 (accessed 29 January 2020).
- Pfluger, B., Tersteegen, B., Franke, B., 2017b. Langfristszenarien für die Transformation des Energiesystems in Deutschland. Modul 3: Referenzszenario und Basisszenario. Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie. BMWI, Berlin. https://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-1-hintergrund-szenarioarchitektur-und-uebergeordnete-rahmenparameter.pdf?__blob=publicationFile&v=3 (accessed 29 January 2020).
- Pfluger, B., Tersteegen, B., Franke, B., 2017c. Langfristszenarien für die Transformation des Energiesystems in Deutschland. Modul 5: Szenario Alternative regionale EE-Verteilung. Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie. BMWI, Berlin. https://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-1-hintergrund-szenarioarchitektur-und-uebergeordnete-rahmenparameter.pdf?__blob=publicationFile&v=5 (accessed 29 January 2020).
- Reichenberg, L., Wojciechowski, A., Hedenus, F., Johnsson, F., 2017. Geographic aggregation of wind power-an optimization methodology for avoiding low outputs. Wind Energ. 20 (1), 19–32. https://doi.org/10.1002/we.1987.
- RTE, 2019. Bilan Electrique 2018. Réseau de Transport d'Electricité. https://bilan-electrique-2018.rte-france.com/.

References (6/7)

- Ryberg, D.S., Caglayan, D.G., Schmitt, S., Linßen, J., Stolten, D., Robinius, M., 2019. The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs. Energy 182, 1222–12v38. https://doi.org/10.1016/j.energy.2019.06.052.
- TenneT, 2019. Annual Market Update 2018. Tennet Holding BV. https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Technical_Publications/Dutch/Annual_Market_Update_2018_-_Final.pdf. (accessed 29 January 2020).
- Tveten, Å.G., Kirkerud, J.G., Bolkesjø, T.F., 2016. Integrating variable renewables: the benefits of interconnecting thermal and hydropower regions. International Journal of Energy Sector Management 10 (3), 474–506. https://doi.org/10.1108/IJESM-08-2014-0006.
- Ueckerdt, F., Hirth, L., Luderer, G., Edenhofer, O., 2013. System LCOE: What are the costs of variable renewables? Energy 63, 61–75. https://doi.org/10.1016/j.energy.2013.10.072.
- Vestas, 2018. Vestas sells first V120-2.0 MW turbines in North America with 138 MW order from Xcel Energy Inc. https://www.vestas.com/en/media/company-news?y=2018&l=142&n=3481884#!NewsView (accessed 29 January 2020).
- WindEurope, 2019. Wind energy in Europe in 2018: Trends and statistics, Brussels.
- WindGuard, 2017. Status des Offshore-Windenergieausbaus in Deutschland 2018. Deutsche WindGuard GmbH, Varel. https://www.wind-energie.de/fileadmin/redaktion/dokumente/pressemitteilungen/2019/Factsheet_Status_des_Offshore-Windenergieausbaus_in_Deutschland_2018.pdf.
- WindGuard, 2018a. Status of Land-based Wind Energy Development in Germany 2018. Deutsche WindGuard GmbH, Varel. https://www.wind-energie.de/fileadmin/redaktion/dokumente/dokumente-englisch/publications/Factsheet_Status_of_Wind_Energy_Development_in_Germany_-_Year_2018.pdf (accessed 29 January 2020).
- WindGuard, 2018b. Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz Teilvorhaben II e): Wind an Land. Zwischenbericht. Deutsche WindGuard GmbH, Varel. https://www.windguard.de/veroeffentlichungen.html?file=files/cto_layout/img/unternehmen/veroeffentlichungen/2018/Zwischenbericht%202018%20%E2%80%93%20Erfahrungsbericht%20gemaess%20%C2%A7%2097%20EEG%20%E2%80%93%20Wind%20an%20Land.pdf (accessed 15 May 2019).

References (7/7)

- WindGuard, 2019. Status des Windenergieausbaus an Land in Deutschland, 1. Halbjahr 2019. Deutsche WindGuard GmbH, Varel. https://www.wind-energie.de/fileadmin/redaktion/dokumente/publikationen-oeffentlich/themen/06-zahlen-und-fakten/20190725_Factsheet_Status_des_Windenergieausbaus_an_Land_-_Halbjahr_2019.pdf (accessed 5 October 2019).
- Wiser, R., Bolinger, M., 2018. 2018 Wind Technologies Market Report. U.S. Department of Energy. https://emp.lbl.gov/publications/2018-wind-technologies-market-report (link is external) (accessed 29 January 2020).
- Zaremba, N., 2019. Von Windenergie bis Wasserstoff. Was noch alles im Klimapaket enthalten ist. https://www.tagesspiegel.de/wirtschaft/von-windenergie-bis-wasserstoff-was-noch-alles-im-klimapaket-enthalten-ist/25040400.html (accessed 21 September 2019).