Universität Siegen

Onshore wind energy
German situation & design aspects

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„Soil and water in the context of renewable energy“
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Naturwissenschaftlich-Technische Fakultät
Department Bauingenieurwesen – Lehrstuhl für Geotechnik
Univ.-Prof. Dr.-Ing. habil. Kerstin Lesny

Use of renewable energies in Germany

Primary sources


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- Wind energy
- Solar power
- Biomass
- Hydro-power
- Ocean energy
- Geother-mal energy


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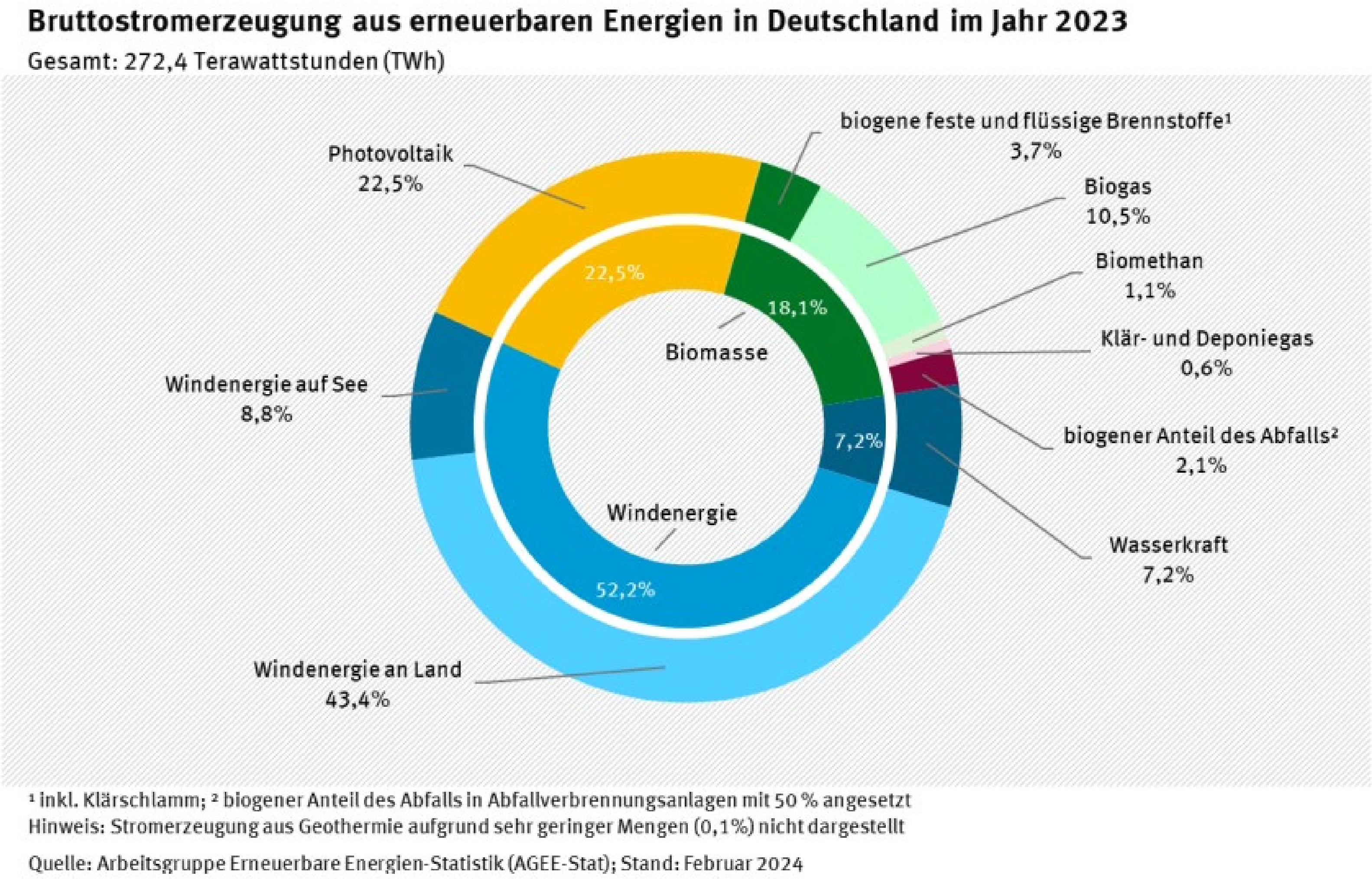
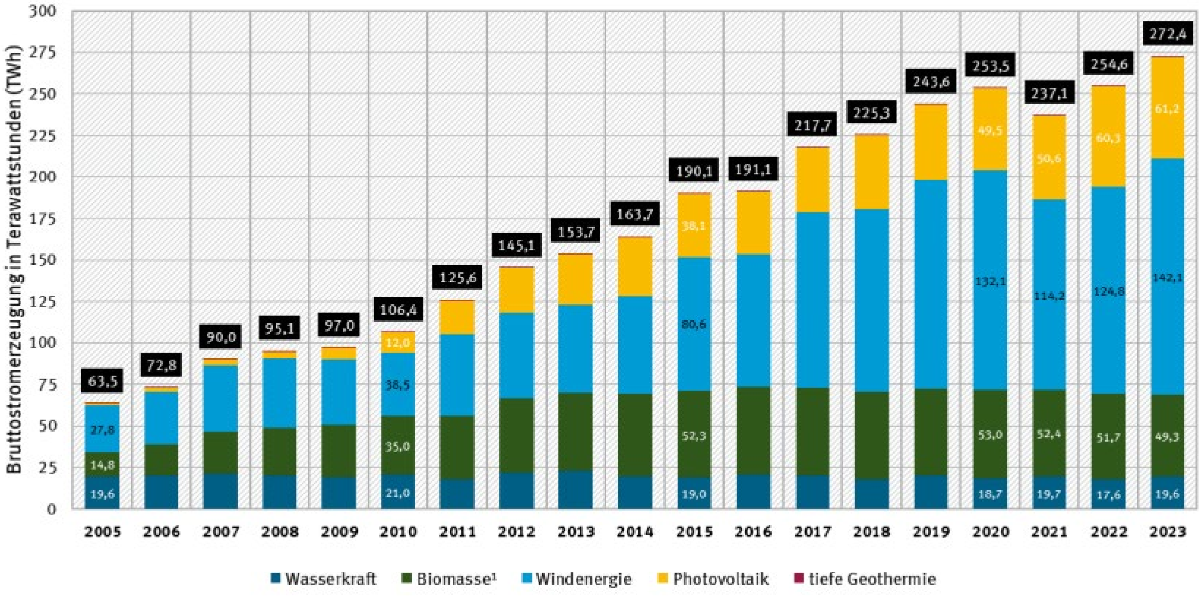
General statistics



General statistics

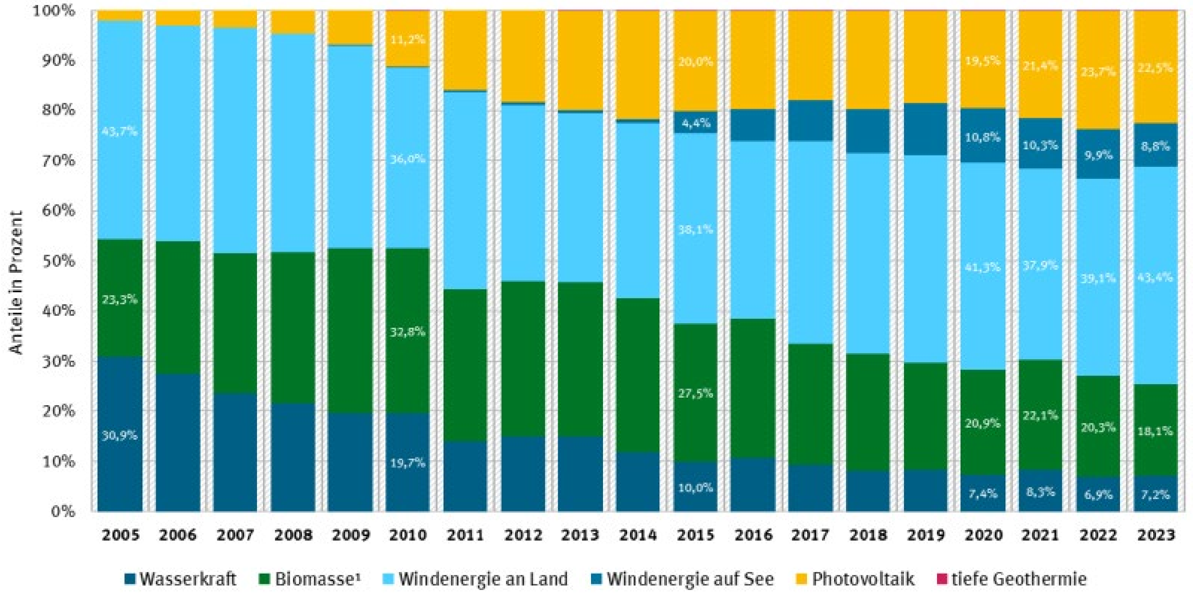
Entwicklung der Bruttostromerzeugung aus erneuerbaren Energien in Deutschland



¹ inkl. feste, flüssige und gasförmige Biomasse, Klärschlamm sowie dem biogenen Anteil des Abfalls (in Abfallverbrennungsanlagen mit 50 % angesetzt, ab 2008 nur Siedlungsabfälle)

Quelle: Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Stand: Februar 2024

Entwicklung der Zusammensetzung des erneuerbaren Stroms in Deutschland



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Quelle: Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Stand: Februar 2024

Renewable Energies Act (Erneuerbare Energien Gesetz – EEG)

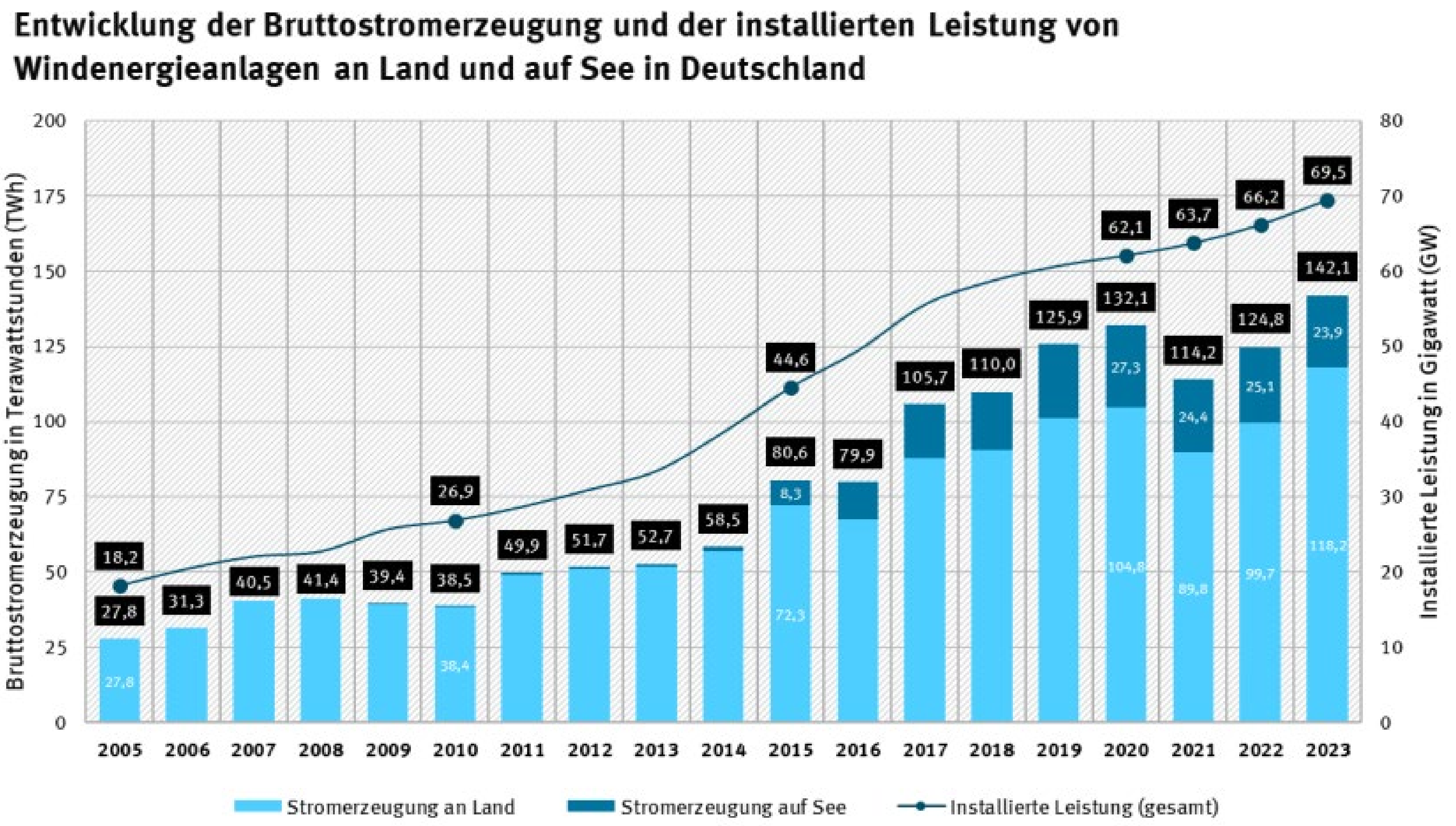
Amendment in 2023 has sharpened climate change goals:

- Construction and operation of renewable energy plants is in the *overriding public interest* and *serves public safety.*
- Climate neutral power supply until 2035 instead of 2050.
- Share of renewable energies on gross electricity production 80% instead of 65%.
- To reach these goals focus on expansion of solar and wind energy. New expansion rates and goals:

Technology	Increasing expansion rates	Expansion goals for 2030
Solar	22 GW per year	215 GW
Wind onshore	10 GW per year	115 GW
Wind offshore	2023-2026: 5-7 GW per year 2027-2030: 4 GW per year	30 GW

- Remuneration according to EEG: Fixed rates for solar energy whereas remuneration of on-/offshore wind energy is determined from the market premium achieved in previous awards during regular calls for tender. E.g. remuneration for onshore wind energy in 2024 is 7.35 ct/kWh.

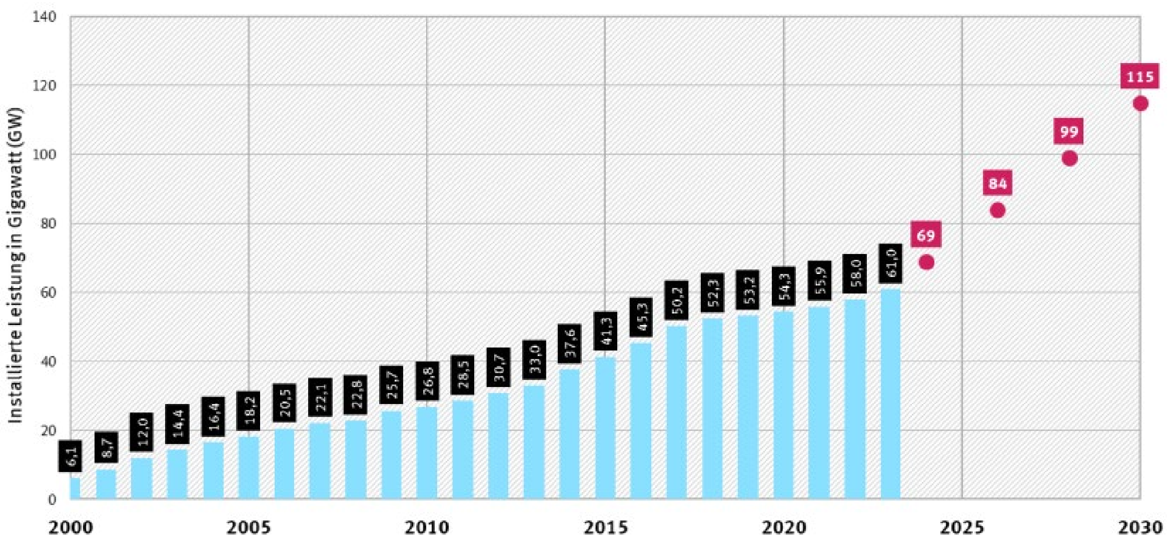
Statistics on on- and offshore wind energy



Statistics on onshore wind energy

Entwicklung der installierten Leistung von Windenergieanlagen an Land in Deutschland

sowie Zubauziele der Bundesregierung nach Erneuerbaren Energien Gesetz (EEG 2023) bis 2030

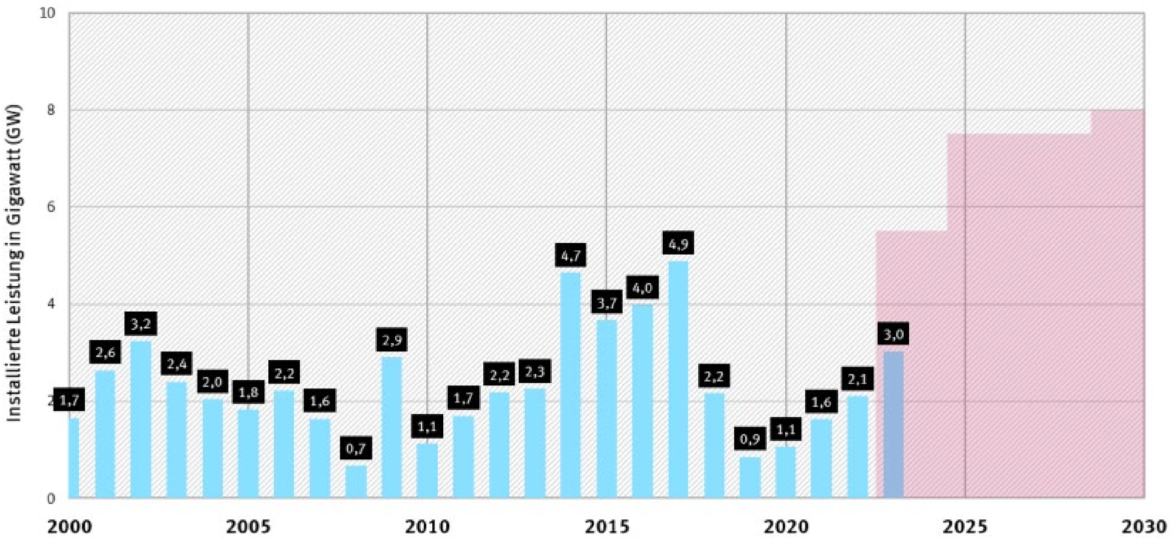


Zielwerte der Jahre 2024 bis 2030 nach EEG 2023.

Quelle: Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Stand: Februar 2024

Entwicklung des Zubaus neuer Windenergieanlagen an Land in Deutschland

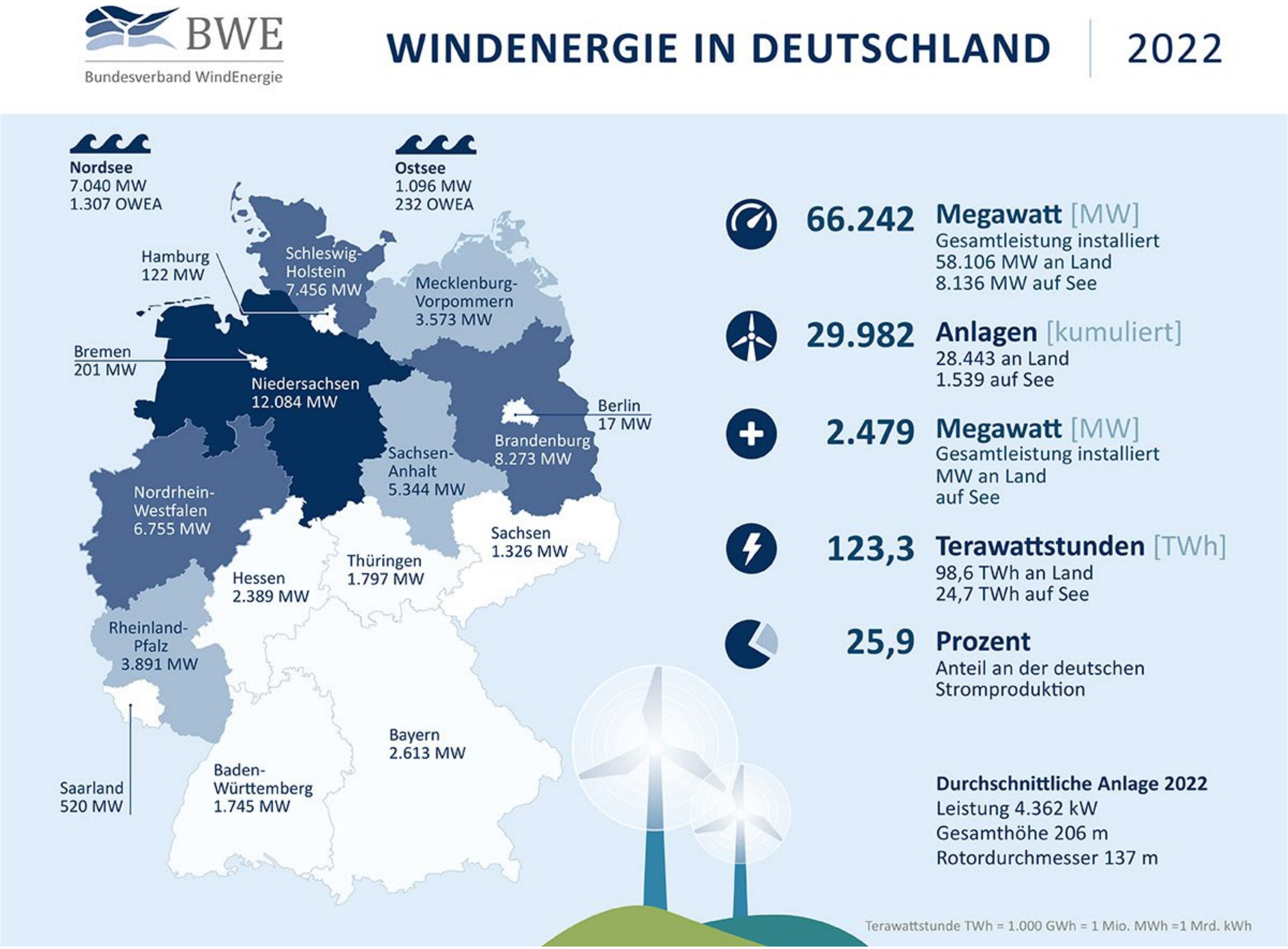
sowie benötigter Zubau nach Erneuerbaren Energien Gesetz (EEG 2023) bis 2030



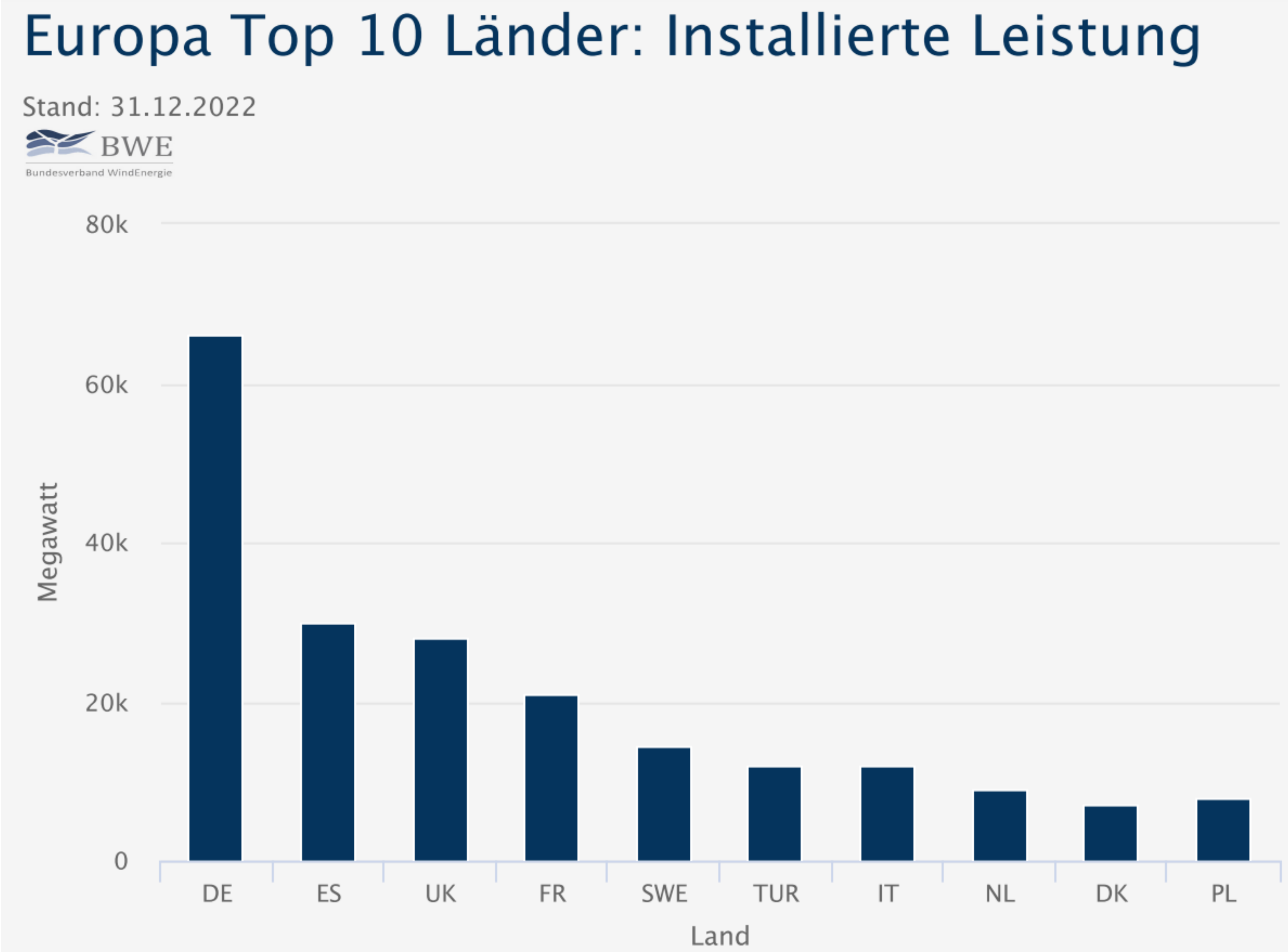
Ab 2023: benötigter Zubau um die Zielwerte der Jahre 2024 bis 2030 nach EEG 2023 zu erreichen.

Quelle: Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Stand: Februar 2024

Current status and future development of onshore wind energy



Current status and future development of onshore wind energy



Legal framework and approval process

Designation of wind energy areas

The *Windenergieflächenbedarfsgesetz* (WindBG) 2023 defines specific goals for the designation of wind developing areas which need to be reached until 2032.

Regional planning act (federal law)

↓

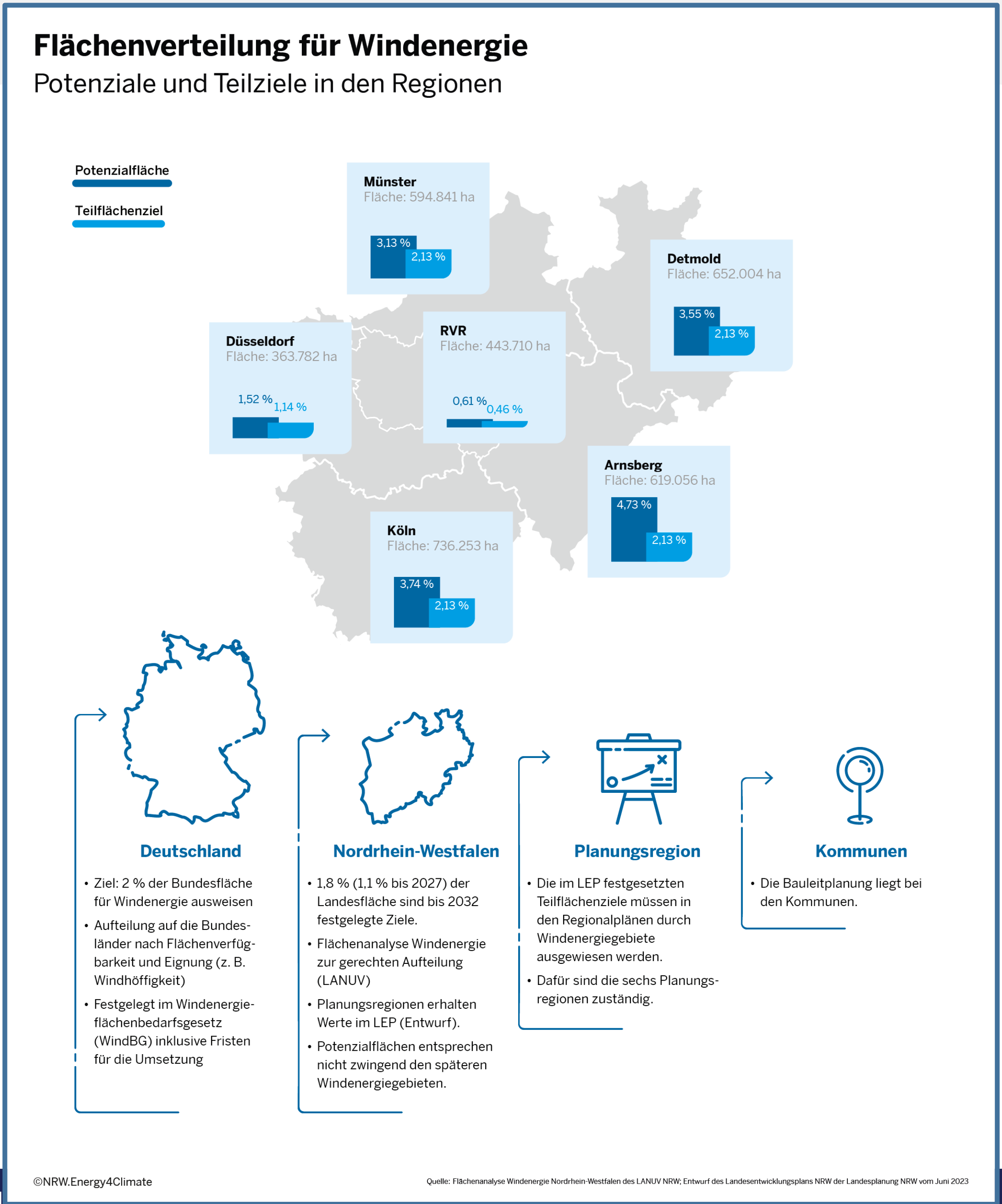
Regional development plan (state level)

↓

Regional plan (level of regional government)

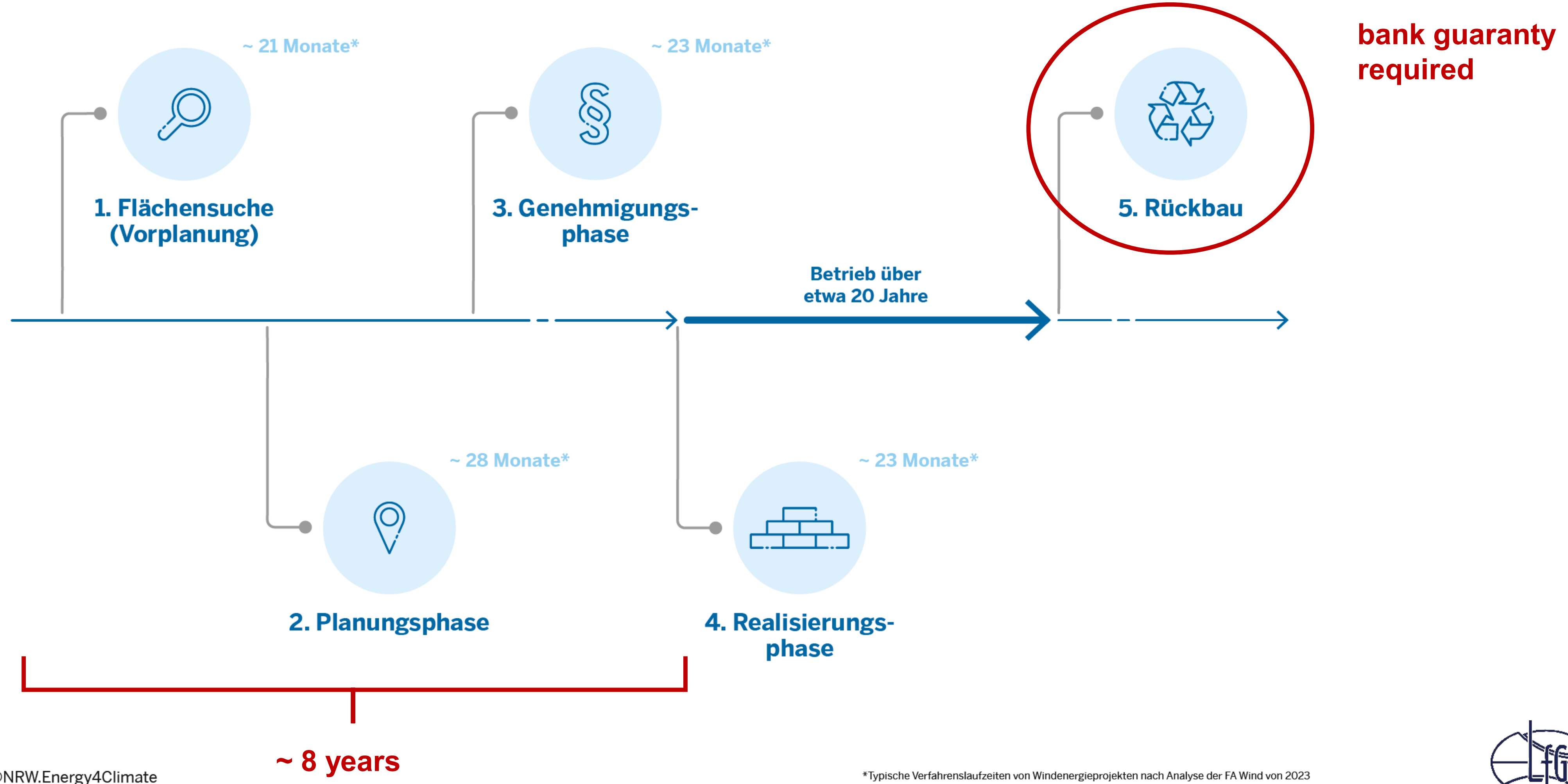
↓

Land use plan (Municipal level) ⟶ federal building code



Legal framework and approval process

Planning procedure and anticipated time frame



©NRW.Energy4Climate

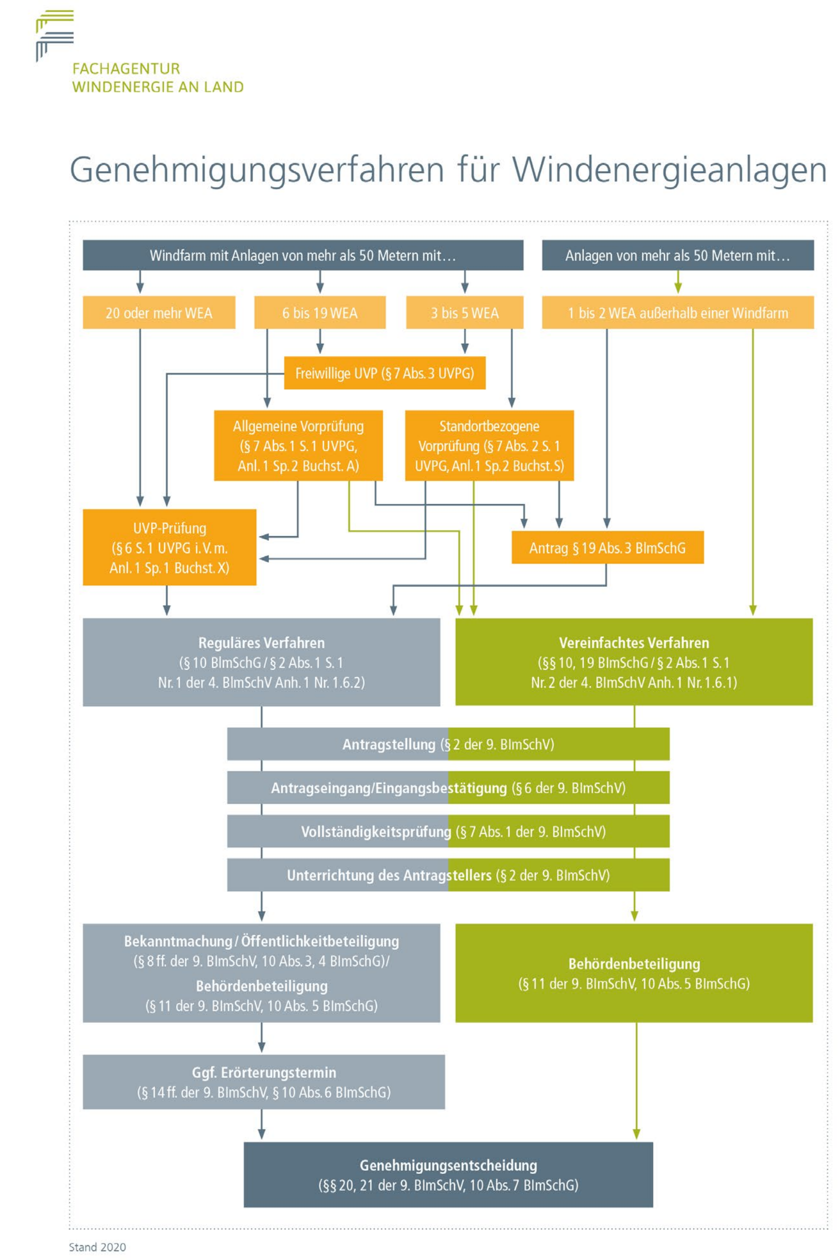
*Typische Verfahrenslaufzeiten von Windenergieprojekten nach Analyse der FA Wind von 2023

Legal framework and approval process

Approval process

- Federal immission control act and federal immission control ordinance → admissibility under immission control law
- Building regulation law → admissibility under building regulations

  - For wind turbines of 50 m hub height and more both approvals are always necessary which are gained in a formal approval process.
  - For wind farms with more than 20 turbines an additional environmental impact assessment is mandatory.
  - For projects with 3 to 20 turbines the approval authority decides if an environmental impact assessment is necessary based on preliminary assessments or decides that it has to be performed in any case.
  - This regular approval procedure is more extensive but offers more legal certainty against lawsuits as it includes a formal public participation process which addresses the relevant stakeholders which is not the case in the simplified procedure.

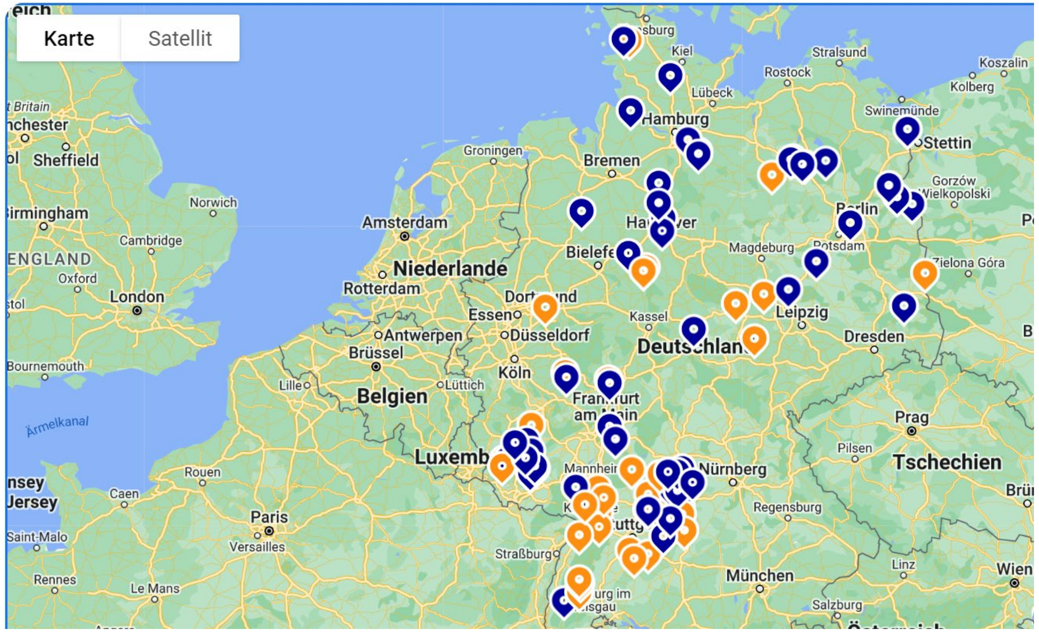


Wind farm Lentföhrden/Weddelbrook, Schleswig Holstein

Developer/Operator: EnBW

- 5 Nordex N 133 turbines
- Hub height 190 m, rotor diameter 133.2 m
- Rated power 4,8 MW

Die Windparks der EnBW im Bau und in der Planung



Wind farm Albringhausen Lower Saxony

Developer/Operator: WestWind Energy

Repowering:

- Dismantling 13 Enron EW 1.5 turbines
- Substitution by 10 Enercon E-160 EP5 E3 turbines with hub height 166 m, rotor diameter 160 m and 5.56 MW rated power
- Construction of new turbines on usually different location within the wind farm according to wind and ground conditions.

Citizen wind farms RothaarWind I and II near Siegen

Concept of public participation

- 5 and 17 Enercon E-138 turbines
- Hub height 110/130 m, rotor diameter 138 m, 4.26 MW rated power
- Operator: RothaarWind GmbH & Co. KG
- Around 90 shareholders, among these the city of Hilchenbach and many private individuals.

General design principles

At the moment competing regulations:

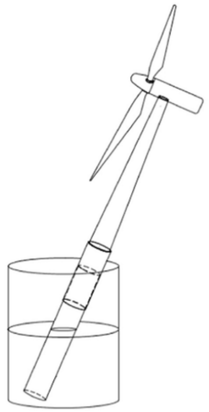
DIN EN IEC 61400 → deals wind turbine structure including foundation as machine components

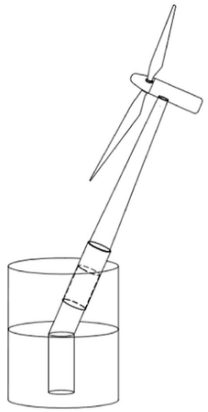
DIN 18088 with DIN EN 1997 → deals wind turbine structure including foundation as a building structure

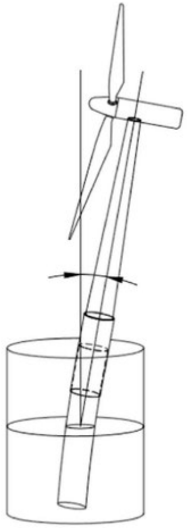
In any case design should follow **limit state design**, i.e. it needs to be verified that none of the following limit states of the structure, which separate permissible from impermissible states, occur:

Ultimate limit state (ULS): Bearing resistance failure, sliding failure, overturning or tilting, structural failure such as a plastic hinge; partial safety factors are introduced on actions and resistances.

Serviceability limit state (SLS): too large settlements or differential settlements, limited range of static and dynamic spring stiffnesses; criteria depend on the specific turbine type.


ULS: Failure through exceeding the foundation's ultimate lateral capacity (soil failure)

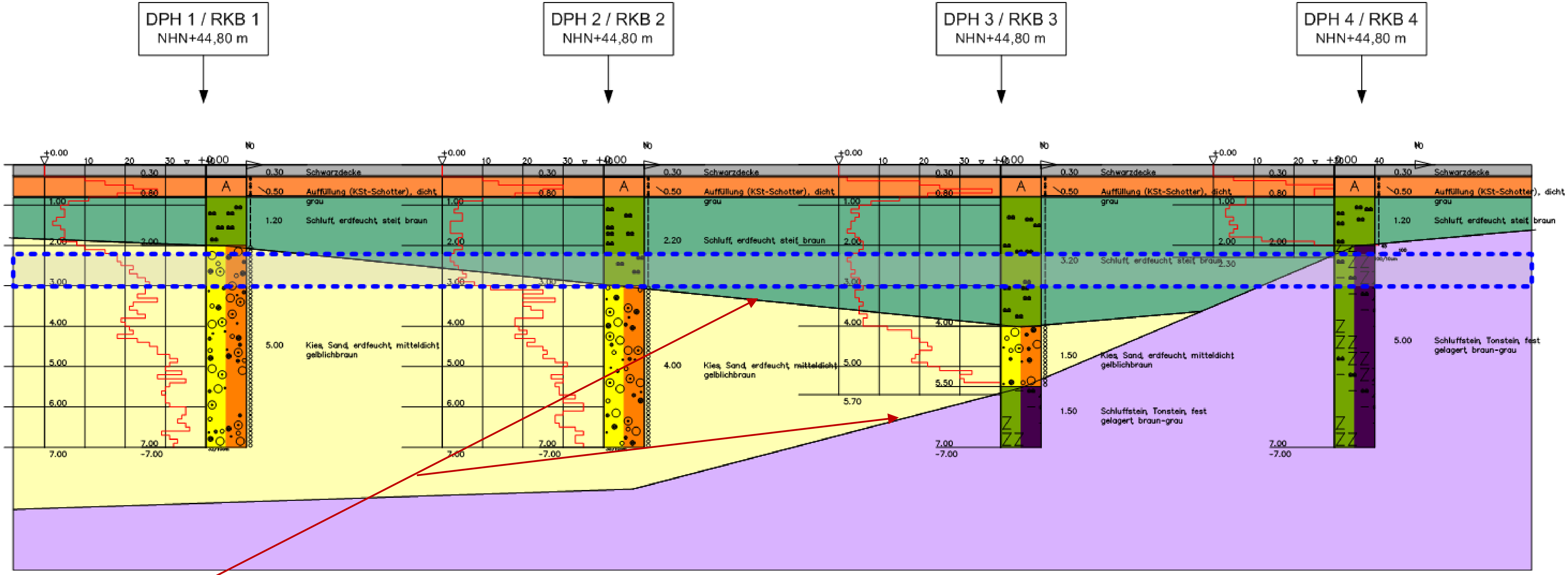

ULS: Failure through plastic hinge of the pile (pile yield failure)


SLS: Tilt angle exceeds allowable value (serviceability failure)

(Arany et al., 2017)

General design principles

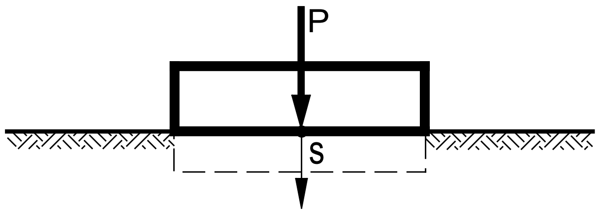
Establishing the ground model from field and laboratory ground investigations:



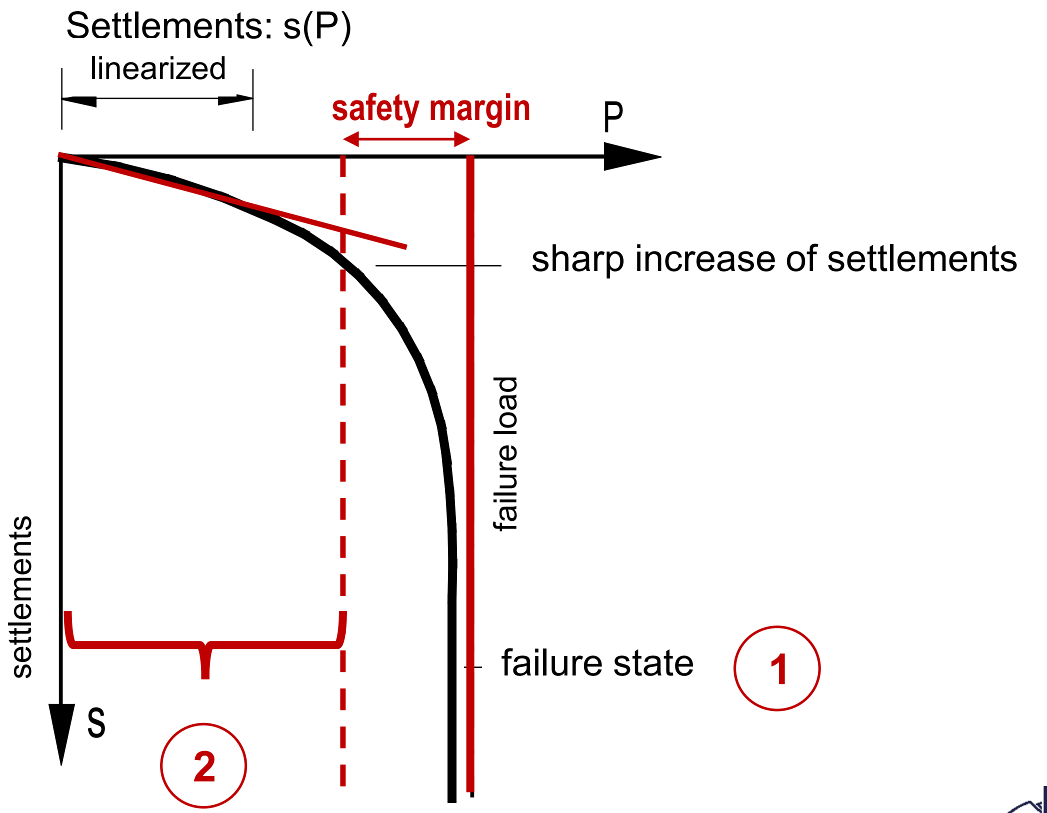
leaves room for interpretation: involved uncertainty

General design principles

Limit State Design - Example: Load test on a footing



Load-deformation curve



2 limit states → 2 design exercises

1 Ultimate Limit State (ULS)

2 Serviceability Limit State (SLS)

Foundation must be designed to withstand all possible limit states (ULS + SLS)!

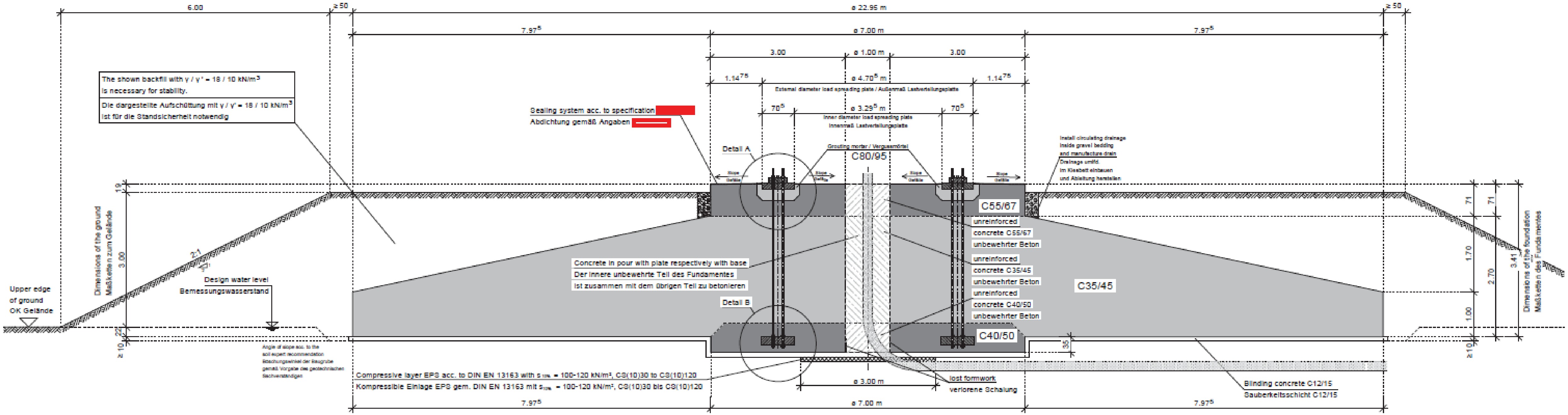
Foundations for onshore wind energy turbines

- Typically type-certified shallow foundations, if necessary together with suitable soil improvement (e.g. by rigid inclusions); more rarely pile foundations.
- Shallow foundation must be fully removed after end of use (besides the turbine with all its components); piles may be left in the ground (cut below ground surface) as removal probably will cause more damage to the environment.

(© FuBau GmbH)

Foundations for onshore wind energy turbines

Typical layout of a shallow foundation for a 6 MW type-certified onshore turbine:



Section A - A
Schnitt A - A

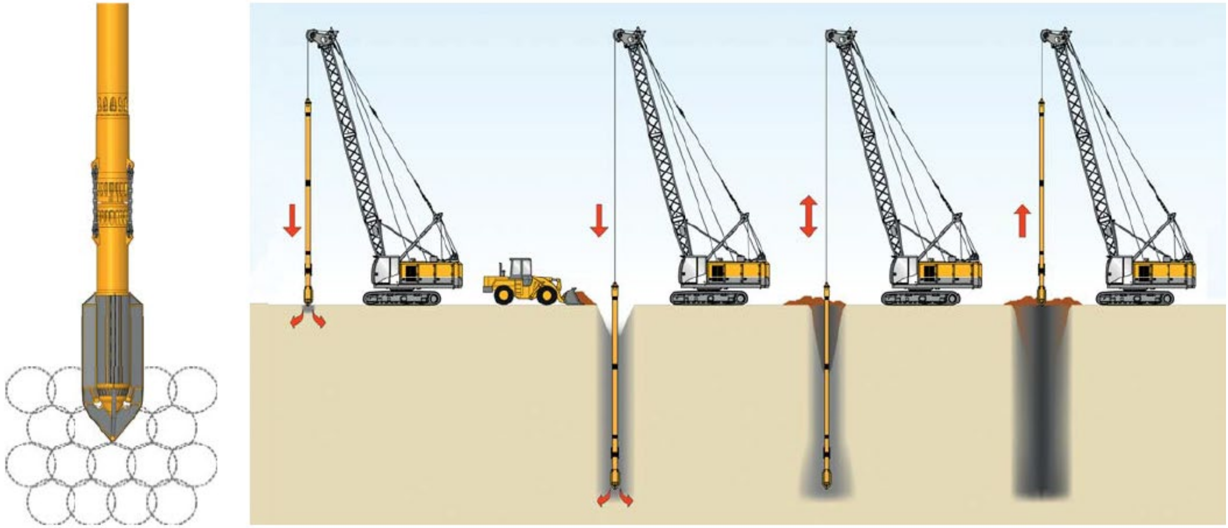
(Source known)

Suitability of the foundation for the respective site conditions must be verified (i.e. verification of the respective ULS / SLS design criteria).

Foundations for onshore wind energy turbines

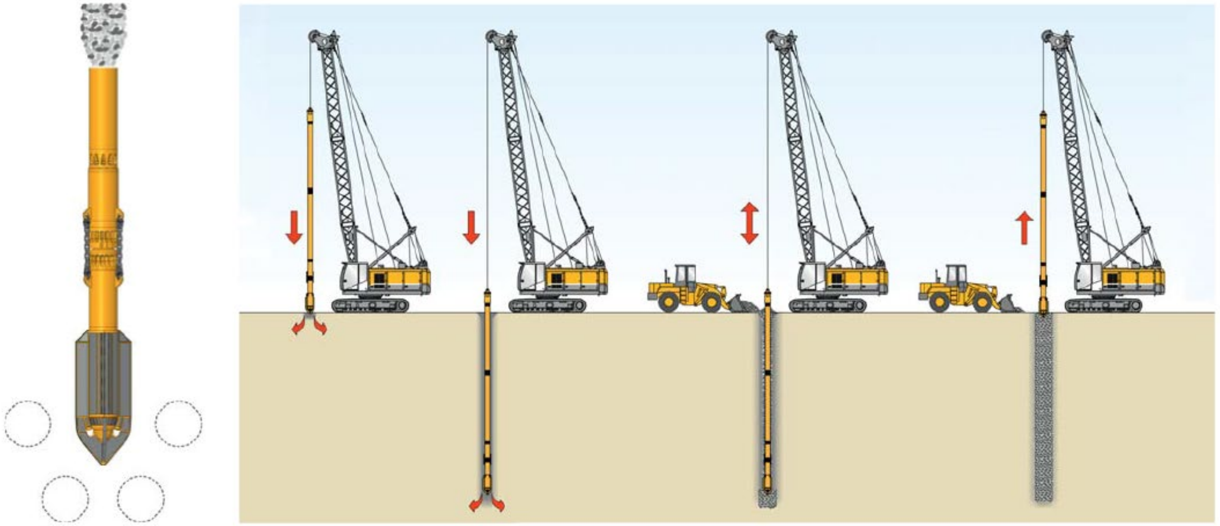
- Ground improvement if ground conditions are not sufficient; two possible options are vibratory compaction or vibration replacement:

Vibratory compaction



Arbeitsablauf Rütteldruckverdichtung RDV

Vibration replacement

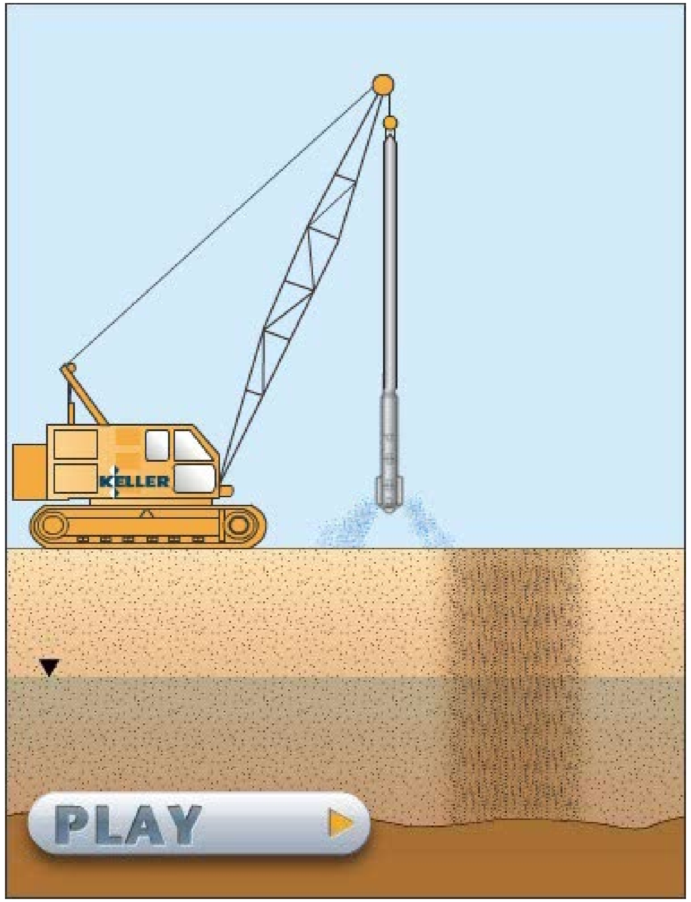


Herstellen Schottersäule (Rüttelstopfverdichtung – Top Feed)

(© Bauer Spezialtiefbau)

Foundations for onshore wind energy turbines

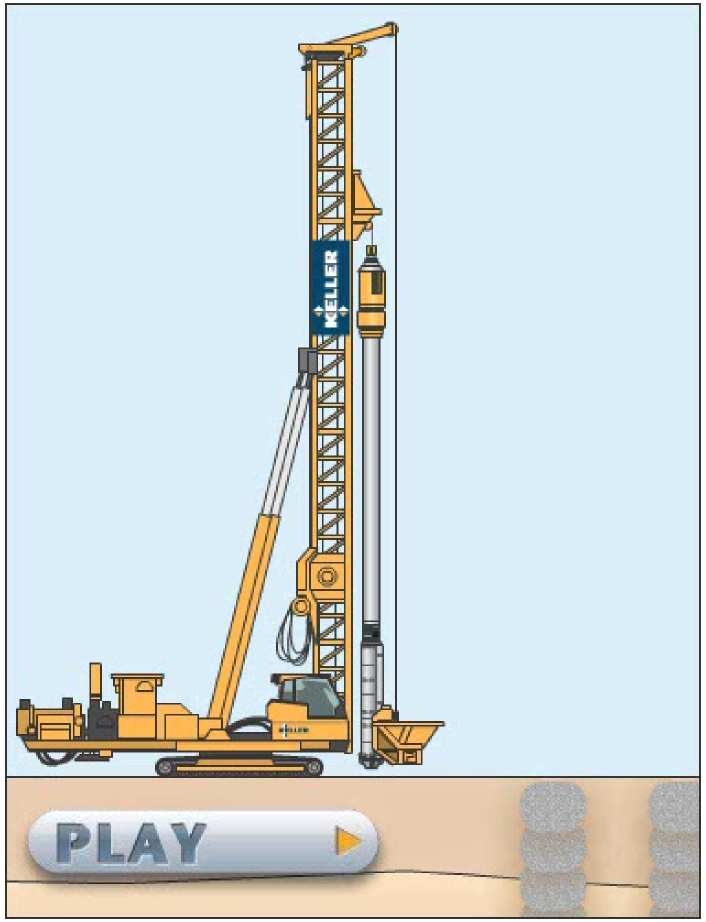
- Vibratory compaction:



(© Keller Grundbau)

Foundations for onshore wind energy turbines

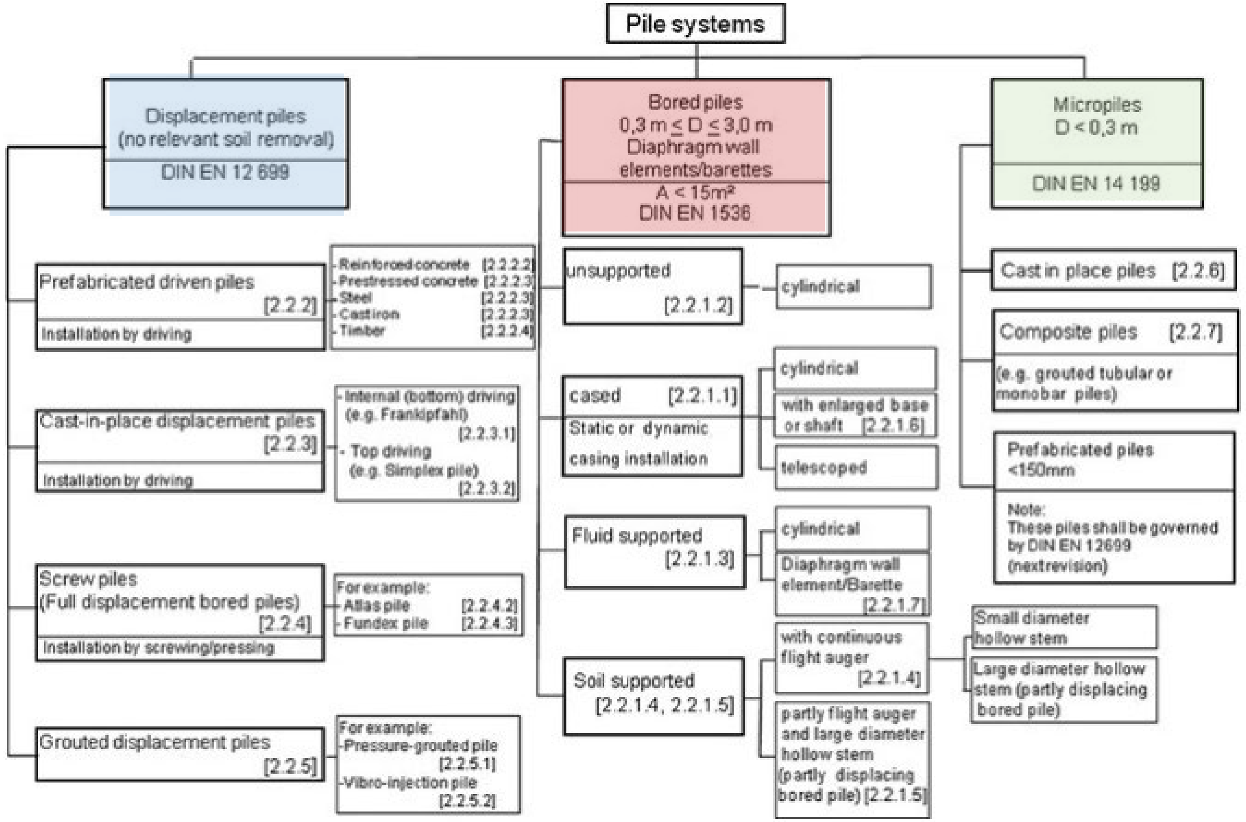
- Vibration replacement:



(© Keller Grundbau)

Foundations for onshore wind energy turbines

- If ground conditions are not sufficient pile foundations are required.
- Bearing behaviour strongly depends on pile material and type of installation:



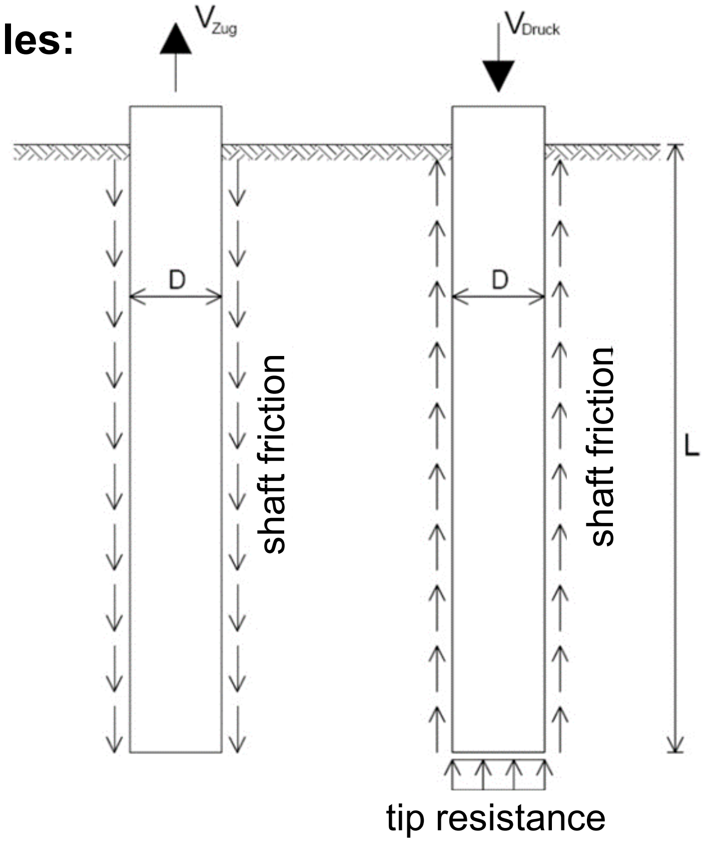
(from the German Recommendations on Piling, 2012)

Design criteria:

- Ground conditions (esp. shear strength)
- Groundwater conditions
- Type and magnitude of loading
- Neighboring structures
- Space limits
- Sensitivity of structure against settlements
- Economic efficiency
- Environmental impact

Foundations for onshore wind energy turbines

Axially loaded piles:



Compression pile (right):
Compression loading; load transfer via pile tip resistance and shaft friction.

Tension pile (left):
Tension loading, load transfer via shaft friction only.

Design parameters: Pile length for a selected diameter

Moderate lateral loading is accomodated by a pile group with one or more inclined piles!

Foundations for onshore wind energy turbines

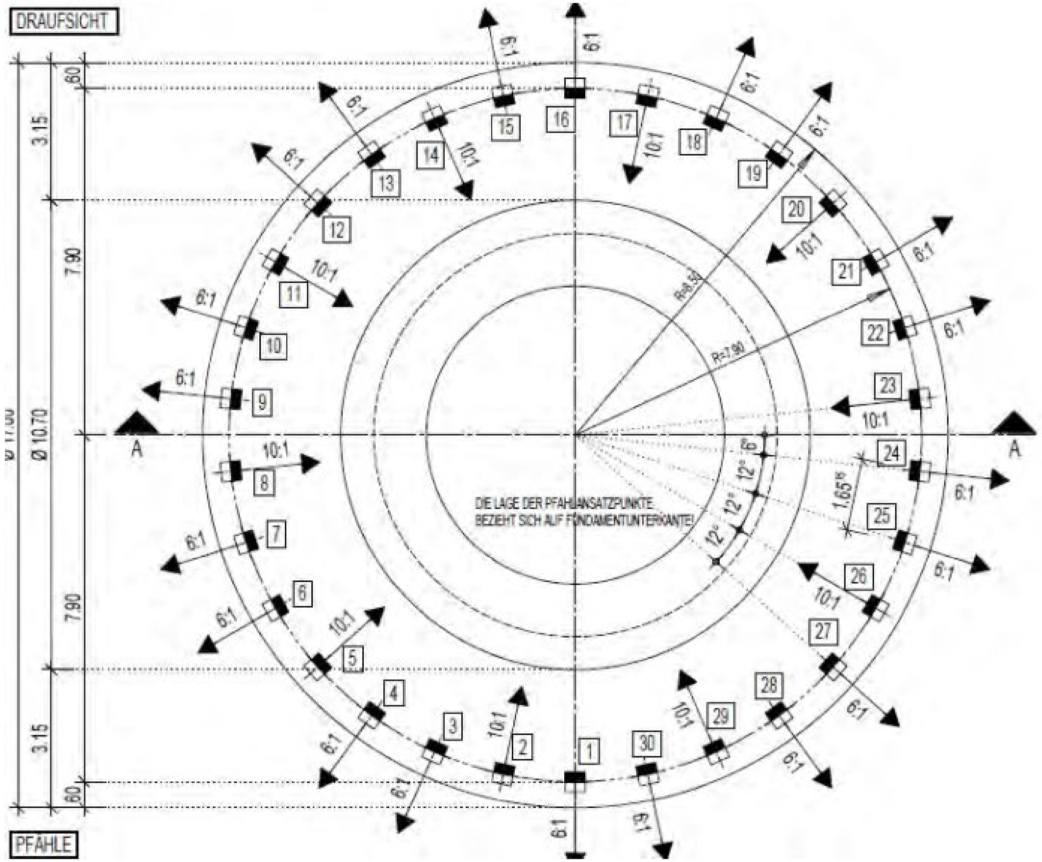
Example: Use of prefabricated driven piles (Centrum Pfähle)

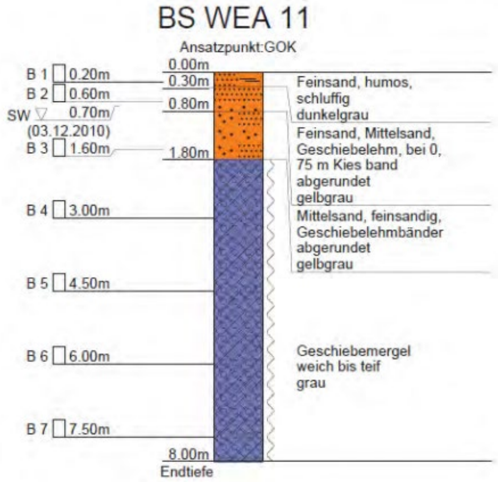
(© K. Lesny)

(© Centrum Pfähle)

Foundations for onshore wind energy turbines

Example: Wind farm Wohnste – pile layout and design parameters





BAUGRUND

SCHICHTENFOLGE: FOLGENDE SCHICHTENFOLGE UND STEIFEMODULE WURDEN FÜR DIE STATISCHEN BERECHNUNGEN ANGESETZT:

von [m OKG]	bis [m OKG]	Schicht [-]	$E_{s, stat.}$ [MN/m²]	$E_{s, dyn.}$ [MN/m²]
0.00	-4,00	keine Bettung	0,00	0,00
-4.00	-8,00	Geschiebemergel - weich / steif	15,00	100,00
-8,00	Pfahlfuß	Geschiebemergel - halbfest / fest	25,00	150,00

GRUNDWASSER: MAXIMALER GRUNDWASSERSTAND IST AN GELÄNDEOBERKANTE.
EXPOSITIONSKLASSE: XC4

PFAHLGRÜNDUNG

STANDORT	ANZAHL PFÄHLE [-]	PFAHL QUERSCHNITT [cm x cm]	PFAHL BEWEHRUNG OBERPFAHL (UNTERPFAHL)	PFAHLFUßTIEFE LOTRECHT [m OKG]	UKF [m OKG]	KAPP-LÄNGE [m]	OK-PFAHL [m OKG]	PFAHL-NEIGUNG	ERF. LÄNGE [m]	GEW. LÄNGE [m]
WEA 19 (PSP 022)	20	45 x 45	TYP 20 (16)	-28,0	-3.00	1.00	-2.00	6 : 1	26,36	27
	10							10 : 1	26,13	26

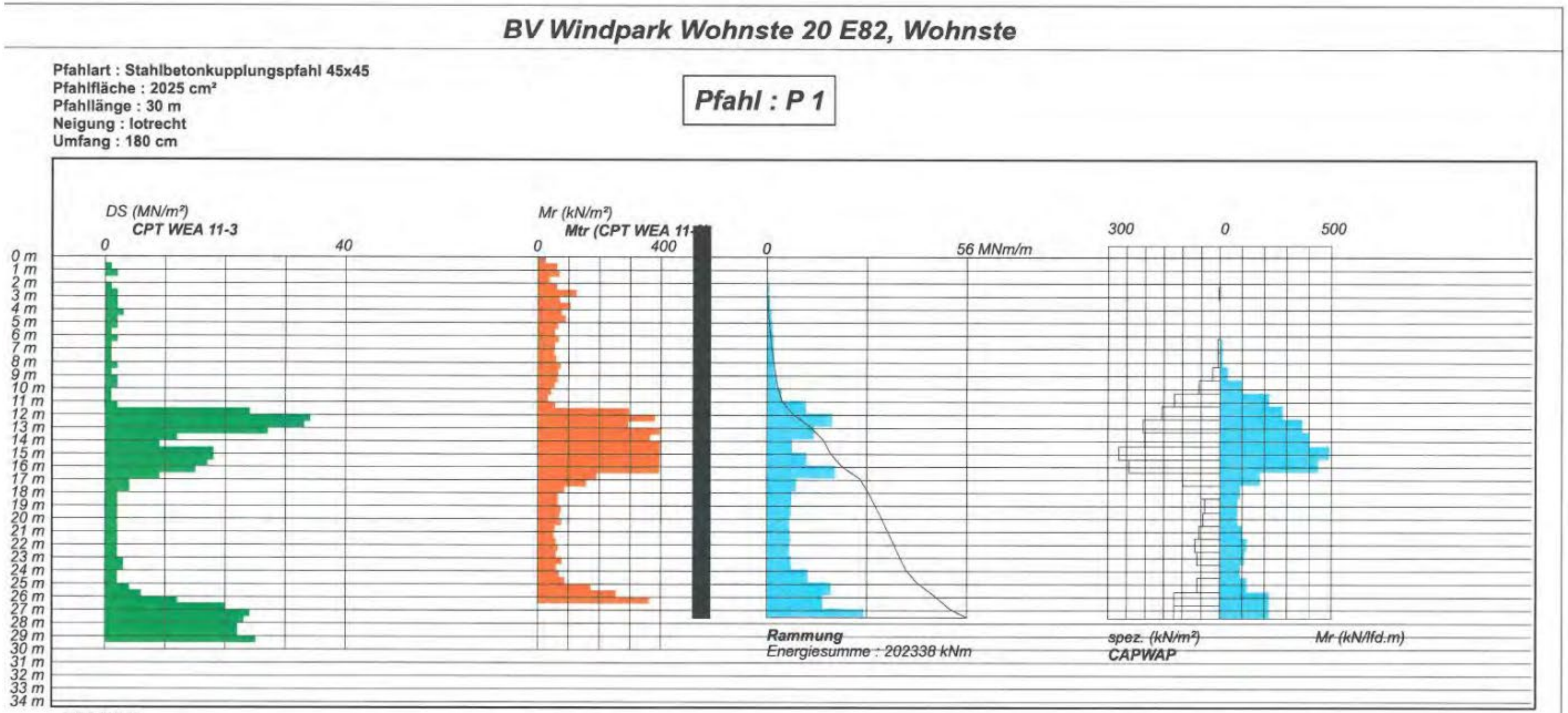
PFAHLLASTEN IM EXTREMLASTFALL

	CHARAKTERISTISCH (γ = 1.0-FACH)	BEMESSUNGSWERT (γ-FACH)	
DRUCK	1584	2027	kN
ZUG	132	359	kN

adopted from:
Wardinghus, P. (2014): Tiefgründung von Windenergieanlagen mittels Pfähle, 5. Fachveranstaltung Baugrunderkundung, Baugrundverbesserung und Gründungen für Windenergieanlagen (Onshore), Haus der Technik, Essen 20.11.2014

Foundations for onshore wind energy turbines

Example: Wind farm Wohnste – pile-driving protocol



MESSUNG

Datum	Fallhöhe	Bär	W (theor.)	Setz./Schlag	Standzeit	W (eingel.)	Case (0,3)	Case (0,4)	CAP (gesamt)	CAP (Mantel)	CAP (Fuß)
25.08.2011	0,95 m	9 t	86 kNm	<< 1 mm	9 T.	35 kNm	4950 kN	4750 kN	4750 kN	3770 kN	980 kN

adopted from:
Wardinghus, P. (2014): Tiefgründung von Windenergieanlagen mittels Pfähle, 5. Fachveranstaltung Baugrunderkundung, Baugrundverbesserung und Gründungen für Windenergieanlagen (Onshore), Haus der Technik, Essen 20.11.2014

Foundations for onshore wind energy turbines

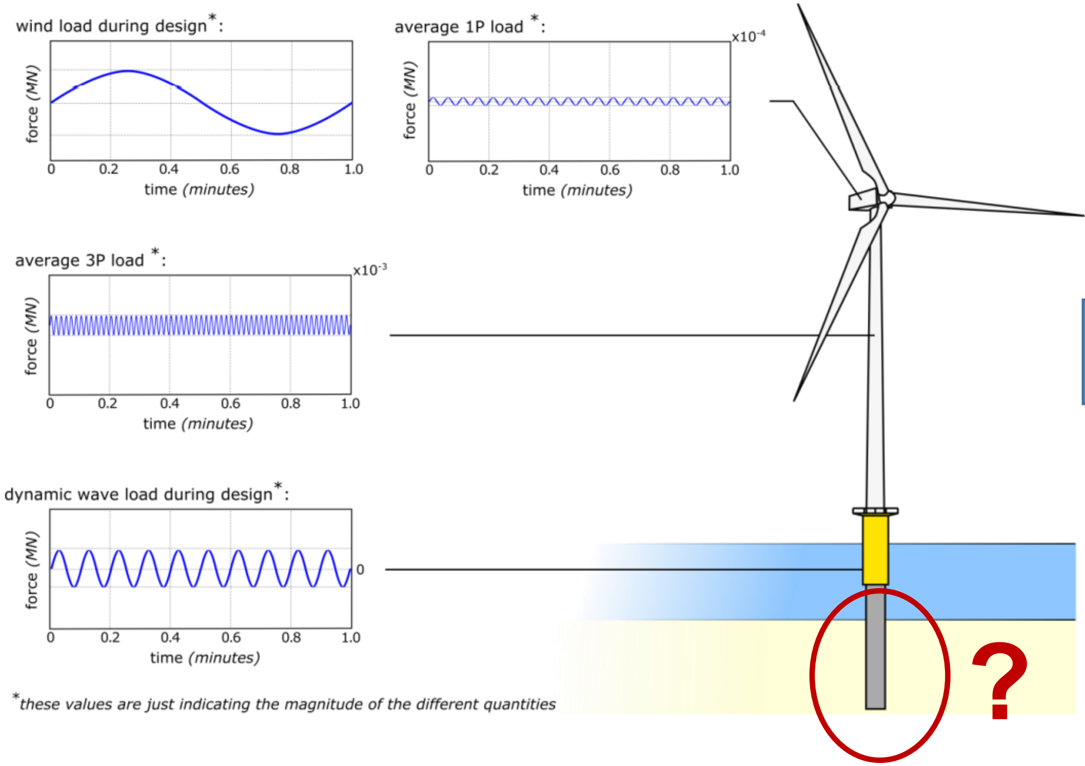
Example: Wind farm Wohnste – construction phase

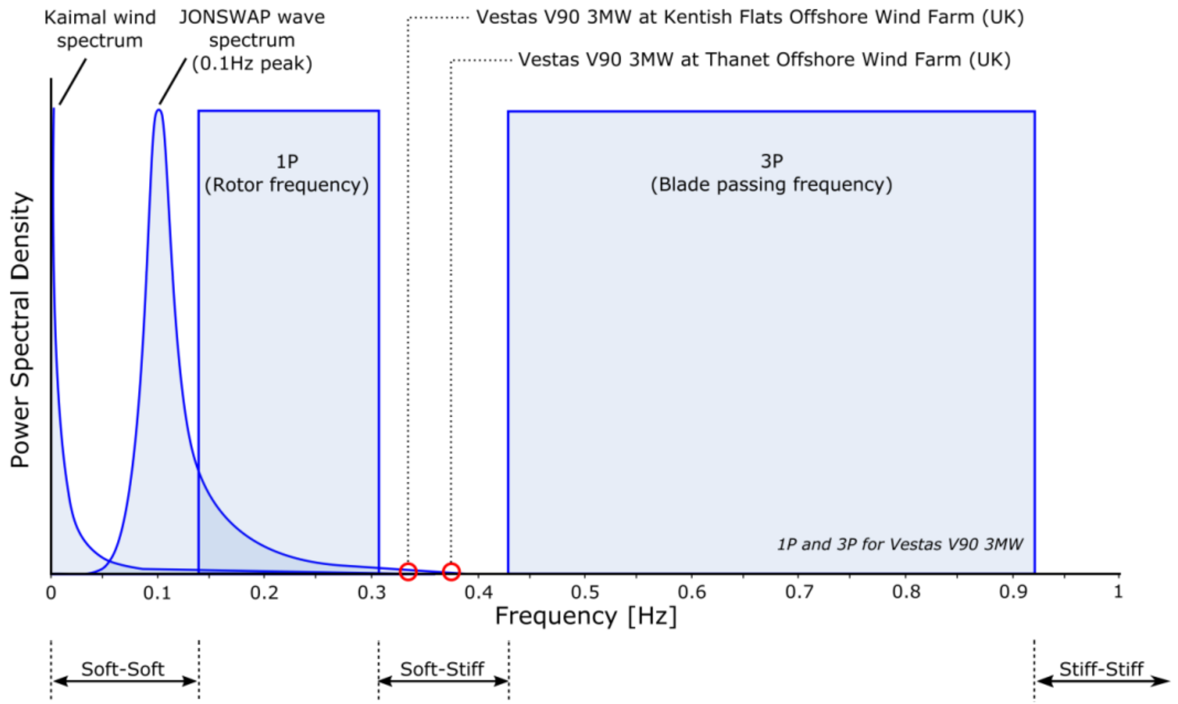



adopted from:
Wardinghus, P. (2014): Tiefgründung von Windenergieanlagen mittels Pfähle, 5. Fachveranstaltung Baugrunderkundung, Baugrundverbesserung und Gründungen für Windenergieanlagen (Onshore), Haus der Technik, Essen 20.11.2014

Soil-Structure-Interaction (SSI) and it‘s effects on structural turbine dynamics

- Research project MakroWind, funded by progres.research NRW at USi, PhD candidate Kachallah A. Kau
- **Problem statement:**





(Bhattacharya et al. (2017): Soil-Structure Interactions (SSI) for Offshore Wind Turbines, to appear in: IET (The Institution of Engineering and Technology) Engineering & Technology Reference [http://digital-library.theiet.org])

Soil-Structure-Interaction (SSI) and it's effects on structural turbine dynamics

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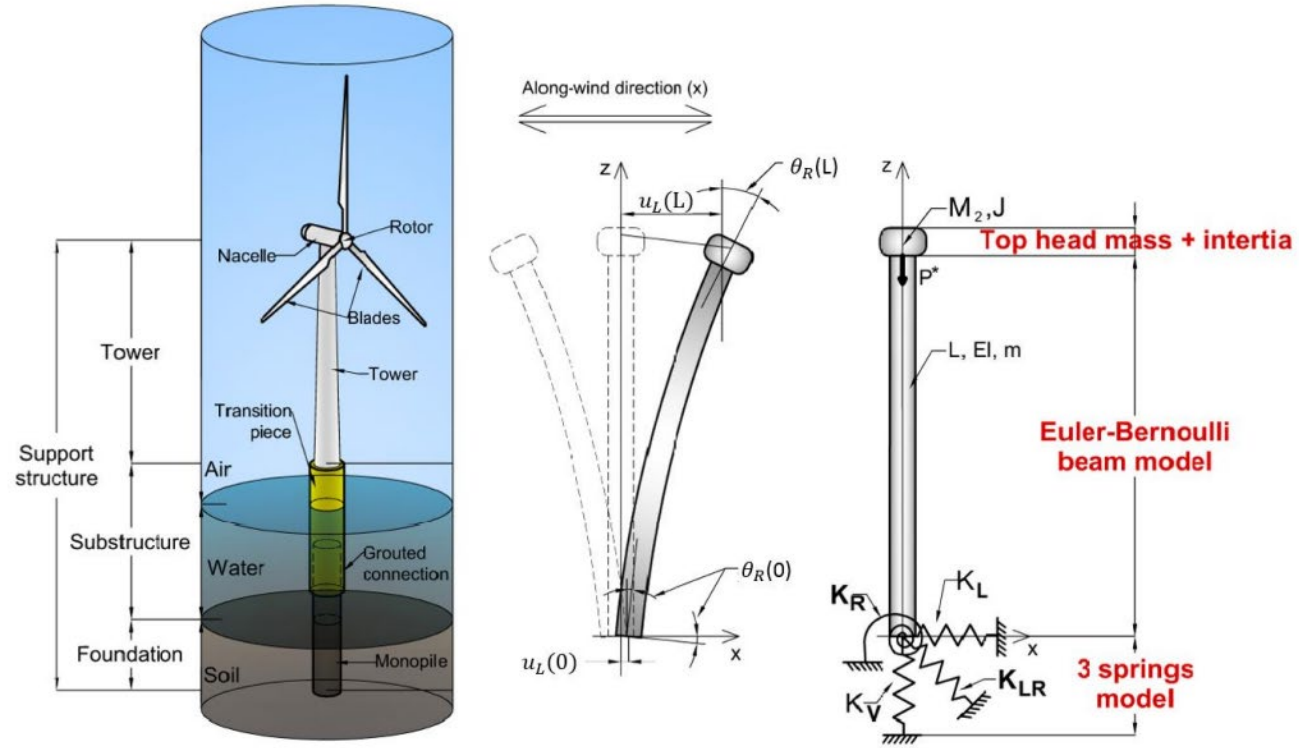
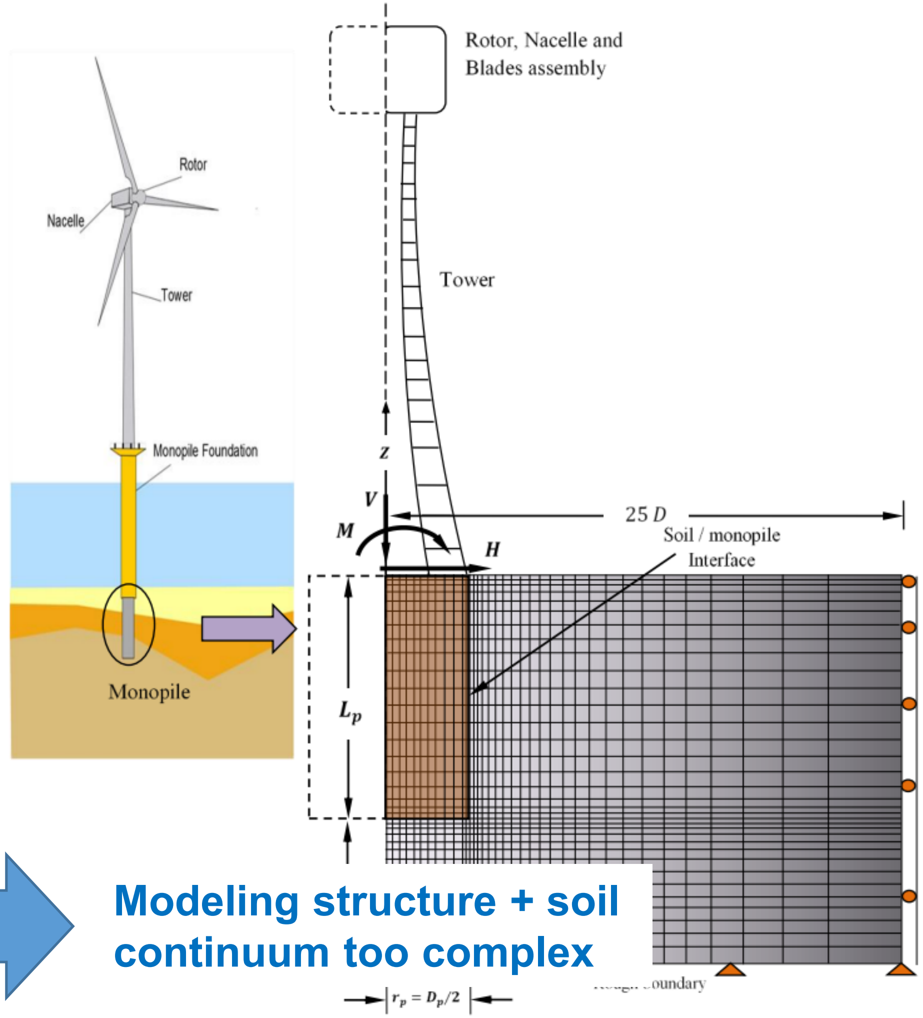
- **Possible solutions:**



(Bhattacharya et al., 2017)

Linear, independent springs too simplified



Modeling structure + soil continuum too complex

Soil-Structure-Interaction (SSI) and it‘s effects on structural turbine dynamics

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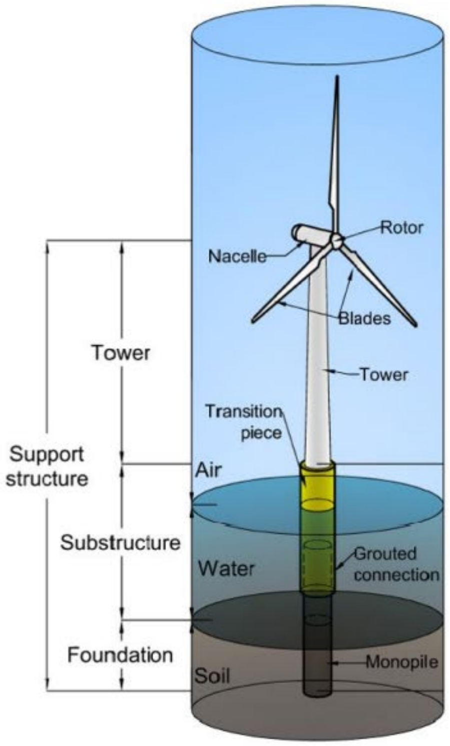
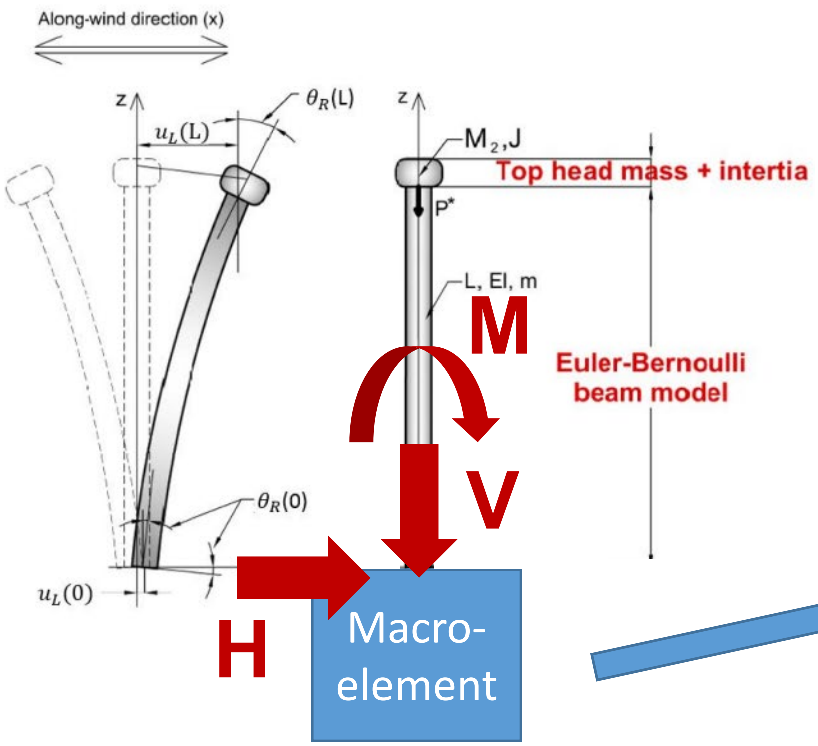
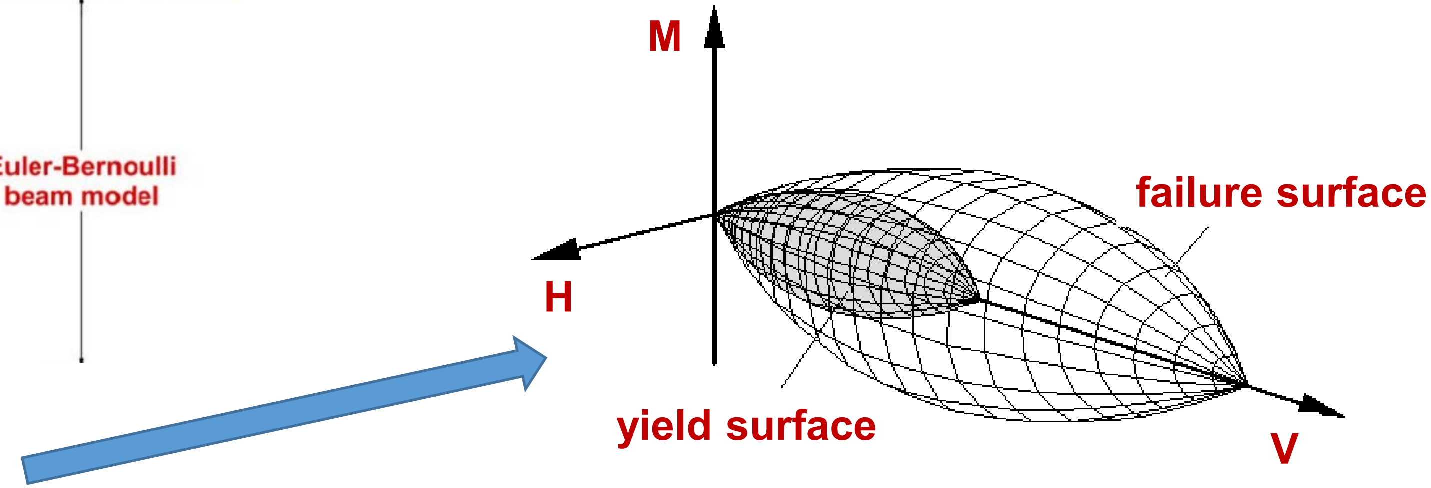
- **Alternative:**



(Bhattacharya et al., 2017)



Substitution of soil continuum by single (macro) element relating forces V, H and moment M with displacements u_i and rotation ω of the foundation.



Soil-Structure-Interaction (SSI) and it‘s effects on structural turbine dynamics

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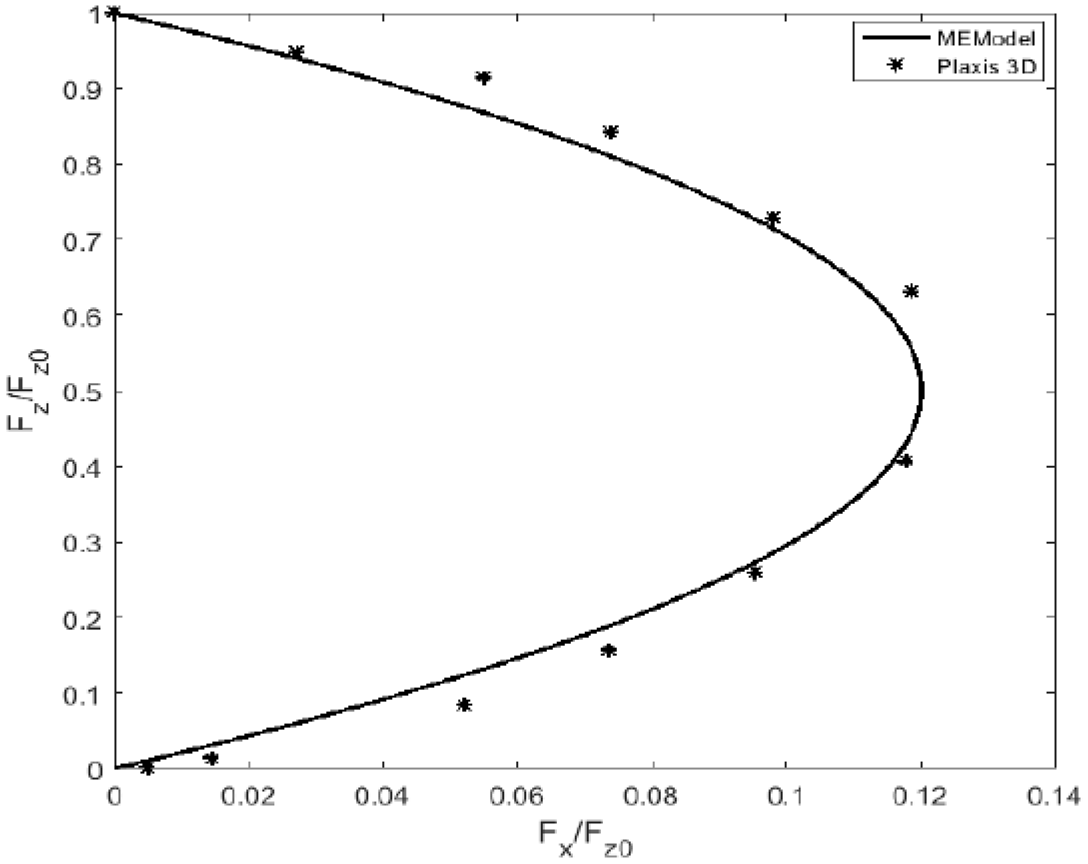
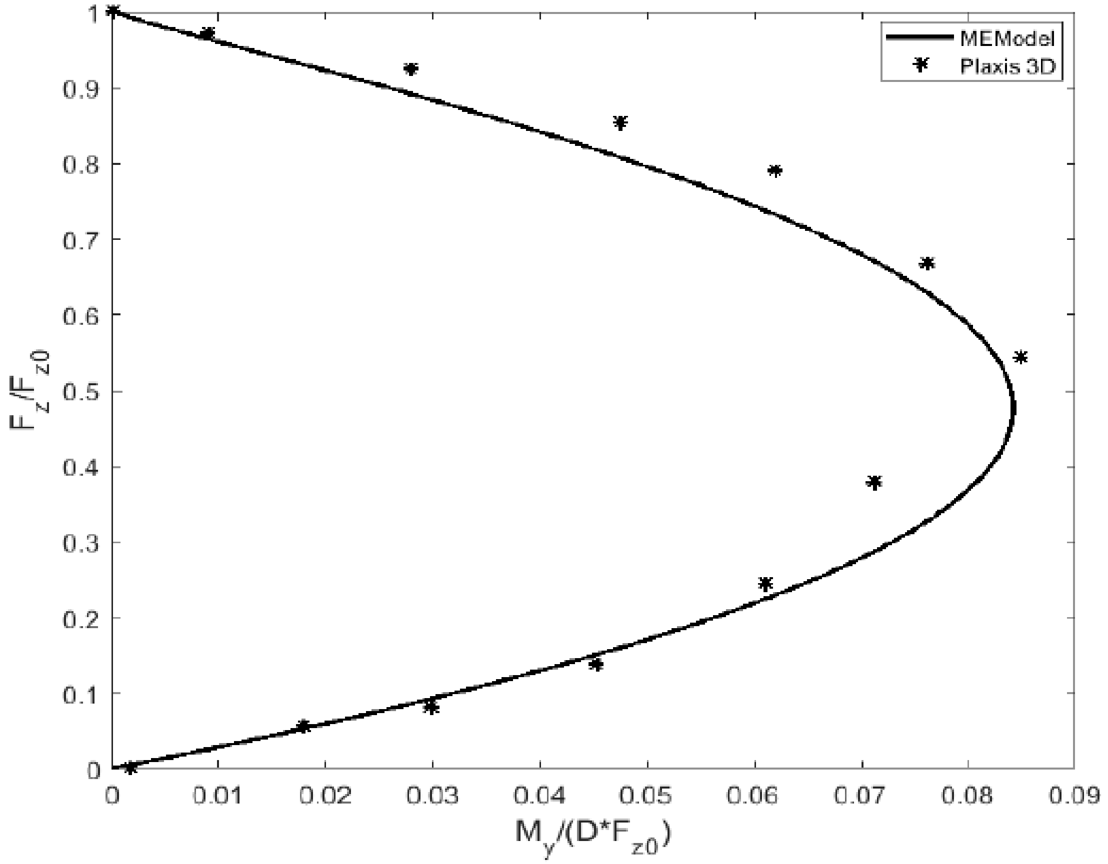
- **Some results:**





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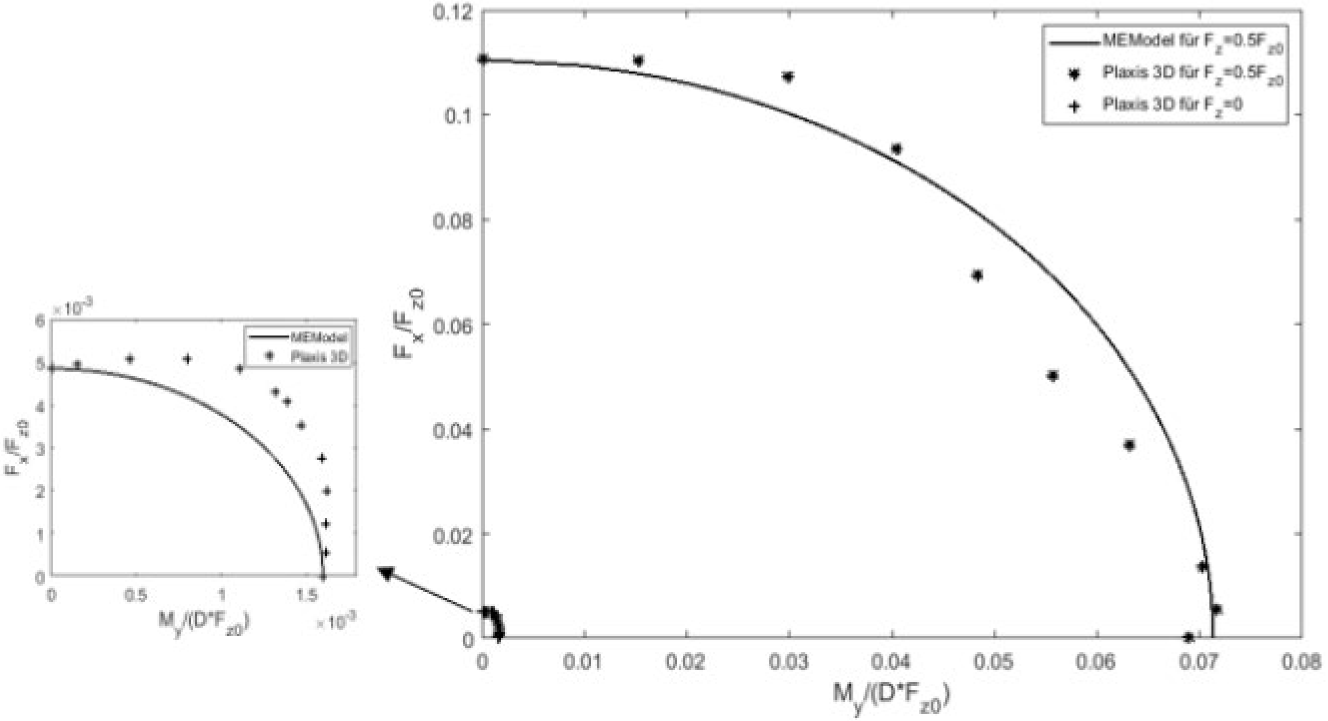

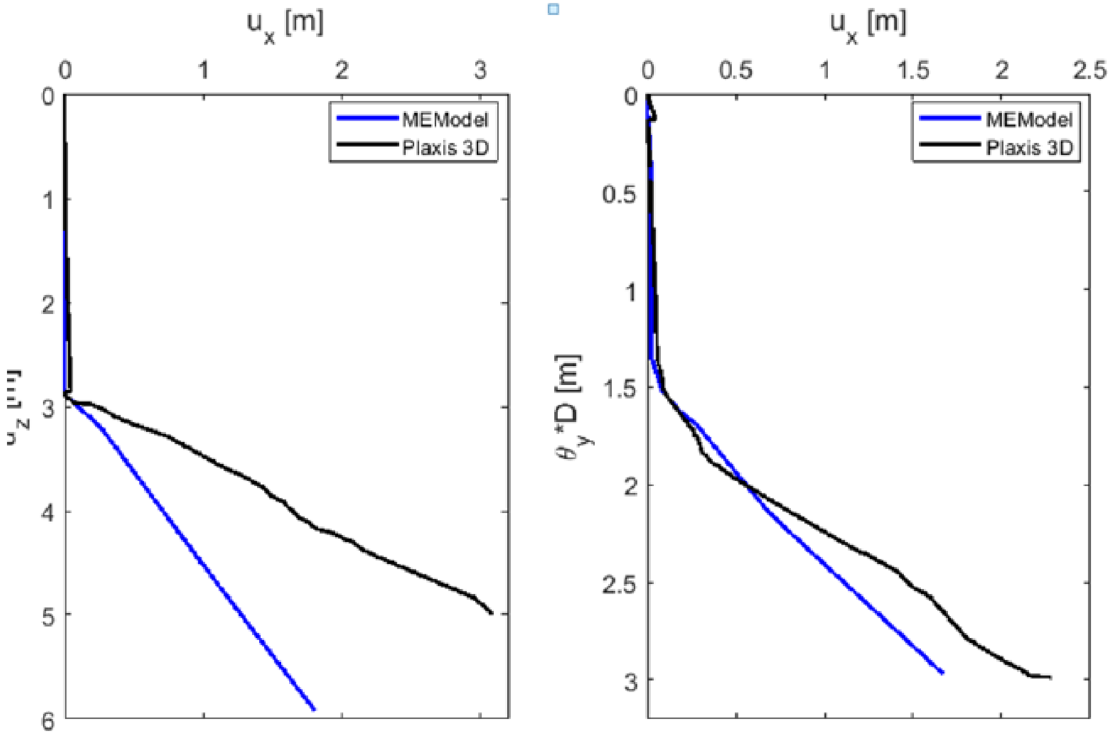

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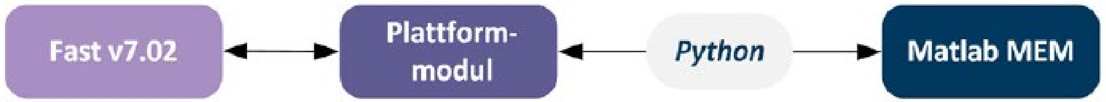
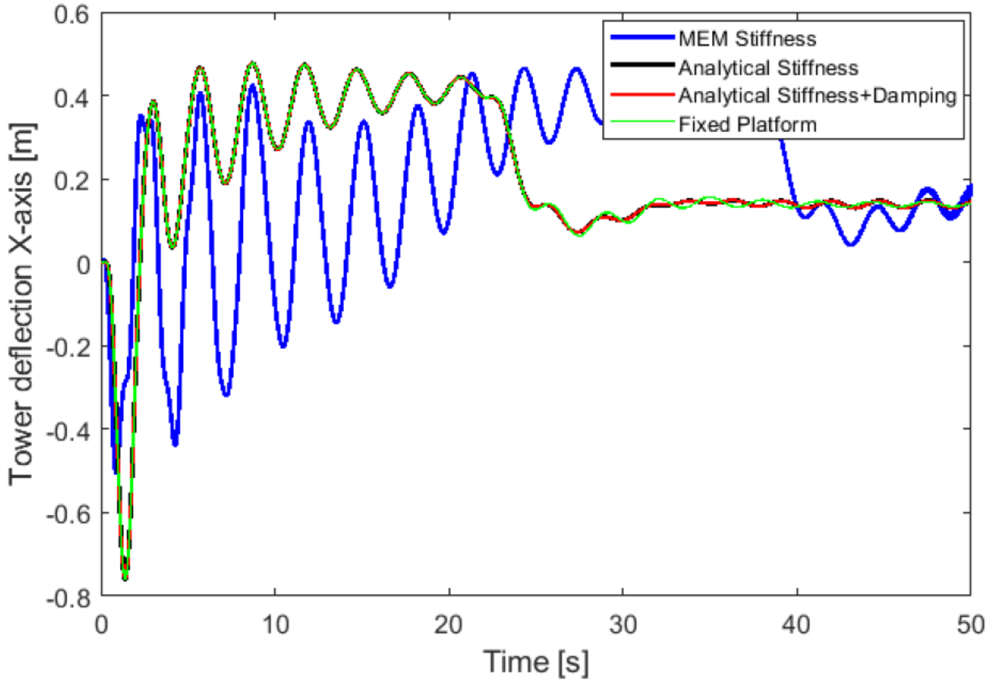
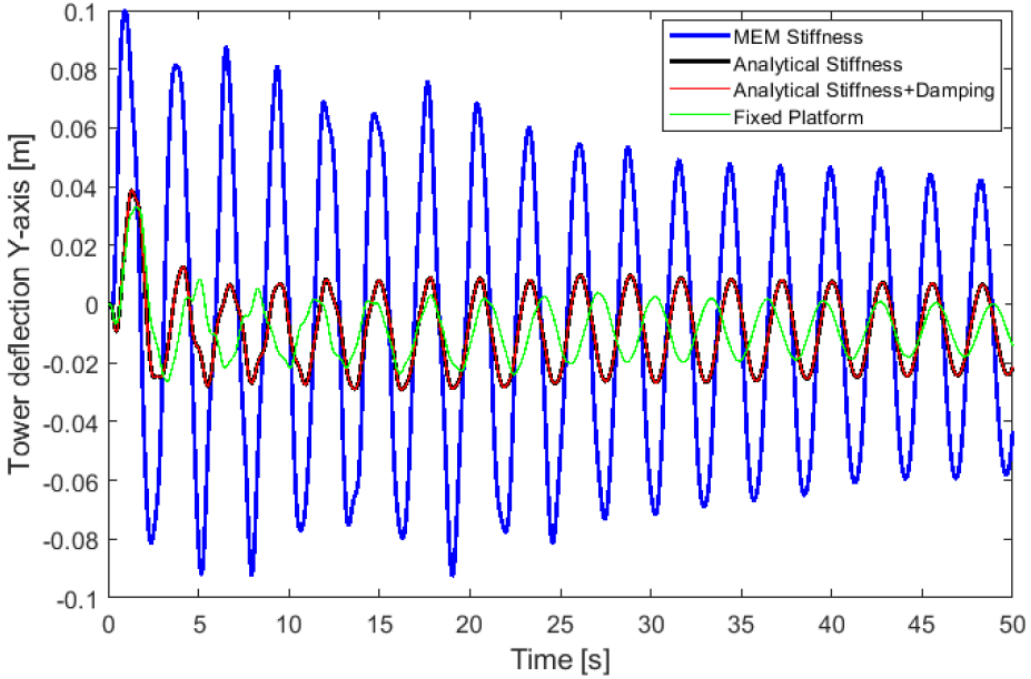
- Research project MakroWind, funded by progres.research NRW at USi, PhD candidate Kachallah A. Kau
- **Some results:**



$$\underline{K}^* = \underline{K}^{-1} = \begin{bmatrix} 7{,}2203 \cdot 10^{14} & -1{,}6628 \cdot 10^{16} & -4{,}2540 \cdot 10^{15} \\ -7{,}3420 \cdot 10^{14} & 1{,}1749 \cdot 10^{16} & 5{,}2454 \cdot 10^{15} \\ -1{,}5205 \cdot 10^{15} & 4{,}4806 \cdot 10^{16} & 7{,}2137 \cdot 10^{15} \end{bmatrix}$$





Conclusions

- Germany plans further expansion of onshore wind energy as a major contributor to reach the goals of climate neutrality.
- For that, wind energy developing areas are currently established in regional development plans on state level to reach these goals.
- As a consequence, onshore wind turbines are now allowed in closer distance to buildings and may probably developed in areas which where formerly less attractive e.g. in hilly or forest areas which suffer from calamities from the past years.
- Onshore wind turbines are usually founded on type-certified shallow foundations maybe in combination with ground improvement measures if ground conditions are not suitable.
- The applicability of the type-certified foundation for certain site conditions must be verified in the design.
- As onshore wind turbines become continuously larger and, with that, also the dynamic turbine loading, the soil-structure interaction (SSI) plays an important role for a reliable performance of the turbine over its anticipated lifetime of 20 years.
- This requires innovative solutions to consider SSI in dynamic analyses. For this, macroelement models may be a suitable alternative.

Thank your very much for your attention! Questions?

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