Improving wind market value with advanced wind turbines

Preliminary results from the IEA project "System-friendly wind & solar power"

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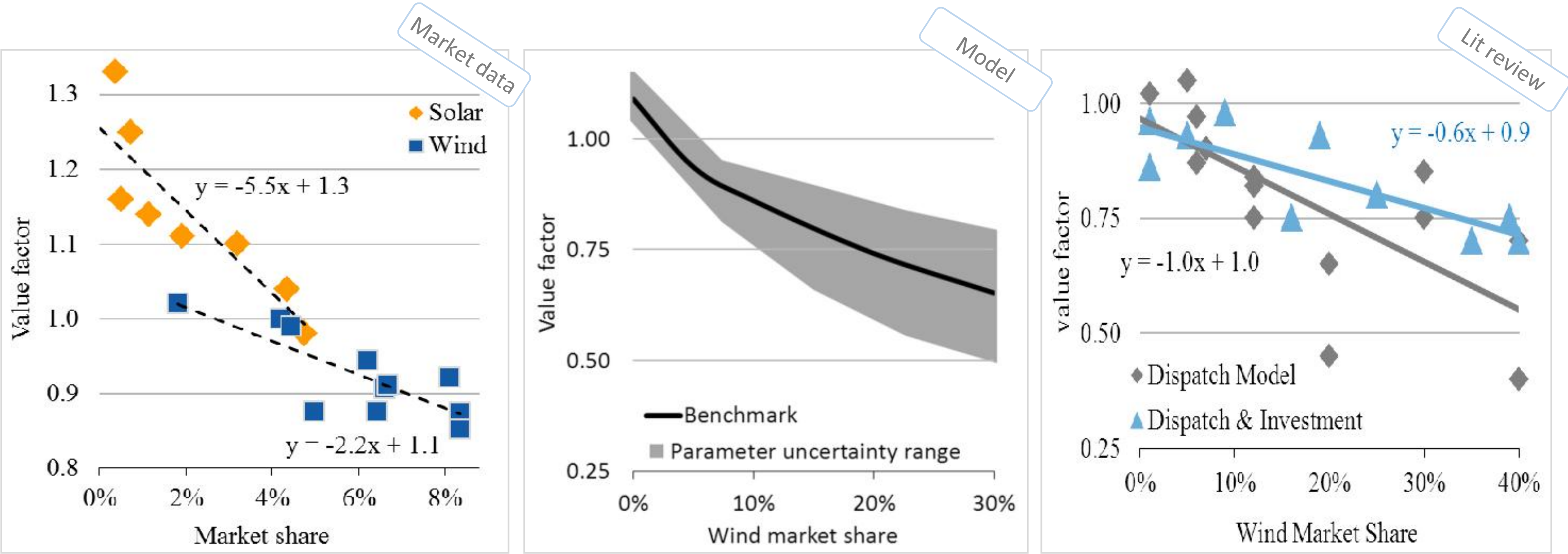
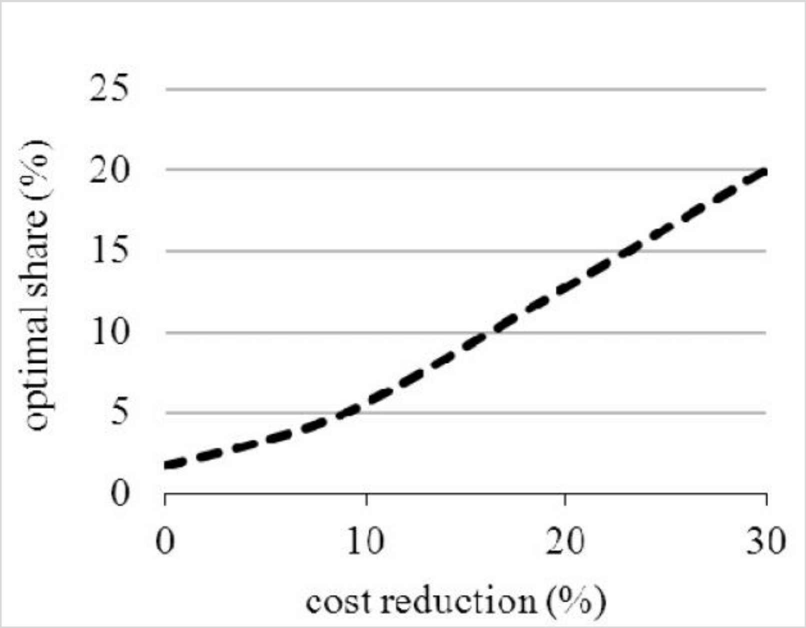
Wind & solar market value drops with penetration

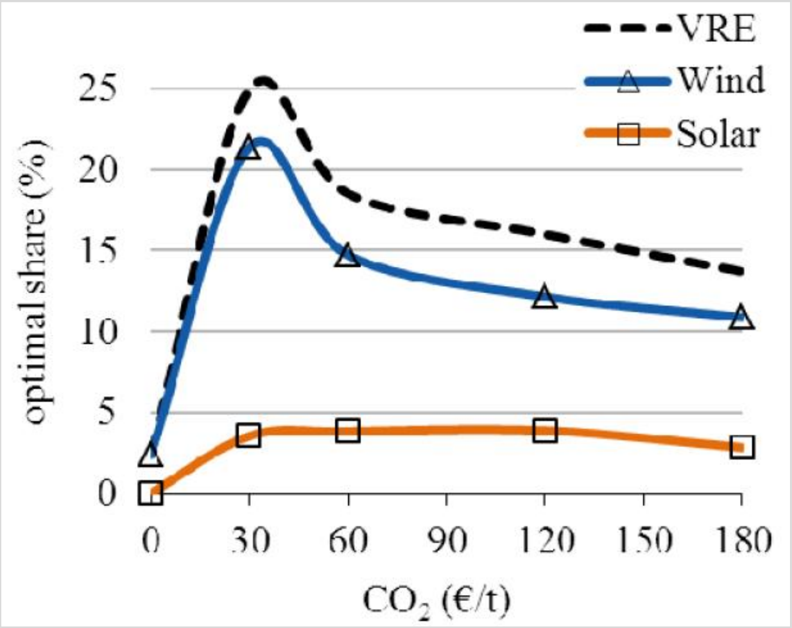


Source: updated from Hirth (2013)

The market value (€/MWh) of wind and solar power drops with increased penetration. Here the market value is expressed relative to the base price as “value factor”.

Hence, wind & solar deployment remains limited





Source: Hirth (2015)

Because of the value drop, deployment of wind and solar power remains limited without subsidies – even under high CO_2 prices and/or further wind power and PV equipment price drops.

How to mitigate the value drop

- Drop in market value threatens renewables future, decarbonization
- We call actions to mitigate the value drop “integration options” or “mitigation measures”
- Such measures include
  - electricity storage
  - interconnections
  - flexible thermal plants
  - demand response
  - reservoir hydro power
- Several recent and ongoing assessments
  - Mills & Wiser (2014): “mitigation report“
  - Fraunhofer ISI (forthcoming): study commissioned by BMWi
  - Hirth (2014), Gilmore et al. (2014): special issue by IET
  - ...

Wind & solar themselves offer integration options

- Value drops because *variability* of wind and solar interacts with *inflexibility* of the rest of the power system
  - → increase power system flexibility ("more wind-friendly")
  - → decrease wind and solar variability ("more system-friendly")

- System-friendly wind & solar power: four strategies
  - Wind vs. solar mix Schaber 2014, Heide et al. 2010, 2011
  - Geographical smoothening Göransson & Johnsson 2013, Consentec & Fraunhofer IWES 2013, Lewis 2010, Mills & Wiser 2010, Elberg & Hagspiel 2013, Schumacher 2013, Brown & Rowlands 2009, Mono et al. 2014
  - Solar PV plant design Hartner 2014
  - Wind turbine design Molly 2011, 2012, Fraunhofer IWES 2013

- Significang body of literature on technological properties of system-friendly wind and solar plants, but little economic evaluation

- **→ we quantify the economic impact of system-friendly wind & solar technologies, mostly in terms of market value gain**

Design options for solar PV and wind power

- Criteria
  - smoother (more constant) generation
  - more predictable / smaller forecast errors
- Solar PV
  - tracking
  - east / west-orientation
  - (compared to fixed mounted south-oriented panels)
- Wind power
  - higher towers
  - larger rotor-to-generator ratio (smaller capacity per area swept W/m^2)
  - = low-wind speed turbines
  - (compared to classical design)
- today: focus on wind power

Methodology: overview

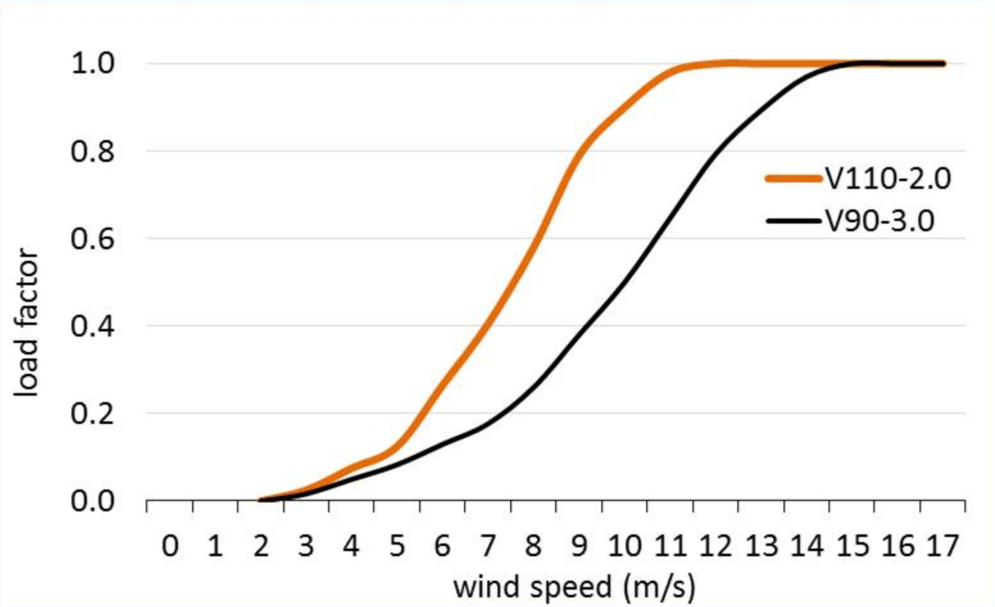
1. Deriving generation profiles of “classical“ and “system-friendly“ wind turbines

2. Evaluating the market value of each profile in EMMA

3. Robustness Checks

4. (Forecast errors)

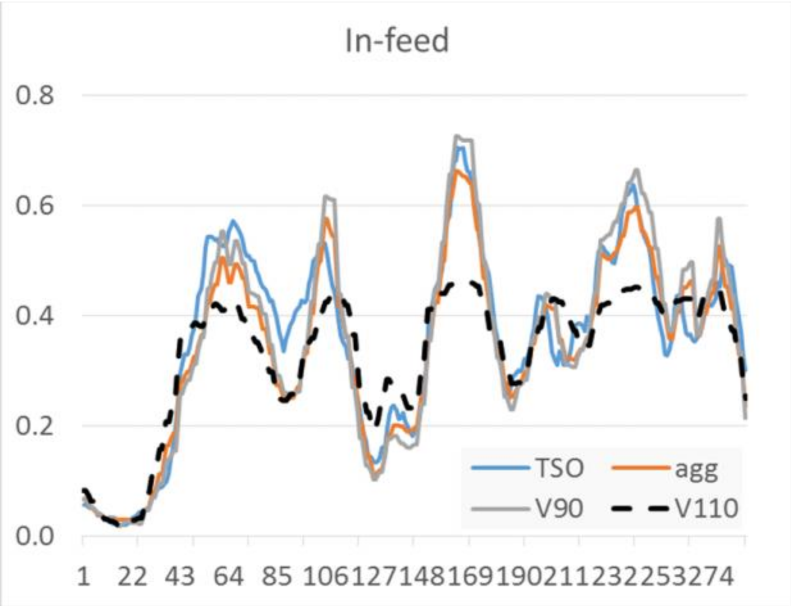
Deriving generation profiles: V110 vs. V90

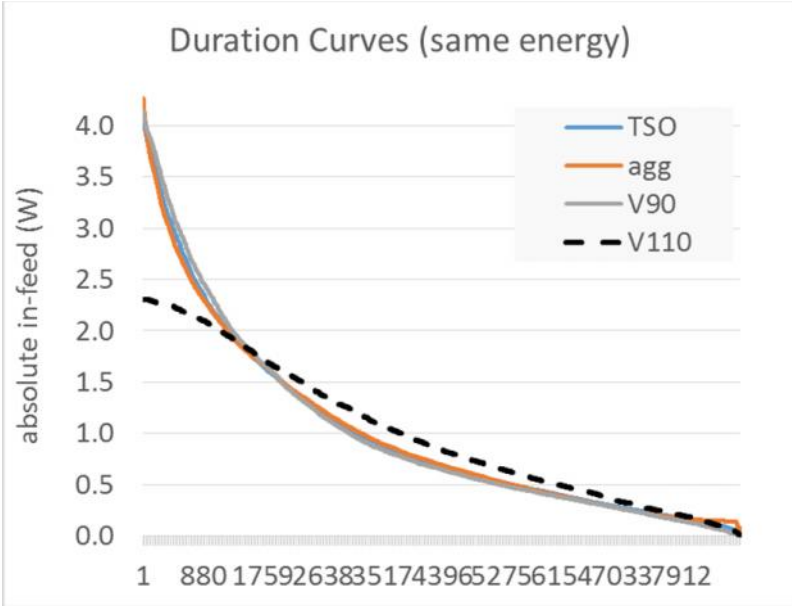


	V90	V110
evaluated at hub height (m)	90	120
generation at intermediate wind speed (8m/s)	30%	60%
cut-in wind speed (m/s)	3.5	3.0
wind speed to reach rated capacity (m/s)	15	11.5
rated power per area swept (W / m^2)	472	211
Capacity factor	~ 0.2	~ 0.4

- Two power curves: Vestas V90-3.0 vs. Vestas V110-2.0 IECIIIA
- Evaluated with ERA-Interim re-analysis weather data
  - three-hourly, 0.75° x 0.75°
  - wind speeds at 90m and 120m
- compare to two additional profiles: TSOs (observed), aggregated power curve

Profiles vary dramatically: V110 is much flatter

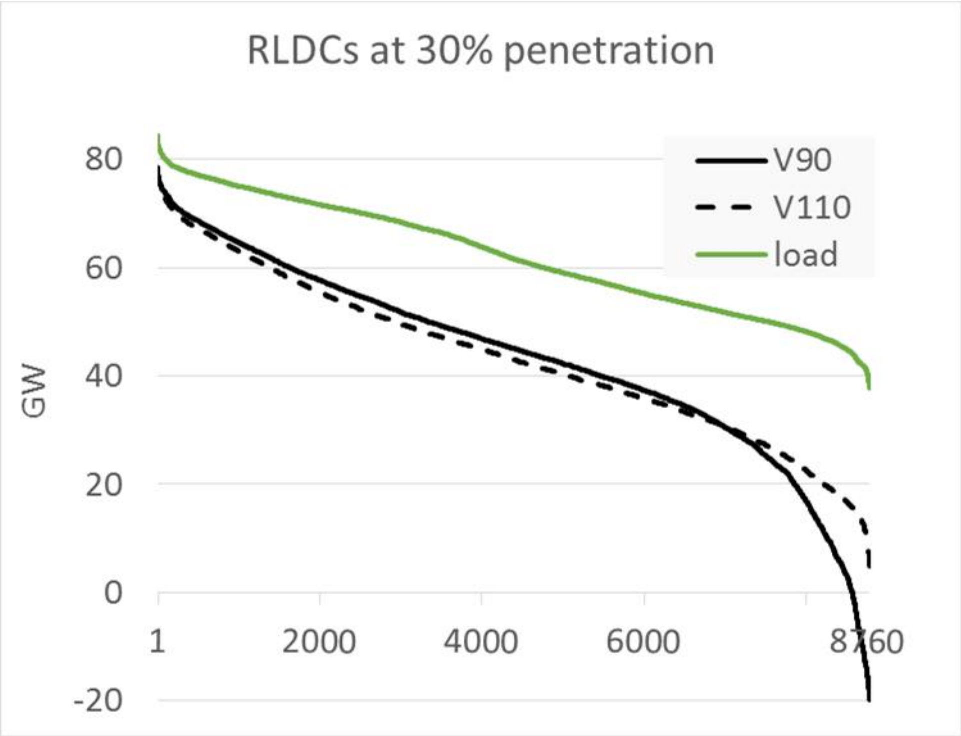


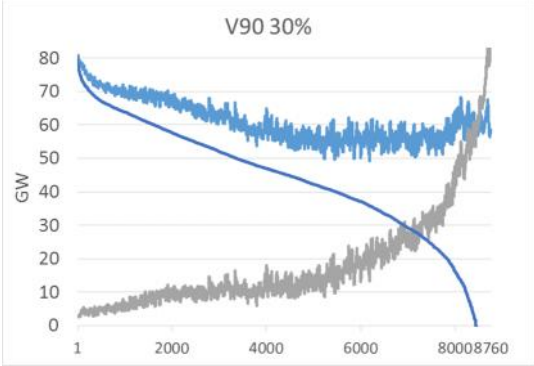


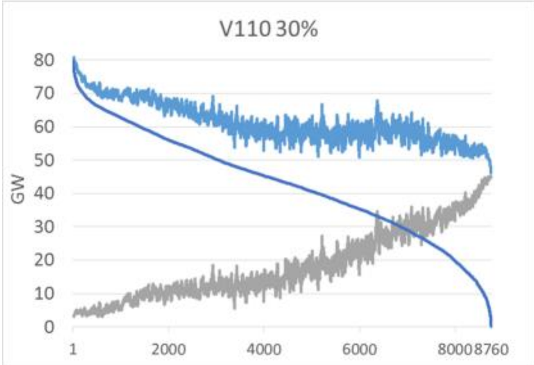
V110 output is less variable than V90 output. (scaled to same yearly output)

V110 output is more evenly distributed than V90 output. (scaled to same yearly output)

Residual load duration curve becomes flatter







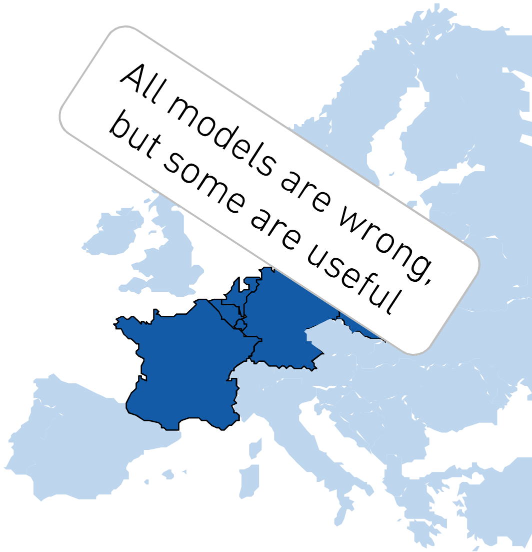
There is overproduction (more wind generation than consumption) with V90 – not with V110. (30% wind penetration)

With V110, hours of low residual load coincide with hours of low load – not with V90.

The Electricity Market Model EMMA

Numerical partial-equilibrium model of the North-Western interconnected power market – integrated dispatch & investment

Open source, back-tested, and published in four peer-reviewed articles



Objective: minimize total system costs

- capital cost of generation, storage, interconnectors
- fuel and CO_2 costs
- fixed and and variable O&M

Decision variables

- hourly production of each generation technology
- hourly electricity trade between regions
- in- /divestment in generation, storage, interconnectors

Constraints

- capacity constraints of plants, storage, interconnectors
- volume constraints of storage
- must-run: balancing reserve requirement, CHP plants
- "extended merit-order dispatch" – no unit commitment

Resolution

- temporal: hours
- spatial: bidding areas (countries) – no load flow
- generation: eleven technologies

Input data

- wind, solar and load data from the same historical year to preserve statistical characteristics and correlations
- existing plant stack

Cost minimization vs. "market model"

- perfectly price-inelastic demand
- economic agents are not explicitly modeled
- social planer solution is equivalent to market equilibrium if markets are perfect & complete

Equilibrium model

- short-/ mid-/long-term equilibrium ("one year")
- no transition path ("up to 2030")
- to identify causal mechanisms and fundamental trade-offs – not to project the future

Implementation

- Ockham's razor
- linear program – no binary variables
- GAMS / cplex

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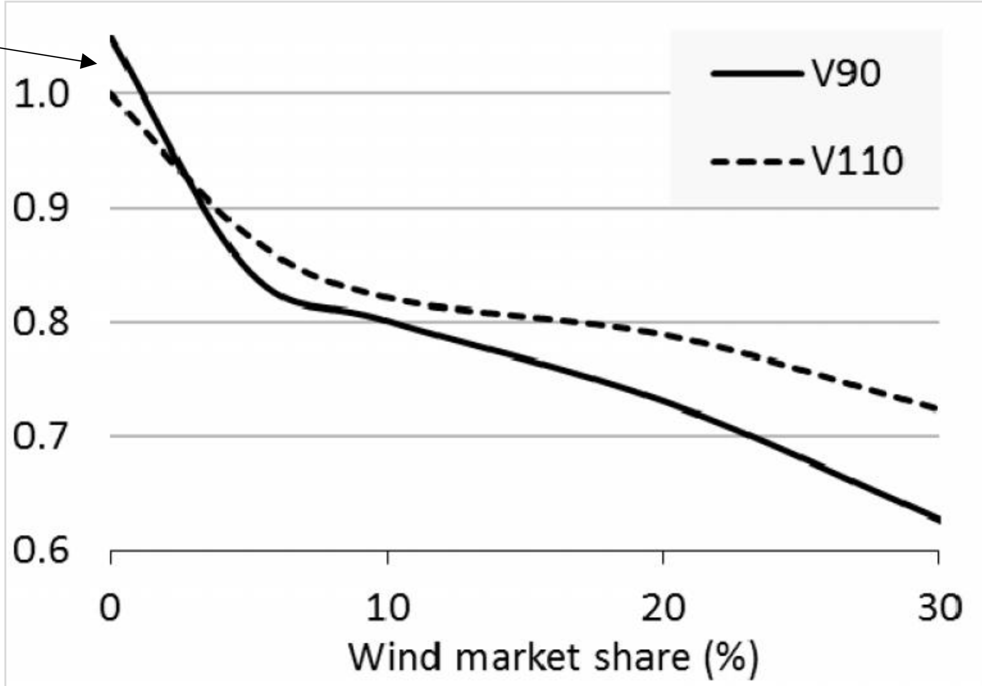
Major result: market value strongly increases

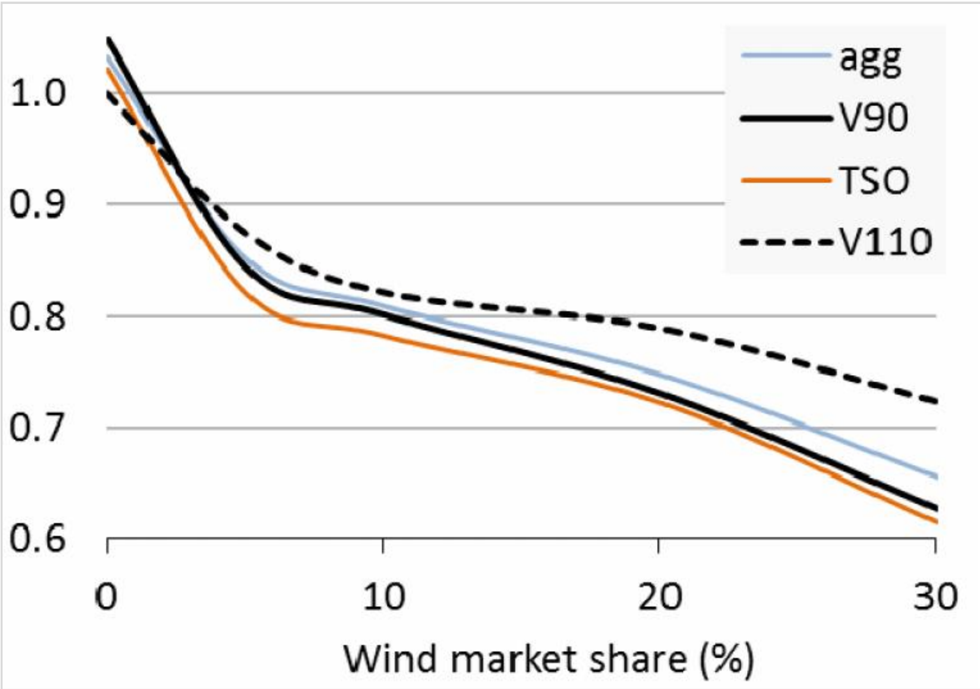
Seasonal correlation with load stronger for V90



Ten percentage-points (16%): “delta”

Wind power from system-friendly turbines is 16% more valuable than wind power from classical turbines (at 30% penetration). This is a large delta.

Effect is large compared to variation among profiles



Delta V110-V90

Different ways of modeling classical turbines

The delta is large compared to the variation among ways to model classical wind turbines – hence it is likely to be not a modeling artefact.

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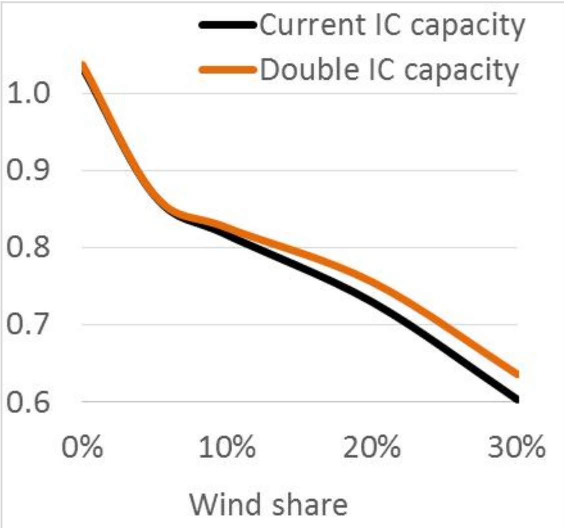
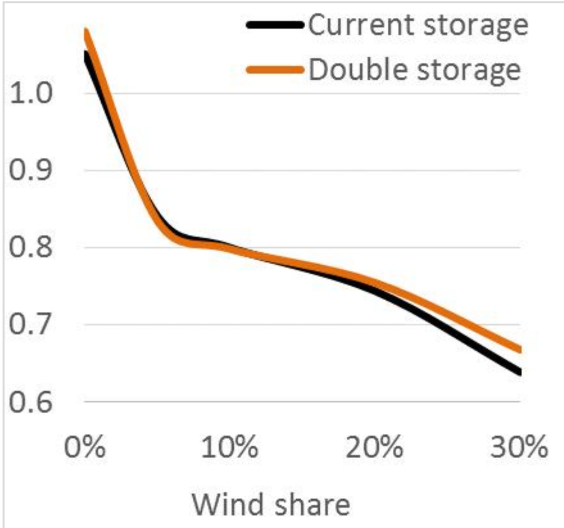
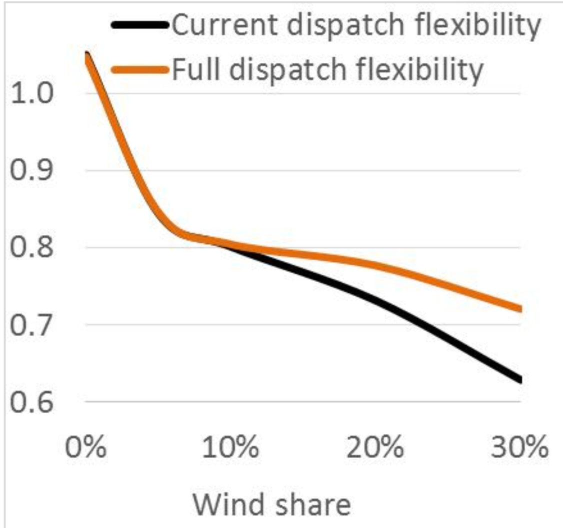
Effect is large compared to other integration options



Doubling storage capacity has small effect (3 percentage-points at 30%).



Doubling interconnector capacity has small effect (3 percentage-points at 30%).



Thermal plant dispatch flexibility has significant effect (9 pp at 30%) – but less than V110 !

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Sensitivities

- We are mainly interested in the market value delta V110 – V90
- This delta depends on a large number of power system parameters

Power System Flexibility

- Thermal plant dispatch flexibility
- Storage
- Interconnectors

Climate policy

- Carbon price

Fuel prices

- Price levels
- Price seasonality

Electricity market design

- Capacity payments
- Price caps

Nuclear policy

- European-wide phase-out
- German phase-out
- Interaction with climate policy

...

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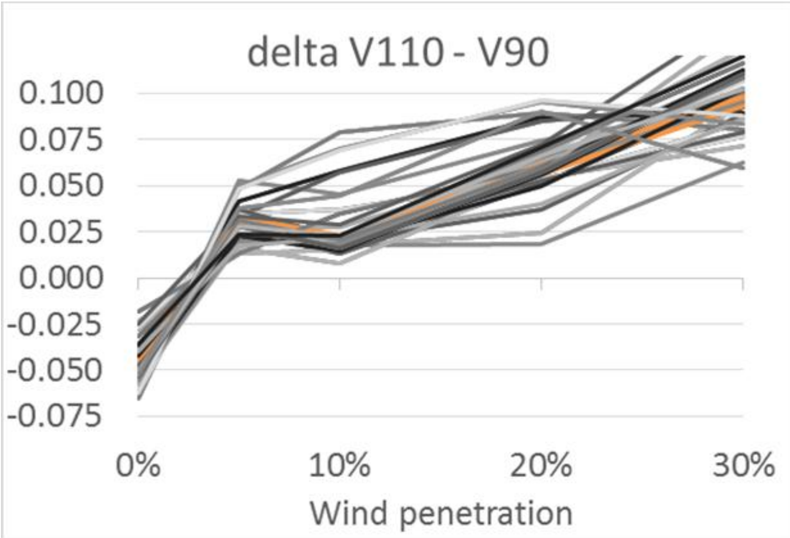
Full list of sensitivities

- 50+ sensitivities, 500+ model runs
- delta (V110 – V90) is very robust
  - in all sensitivities between 9% and 25%
  - mean 17%, median 17%
  - (benchmark was 16%)



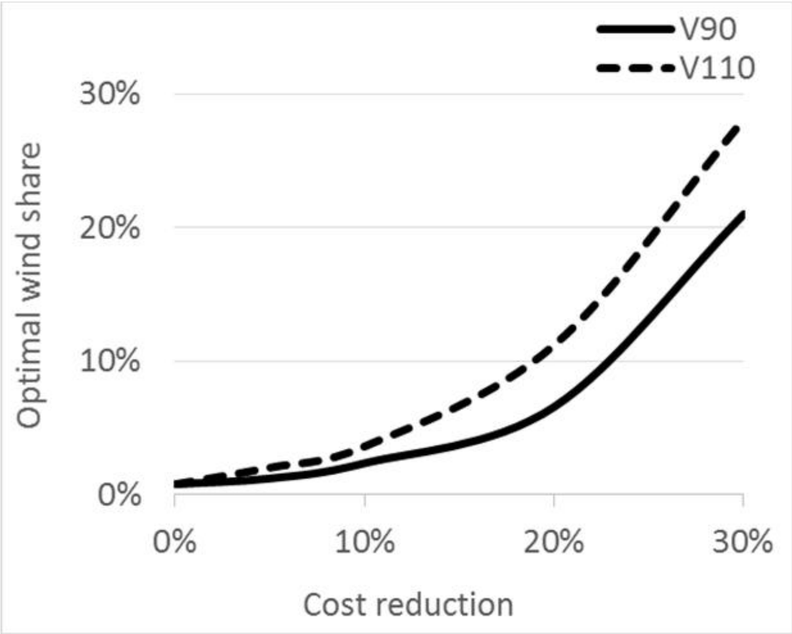
	V90					V110					absolute delta					relative delta				
	0%	5%	10%	20%	30%	0%	5%	10%	20%	30%	0%	5%	10%	20%	30%	0%	5%	10%	20%	30%
GER	1.10	0.84	0.80	0.71	0.62	1.02	0.88	0.82	0.78	0.70	-0.08	0.03	0.02	0.07	0.07	-7%	4%	2%	9%	12%
FRA	1.03	0.85	0.80	0.77	0.66	1.01	0.88	0.82	0.80	0.77	-0.02	0.03	0.02	0.03	0.11	-2%	3%	2%	4%	17%
NLD	1.10	0.87	0.82	0.73	0.63	1.02	0.92	0.87	0.82	0.75	-0.07	0.05	0.05	0.09	0.12	-7%	5%	6%	12%	18%
BEL	1.07	0.83	0.79	0.69	0.55	1.01	0.86	0.80	0.76	0.67	-0.06	0.03	0.01	0.07	0.12	-5%	3%	2%	11%	21%
POL	0.95	0.82	0.79	0.68	0.56	0.93	0.84	0.82	0.78	0.67	-0.01	0.02	0.03	0.09	0.11	-1%	3%	4%	14%	19%
bench	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
allConstraints (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.73	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
noAS	1.05	0.85	0.80	0.76	0.67	1.00	0.88	0.82	0.80	0.76	-0.05	0.03	0.02	0.04	0.09	-5%	4%	2%	5%	13%
noCHP	1.05	0.85	0.80	0.77	0.68	1.00	0.87	0.82	0.80	0.78	-0.05	0.03	0.02	0.02	0.09	-4%	4%	2%	3%	14%
noAll	1.05	0.85	0.80	0.78	0.72	1.00	0.87	0.82	0.80	0.78	-0.05	0.03	0.02	0.02	0.06	-4%	4%	2%	2%	9%
today/endo (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
cheapIC	1.04	0.85	0.81	0.74	0.65	0.99	0.88	0.83	0.80	0.73	-0.04	0.03	0.02	0.05	0.08	-4%	4%	2%	7%	13%
today	1.03	0.87	0.82	0.73	0.60	0.99	0.89	0.83	0.79	0.71	-0.04	0.03	0.02	0.06	0.11	-4%	3%	2%	9%	18%
zeroNTC	1.01	0.81	0.77	0.67	0.53	0.97	0.85	0.79	0.73	0.63	-0.04	0.04	0.02	0.07	0.10	-4%	4%	3%	10%	19%
doubleNTC	1.04	0.87	0.83	0.76	0.64	1.00	0.89	0.84	0.81	0.73	-0.04	0.03	0.01	0.05	0.10	-4%	3%	2%	7%	15%
20 €/t (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
0 €/t	1.06	0.78	0.69	0.58	0.48	1.00	0.83	0.73	0.65	0.57	-0.06	0.05	0.05	0.07	0.09	-6%	7%	7%	13%	19%
50 €/t	1.06	0.84	0.74	0.64	0.59	1.01	0.88	0.80	0.73	0.68	-0.05	0.04	0.06	0.09	0.09	-4%	5%	8%	14%	15%
100 €/t	1.11	0.79	0.67	0.56	0.49	1.04	0.84	0.75	0.64	0.57	-0.07	0.05	0.08	0.09	0.08	-6%	6%	12%	16%	16%
allTech (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
allTech100	1.11	0.79	0.67	0.56	0.49	1.04	0.84	0.75	0.64	0.57	-0.07	0.05	0.08	0.09	0.08	-6%	6%	12%	16%	16%
NoNuc100	1.07	0.87	0.77	0.67	0.61	1.02	0.90	0.83	0.76	0.71	-0.04	0.03	0.06	0.08	0.10	-4%	4%	7%	13%	16%
NoNucCCS100	1.03	0.91	0.89	0.82	0.75	1.00	0.92	0.89	0.87	0.82	-0.03	0.02	0.01	0.05	0.07	-3%	2%	1%	7%	10%
todayFuel (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
doubleCoal	1.04	0.85	0.81	0.74	0.64	1.00	0.88	0.83	0.80	0.73	-0.05	0.03	0.01	0.06	0.09	-4%	4%	2%	8%	15%
doubleGas	1.09	0.82	0.74	0.66	0.57	1.03	0.86	0.78	0.71	0.65	-0.06	0.03	0.04	0.05	0.08	-6%	4%	5%	8%	13%
shaleGas	1.05	0.82	0.75	0.66	0.53	0.99	0.84	0.78	0.73	0.64	-0.06	0.03	0.03	0.06	0.10	-6%	3%	4%	9%	19%
today (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	16%
expensive	1.06	0.85	0.80	0.72	0.63	1.01	0.89	0.82	0.77	0.71	-0.05	0.04	0.02	0.05	0.08	-5%	4%	3%	7%	13%
today/endo (bench)	1.05	0.84	0.80	0.73	0.63	1.00	0.88	0.82	0.79	0.72	-0.05	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	15%
cheapSto	1.06	0.84	0.80	0.73	0.63	1.01	0.88	0.82	0.79	0.72	-0.06	0.03	0.02	0.06	0.10	-5%	4%	3%	8%	15%
todaySto	1.05	0.84	0.80	0.74	0.64	1.00	0.86	0.82	0.79	0.74	-0.05	0.02	0.02	0.05	0.10	-5%	2%	2%	7%	16%
zeroSto	1.05	0.84	0.80	0.73	0.60	1.00	0.88	0.82	0.79	0.71	-0.05	0.03	0.02	0.06	0.11	-5%	4%	3%	8%	18%
doubleSto	1.08	0.83	0.80	0.75	0.67	1.02	0.85	0.82	0.79	0.75	-0.06	0.02	0.02	0.04	0.09	-5%	2%	3%	5%	13%
EOM (bench)	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
CapPayment	0.99	0.90	0.87	0.79	0.65	0.97	0.91	0.89	0.86	0.77	-0.02	0.01	0.02	0.07	0.12	-2%	2%	2%	8%	19%
1000€ (bench)	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
500€	1.04	0.87	0.83	0.75	0.62	1.00	0.89	0.84	0.81	0.73	-0.04	0.02	0.02	0.06	0.11	-4%	3%	2%	7%	18%
250€	1.01	0.88	0.84	0.76	0.63	0.98	0.90	0.86	0.82	0.74	-0.03	0.03	0.02	0.06	0.11	-3%	3%	2%	8%	17%
150€	0.99	0.92	0.87	0.78	0.64	0.98	0.94	0.90	0.84	0.75	-0.02	0.01	0.04	0.06	0.11	-2%	1%	4%	8%	17%
low (bench)	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
high efficiency	1.07	0.86	0.81	0.72	0.58	1.01	0.88	0.83	0.78	0.68	-0.06	0.02	0.02	0.06	0.11	-5%	2%	2%	8%	19%
eff gas	1.07	0.86	0.81	0.72	0.58	1.01	0.88	0.83	0.78	0.68	-0.06	0.02	0.02	0.06	0.11	-5%	2%	2%	8%	19%
2010p (bench)	1.07	0.86	0.82	0.75	0.59	1.01	0.89	0.84	0.81	0.71	-0.05	0.02	0.01	0.06	0.11	-5%	3%	2%	8%	19%
2008p																				
2009p	1.03	0.85	0.81	0.74	0.60	1.00	0.87	0.83	0.80	0.73	-0.04	0.02	0.02	0.06	0.14	-4%	2%	3%	8%	23%
2011p	1.08	0.90	0.85	0.75	0.61	1.05	0.93	0.87	0.82	0.73	-0.03	0.02	0.02	0.07	0.12	-3%	3%	3%	9%	19%
2012p	1.02	0.86	0.82	0.74	0.57	1.00	0.89	0.85	0.81	0.72	-0.03	0.03	0.03	0.07	0.14	-2%	4%	4%	10%	25%
nuc inv (bench)	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
100 €/t	1.09	0.83	0.70	0.57	0.50	1.03	0.88	0.77	0.67	0.59	-0.06	0.05	0.07	0.10	0.08	-6%	6%	10%	17%	17%
Phase-Out	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
Phase-Out100	1.09	0.81	0.69	0.56	0.49	1.02	0.86	0.76	0.65	0.58	-0.06	0.05	0.07	0.10	0.09	-6%	6%	10%	17%	18%
seasonal (bench)	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
flat	1.05	0.84	0.80	0.73	0.60	1.00	0.88	0.82	0.79	0.71	-0.05	0.03	0.02	0.06	0.11	-5%	4%	3%	8%	18%
free (bench)	1.07	0.86	0.82	0.75	0.61	1.01	0.89	0.84	0.81	0.72	-0.05	0.03	0.02	0.06	0.11	-5%	3%	2%	8%	18%
20% nuclear	1.07	0.87	0.81	0.72	0.59	1.01	0.89	0.84	0.78	0.69	-0.05	0.03	0.02	0.07	0.10	-5%	3%	3%	9%	18%
40% nuclear	1.07	0.85	0.77	0.60	0.45	1.01	0.89	0.81	0.69	0.51	-0.05	0.04	0.04	0.09	0.06	-5%	4%	6%	15%	13%
8760 h	1.06	0.90	0.84	0.74	0.59	1.02	0.93	0.87	0.81	0.71	-0.04	0.02	0.02	0.07	0.12	-3%	3%	3%	10%	20%

System-friendly wind power
- vs. -
wind-friendly power system

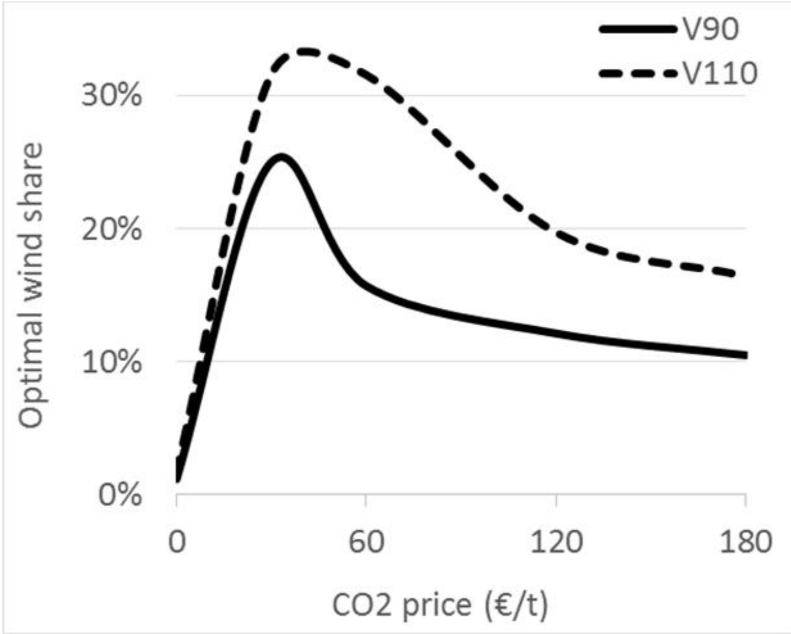
- It is the *interaction* of wind power variability and the inflexibility of the power system that causes wind power's value to decline
- Drop can be mitigated by
  - … making wind power more "system-friendly"
  - … making the power system more "wind-friendly"
  - both measures are likely to be substitutes (i.e., do not add up)
- Indeed: the delta decreases if power system flexibility is increased
  - unconstrained thermal dispatch
  - interconnector capacity
  - storage capacity
- e.g. plant flexibility
  - flexibility: +0.09
  - V110: +0.10
  - both: +0.15

		Value Factor		
		V90	V110	rel. delta
Thermal plant flexibility	Benchmark	0.63	0.72	16%
	Unconstraint thermal dispatch	0.72	0.78	9%
Interconnector capacity	No interconnectors	0.53	0.63	19%
	Double current interconnector capacity	0.64	0.73	15%
Storage	No Storage	0.60	0.71	18%
	Double current storage capacity	0.67	0.75	13%

System-friendly design drives up penetration by 50%



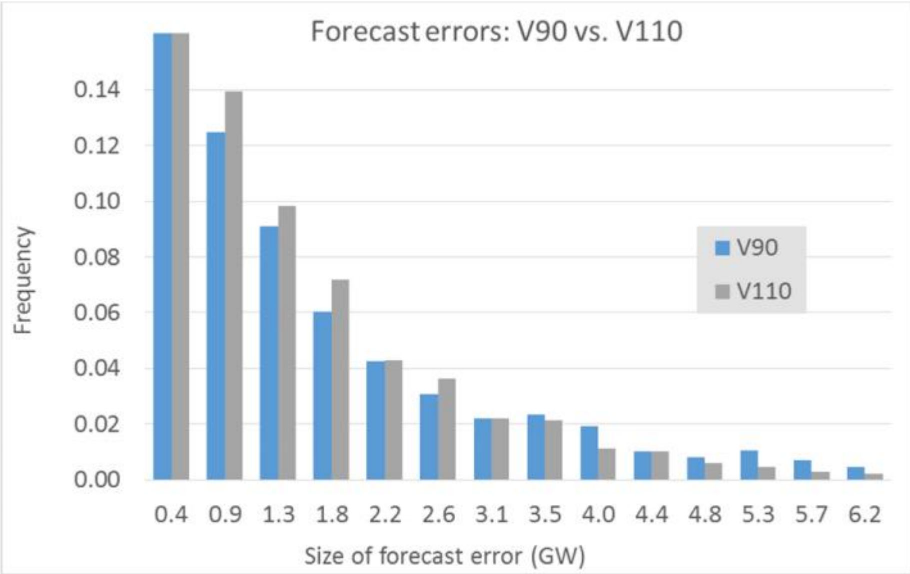
Cheaper turbines increase wind power deployment. With system-friendly turbines, this effect is larger (30% more deployment).



Higher carbon prices drive wind deployment. With system-friendly turbines, deployment is up to 50% higher.

Forecast errors

- (Spot) market value is not everything
- Forecast errors are costly, e.g. because balancing reserves need to be hold and activated
- It is a priory unclear if V110 has more or less forecast errors
  - less capacity (- errors)
  - steeper power curve (+ errors)
- Assessed by evaluation one-hour persistence forecast errors
  - change $wind_t$ vs. $wind_{t-1}$
  - can also be interpreted as one-hour wind ramps



Distribution of forecast errors at 30% wind penetration. Large forecast errors (> 4 GW) are less frequent with V110 turbines.

preliminary

Questions

- Relevant literature?
- Do you buy the story?
- Convincing methodology to derive in-feed profiles?
- More robustness tests?

Improving wind market value with advanced wind turbines

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