Modeling system operation cost and grid extension cost for different wind penetrations based on Green*Net*

Dr. Hans Auer

Energy Economics Group (EEG)
Vienna University of Technology
Austria

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1. Intermittency of Wind Generation

Balancing the system

• Extra short-term balancing requirements & cost due to intermittency of wind

- Note, there are fluctuations (and forecast errors) of both supply and demand (being not correlated in general)

Maintaining system security

• Limited contribution of wind to system security

• Correlation of wind outputs, risk of low wind speeds for longer periods

• Controversal discussion on wind contribution to capacity at peak load

- Wind contributes significantly less than conventional generation
- No empirical evidence that there is no contribution of wind on peak events
- Benchmark for system stability on peak events: Probability of loss of generation for the biggest (conventional) units in a system, but not wind!
- Therefore, additional system operation requirements and cost finally is no „MW to MW“ discussion on peak events (i.e. no discussion on backing up a particular plant or plant type (wind))

2. Quantifying Additonal System Operation Cost

2.1 Allocation of additional capacity cost (based on ILEX)

- Conventional generation delivers two services: energy and capacity
- Wind provides…

  …significantly less to capacity margin (if capacity credit is taken into account)

  …no capacity margin (if no capacity credit is taken into account)
- To be equivalent to conventional generation: additional back-up generation is required (Note, this is no „MW to MW“ discussion addressing peak events)
- Major question: amount of additional back-up generation?
- In practice, additional back-up generation could come from both:

  -> existing conventional thermal generation units or new OCGT (Open Cycle Gas Turbines) suitable for peaking generation

  -> pumped hydro storage plants
- Benchmarks for additional capacity cost of „thermal equivalent“ (see next slide) are - in principle - also applicable for pumped hydro storage plants

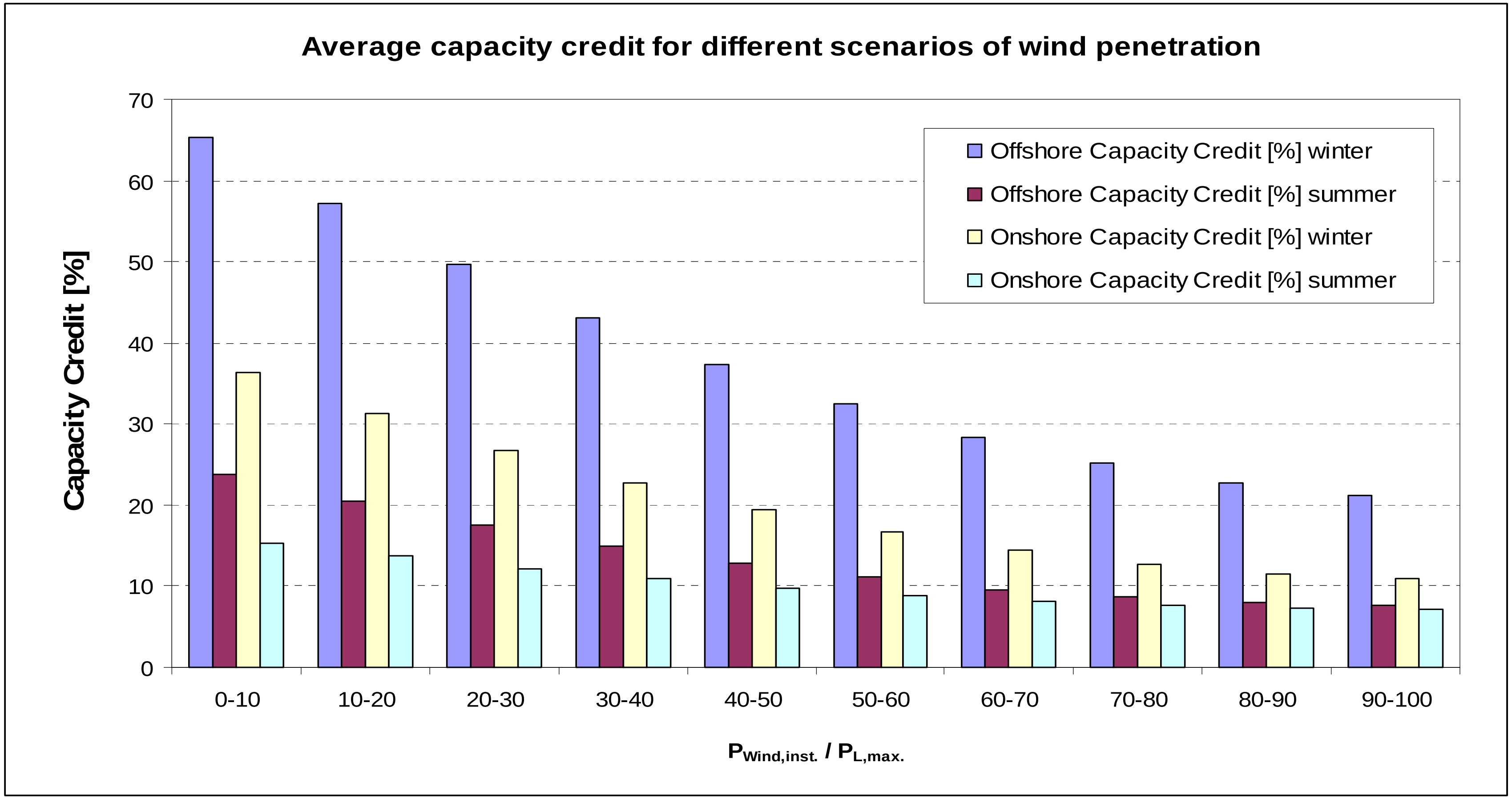
Quantifying the „thermal equivalent“ based on ILEX

Example - Calculation of additional capacity cost maintaining system security		
Wind capacity	**15**	**GW**
Full load hours	**2600**	**h**
Wind generation	**39000**	**GWh**
Without capacity credit		
CCGT load factor	80	%
CCGT full load hours	7008	h
Thermal capacity equivalent	5,57	GW
Capacity credit wind	0	%
Capacity contribution wind	0	GW
Required thermal capacity	5,57	GW
Specific cost of thermal equivalent	55	€/kW/yr
Capacity cost	306	Mio.€
Capacity cost per MWh Wind	**7,85**	**€/MWh**
With capacity credit		
CCGT load factor	80	%
CCGT full load hours	7008	h
Thermal capacity equivalent	5,57	GW
Capacity credit wind	27	%
Capacity contribution wind	4,05	GW
Required thermal capacity	1,52	GW
Specific cost of thermal equivalent	55	€/kW/yr
Capacity cost	83	Mio.€
Capacity cost per MWh Wind	**2,14**	**€/MWh**

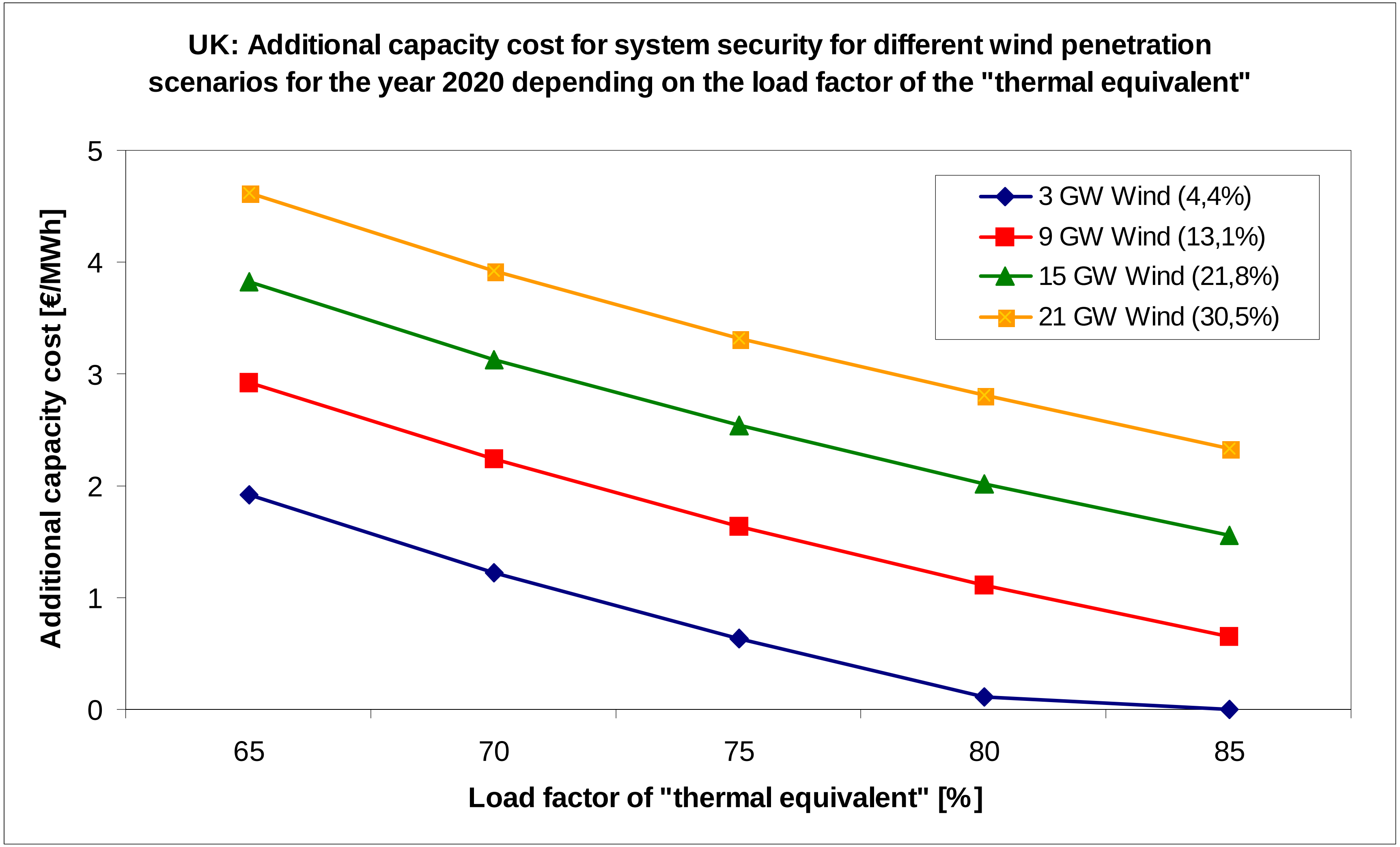
Simulation of 15 GW wind penetration in the UK in 2020 (21,8% of UK‘s peak load in 2020)
Assumption Onshore : Offshore = 40% : 60%
Source: Green*Net* based on ILEX

Capacity Credit of Wind

The capacity credit is the amount of capacity of conventional generation that can be displaced by intermittent wind capacity whilst maintaining the same degree of system security.

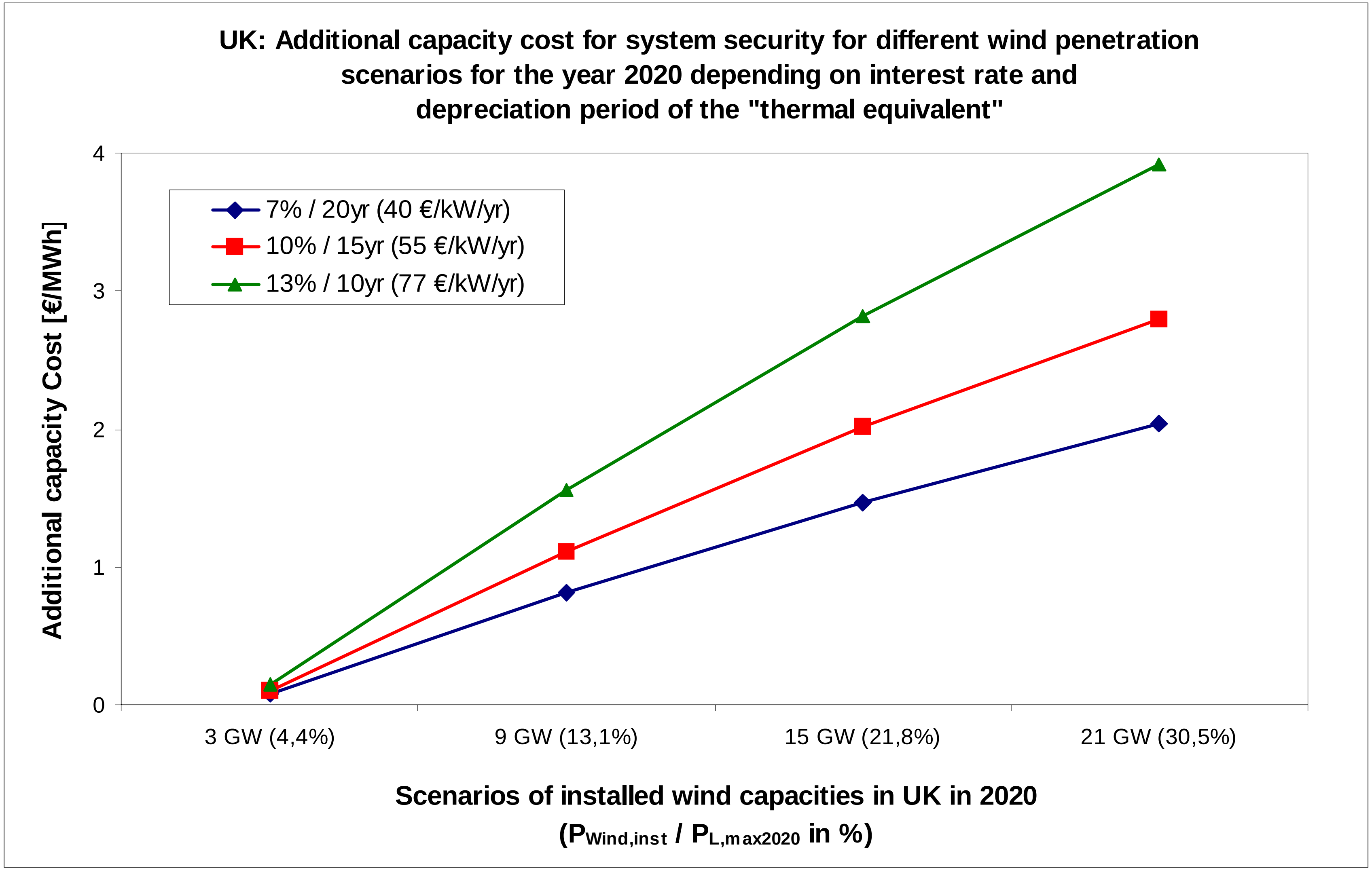


Source: Variety of References, see WP2-Report in GreenNet



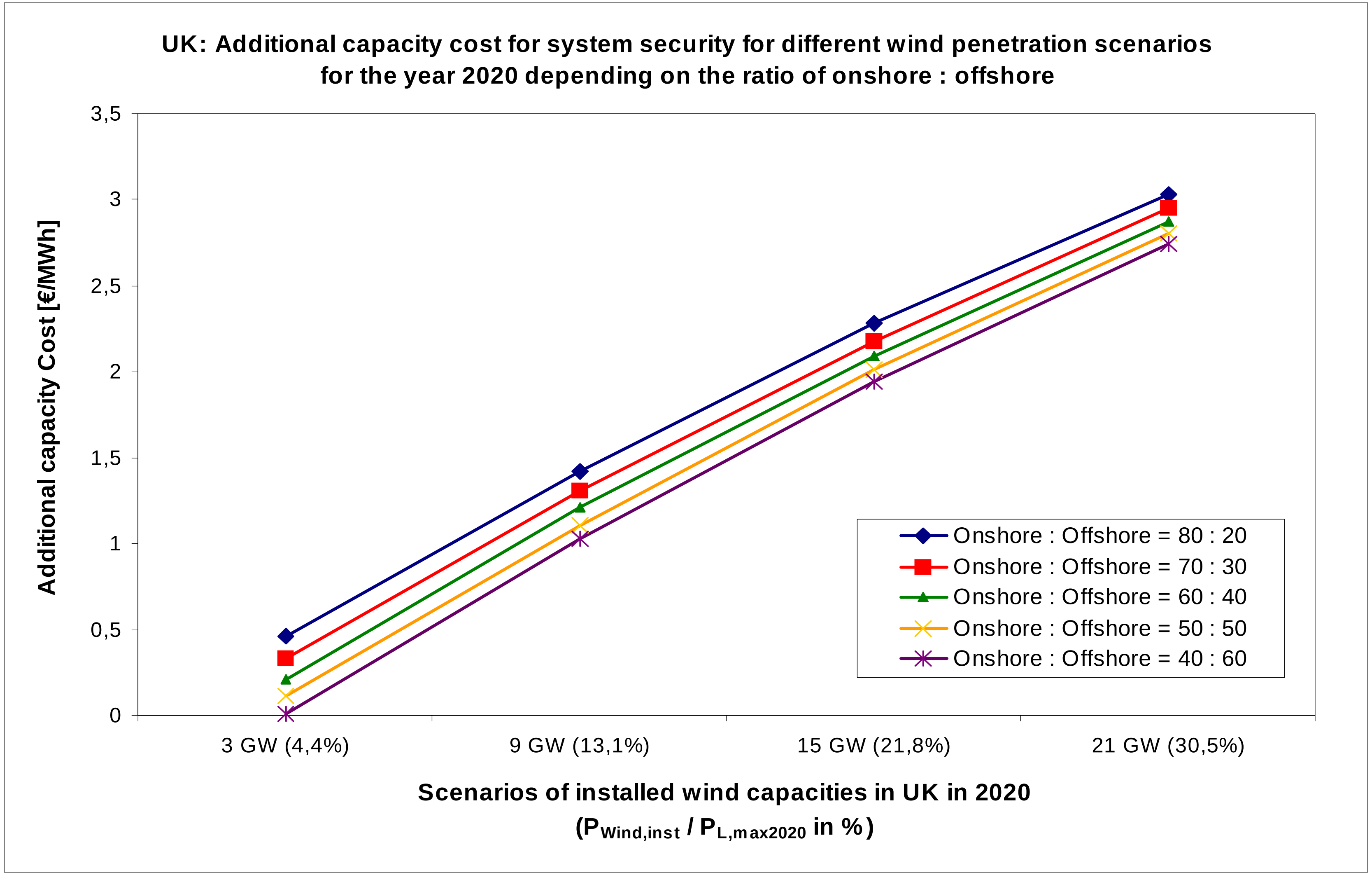
Assumptions on the „thermal equivalent": investment cost 420 €/kW, interest rate 10%, depreciation 15yr (55 €/kW/yr)

Source: Green*Net* based on ILEX



Assumptions on the „thermal equivalent": investment cost 420 €/kW, load factor 80%

Source: GreenNet based on ILEX methodolgy



Assumptions on the „thermal equivalent“: investment cost 420 €/kW, interest rate 10%, depreciation 15 yr, load factor 80%

Source: GreenNet based on ILEX methodolgy

2.2 Allocation of additional balancing cost (literature survey)

- **Besides additional capacity cost also additional balancing cost have to be allocated due to intermittency of wind generation.**
- **Less analyses and empirical data are available addressing these extra balancing cost allocated to wind only, e.g.:**

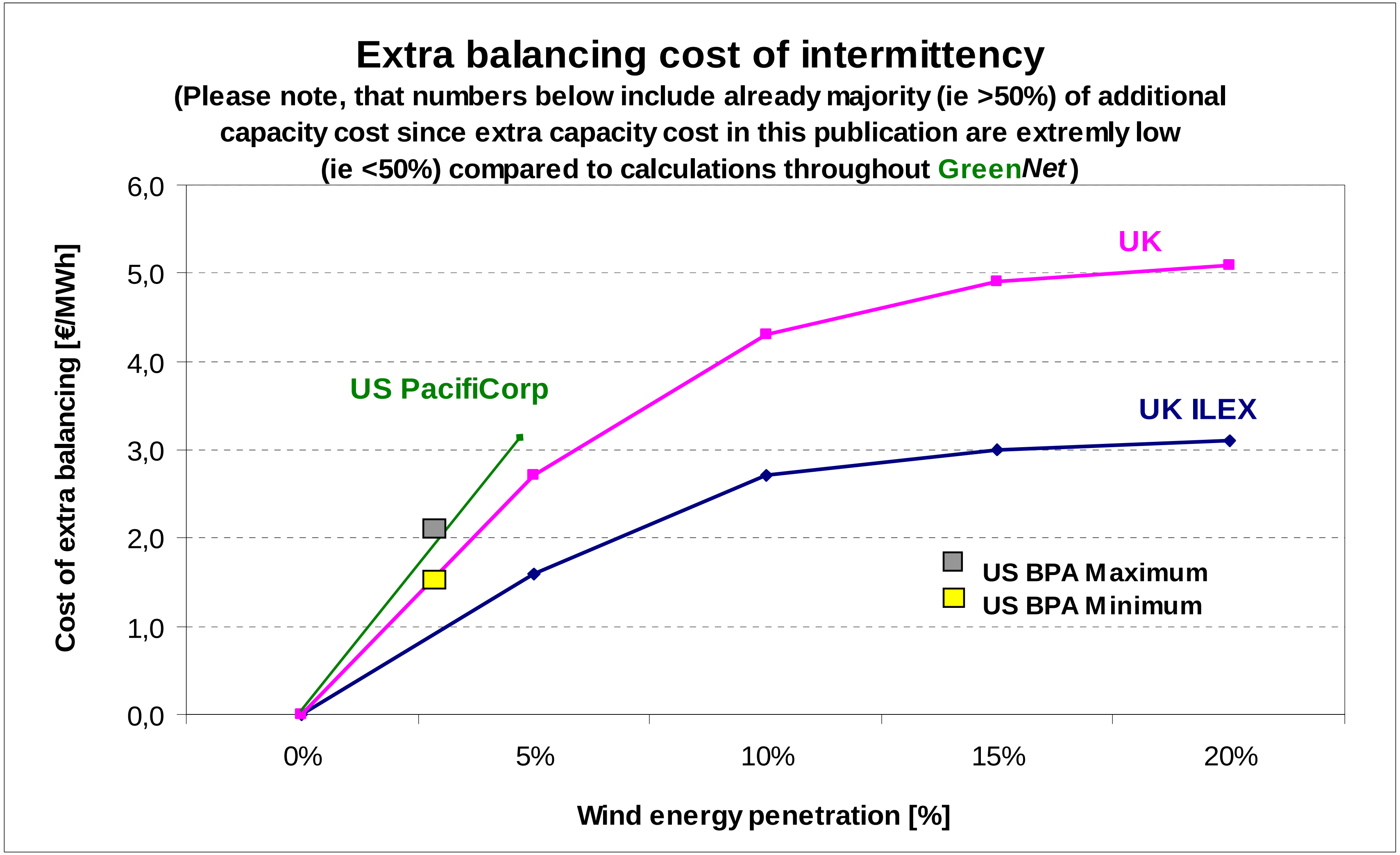
-> Denmark (West): 2-4 €/MWh (average: 3 €/MWh) for around 20% wind penetration, Source: Morthorst (2003)

-> Germany (E.ON): astronomical 7 €/MWh for 16% wind penetration in 2016, Source: Elsässer (2003), Fuchs (2002); Further Info: another astronomical additional 15 €/MWh on capacity cost (i.e. extra balancing cost are around 50% of extra capacity cost)

-> UK: 2-4 €/MWh depending on wind penetration up to 30%, Source: ILEX (2002); Further Info: extra balancing cost are also 50% of extra capacity cost

-> U.S. Examples from *Wind Power Monthly, Issue 02/2004*:
3 $/MWh imbalance cost at 20% wind penetration for PacifiCorp Northwest;
2 $/MWh imbalance cost at 5% wind penetration for Bonneville Power Administration (BPA) based on analyses by Eric Hirst;

=> Additional balancing cost are roughtly 50% of additional capacity cost !



Source: David Milborrow: „The Real Cost of Integrating Wind“, Windpower Monthly, Issue 02/2004

2.3 Modeling additional system operation cost for different wind penetrations in Germany based on the simulation software Green*Net*

Assumptions for Germany showing different „screen shots“ for the year 2020

GERMANY		
Peak load 2002 (GW); Load increase factor for 2020	75,8	1,3
Ratio Onshore : Offshore	50	50
Full load hours Onshore; Offshore	2000	3000
Full load hours Weighted		2500
CCGT load factor (%); Annualised cost (€/kW/yr)	80	55

Capacity Credit depending on $P_{Wind,inst}$ in Germany

Installed Wind Capacity GW	PWind,inst / PL,max %	Capacity Credit		
		Winter	Summer	Average
5	5,1	50,8	19,5	35,2
10	10,1	44,2	17,1	30,6
15	15,2	44,2	17,1	30,6
20	20,3	38,2	14,9	26,5
25	25,4	38,2	14,9	26,5
30	30,4	32,9	12,9	22,9
35	35,5	32,9	12,9	22,9
40	40,6	28,4	11,3	19,8

Germany: Simulation of additional system operation cost (capacity cost & balancing cost) for different wind penetrations for the year 2020

Default parameter settings in Green*Net*…

Germany		Average Annual Capacity Credit						w/o Capacity Credit
Wind capacity	**GW**	**5**	**10**	**15**	**20**	**25**	**30**	**30**
Full load hours	h	2500	2500	2500	2500	2500	2500	2500
Wind generation	GWh	12500	25000	37500	50000	62500	75000	75000
CCGT load factor	%	80	80	80	80	80	80	80
CCGT full load hours	h	7008	7008	7008	7008	7008	7008	7008
Thermal capacity equivalent	GW	1,784	3,567	5,351	7,135	8,918	10,702	10,702
Capacity Credit Wind	%	**35,2**	**30,6**	**30,6**	**26,5**	**26,5**	**22,9**	**0,0**
Wind capacity contribution	GW	1,759	3,061	4,592	5,306	6,632	6,882	0,000
Required thermal capacity	GW	0,024	0,506	0,759	1,829	2,286	3,821	10,702
Specific cost of thermal equivalent	€/kW/yr	55	55	55	55	55	55	55
Capacity cost	Mio.€	1,34	27,84	41,76	100,60	125,74	210,13	588,61
Additional capacity cost per MWh Wind	**€/MWh**	**0,11**	**1,11**	**1,11**	**2,01**	**2,01**	**2,80**	**7,85**
Additional balancing cost per MWh Wind	**€/MWh**	**0,05**	**0,56**	**0,56**	**1,01**	**1,01**	**1,40**	**3,92**
Additional capacity & balancing cost per MWh Wind	**€/MWh**	**0,16**	**1,67**	**1,67**	**3,02**	**3,02**	**4,20**	**11,77**

…assuming very pessimistic (unrealistic) capacity credits (50% of default settings)

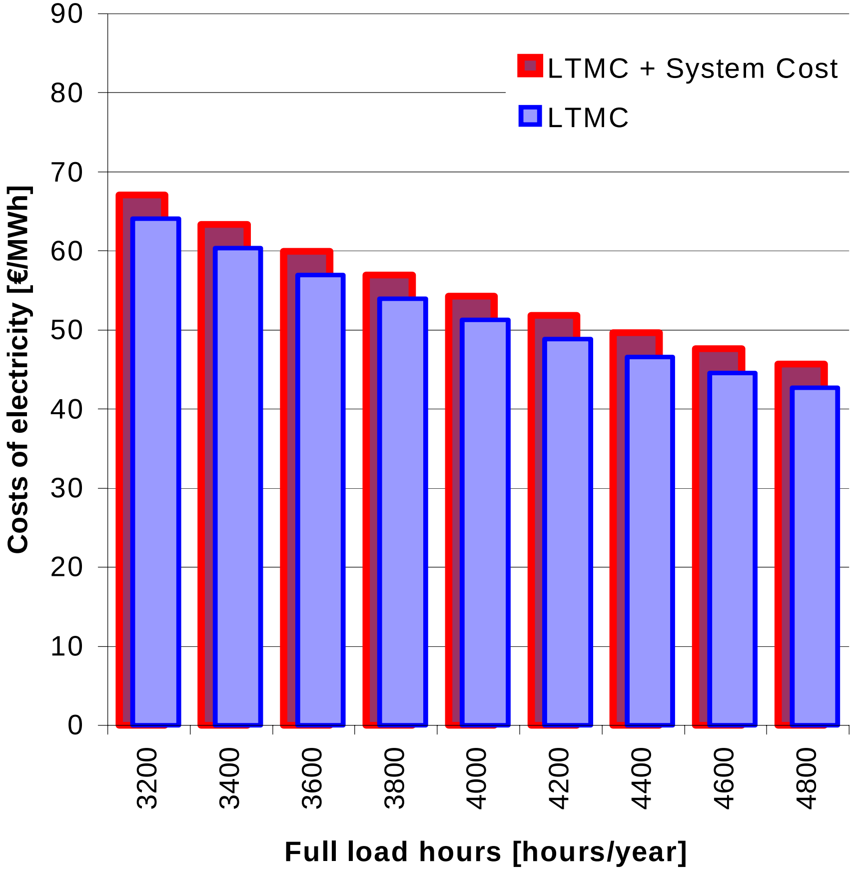
Germany		50% of Average Capacity Credit						w/o Capacity Credit
Additional capacity cost per MWh Wind	**€/MWh**	**3,98**	**4,48**	**4,48**	**4,93**	**4,93**	**5,32**	**7,85**
Additional balancing cost per MWh Wind	**€/MWh**	**1,99**	**2,24**	**2,24**	**2,47**	**2,47**	**2,66**	**3,92**
Additional capacity & balancing cost per MWh Wind	**€/MWh**	**5,97**	**6,72**	**6,72**	**7,40**	**7,40**	**7,99**	**11,77**

3. Long-Term Marginal Cost of Wind Generation in 2004

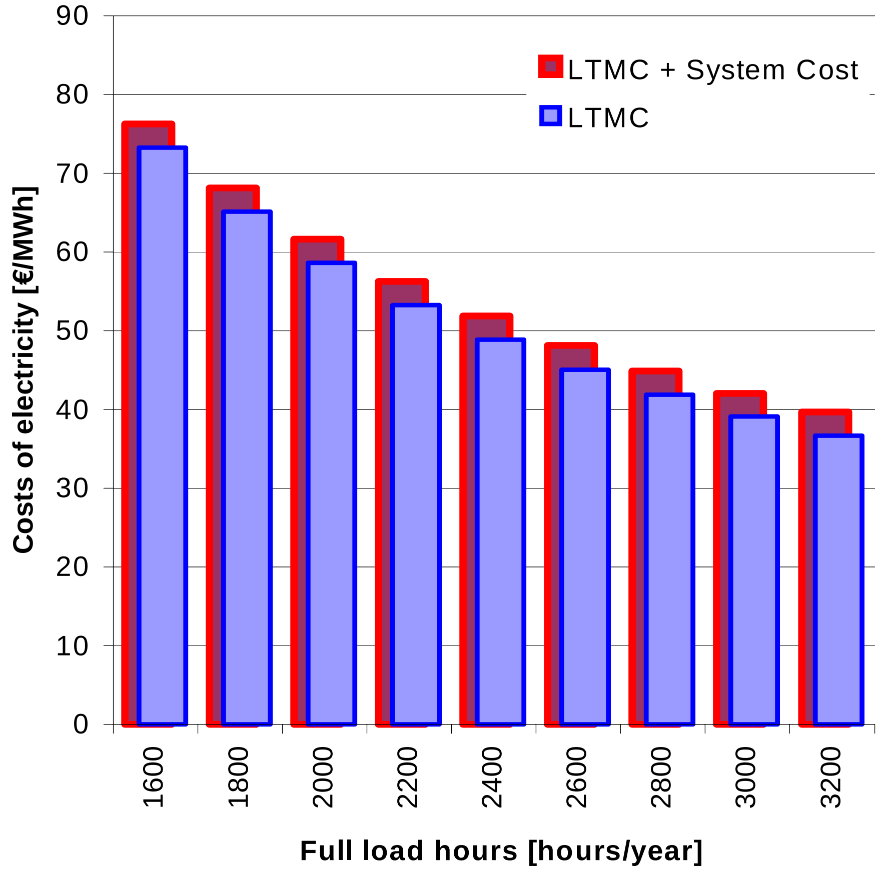
(w/ versus w/o system operation cost)

„BEST CASE“: LTMC based on 6%, 20yr; 3 €/MWh system operation cost in total

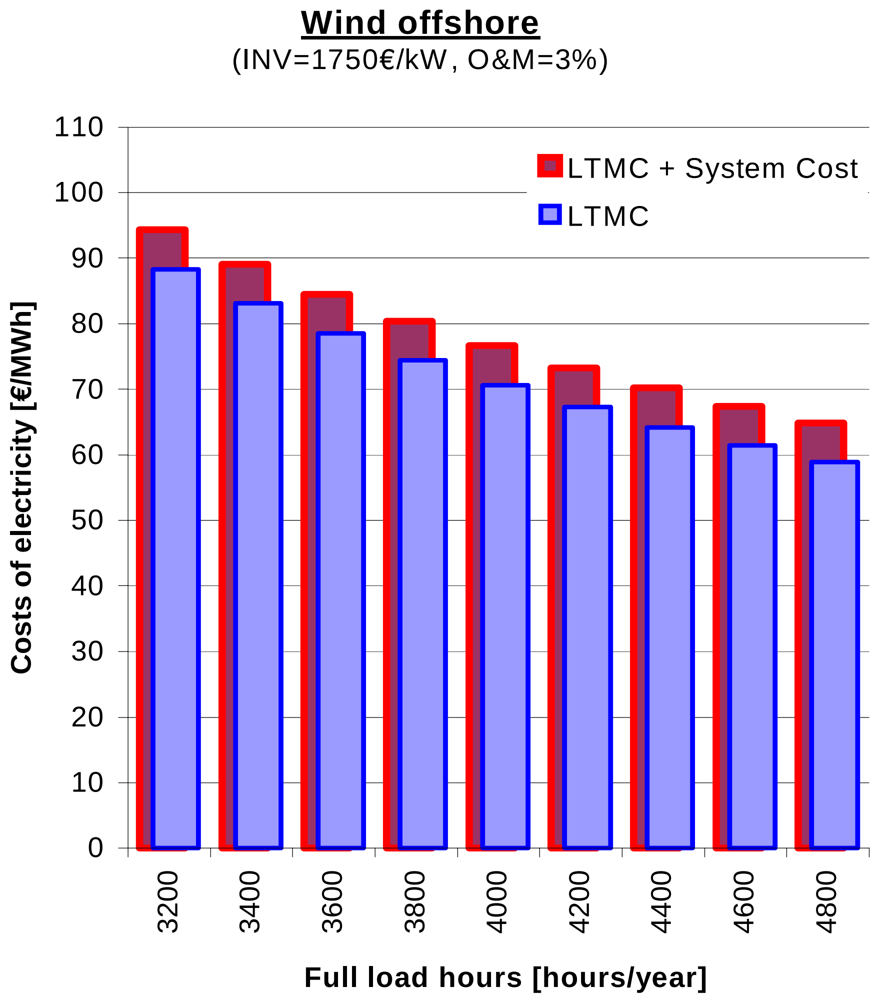
Wind offshore
(INV=1750€/kW, O&M=3%)

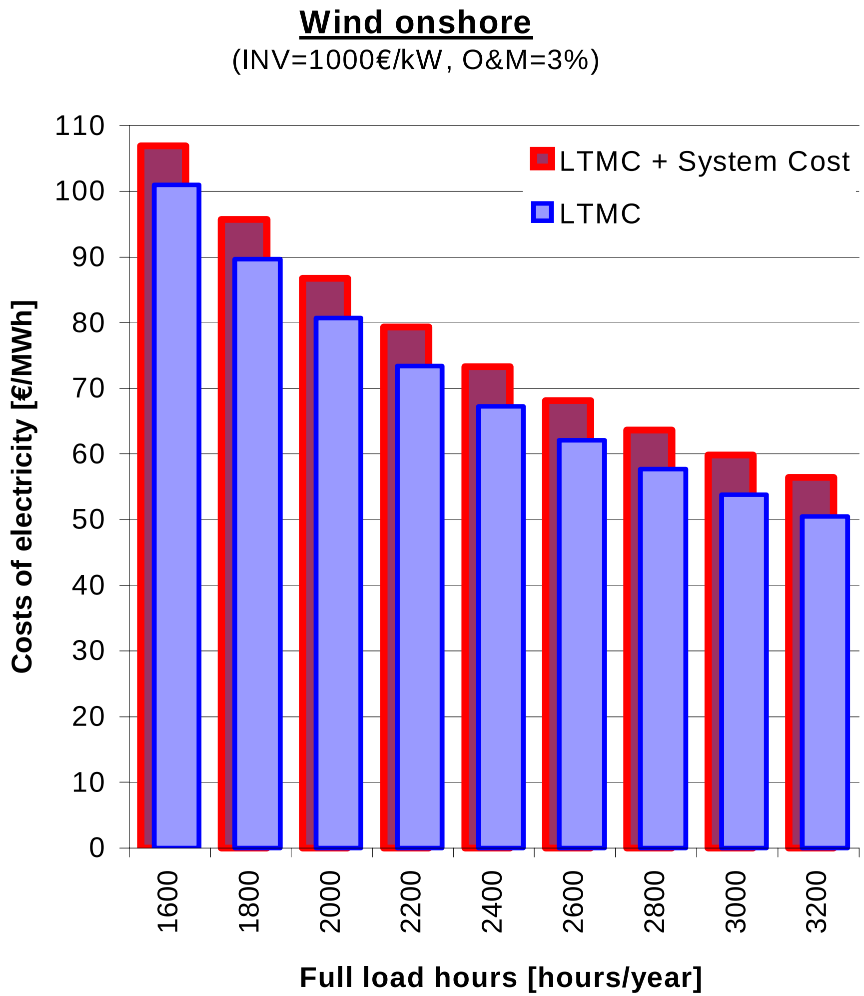


Wind onshore
(INV=1000€/kW, O&M=3%)

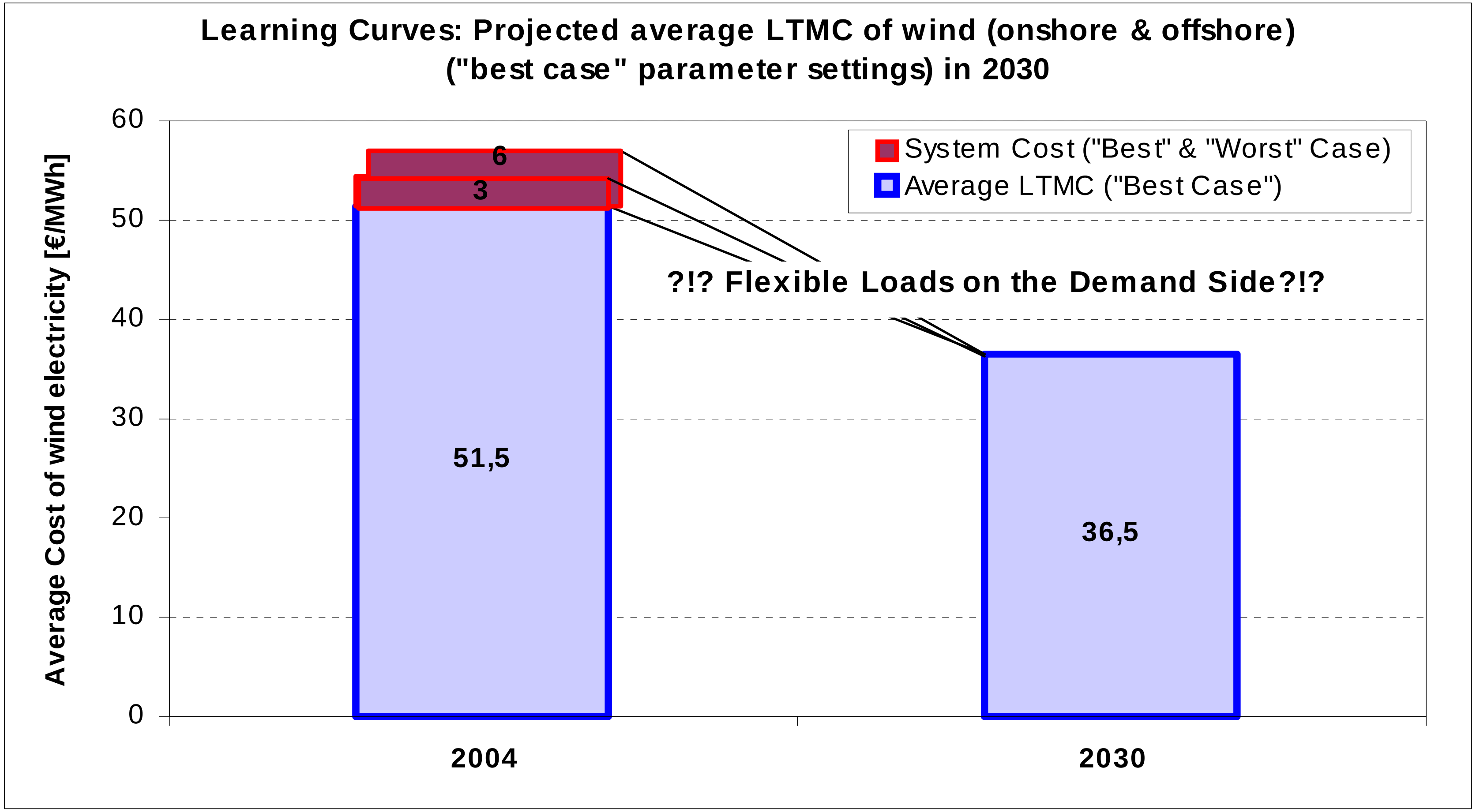


„WORST CASE“: LTMC based on 10%, 15yr; 6 €/MWh system operation cost in total





Learning effects up to the year 2030



Learning rate up to 2020: 9% and from 2020-2030: 5%. Assumption on installed wind capacity worldwide in 2030: 300 GW (according to the new IEA reference projections (WEO 2004). These assumptions result in decreases of LTMC from 2004 to 2030 of 29% (i.e. in 2030 average LTMC are 71% of LTMC in 2004).

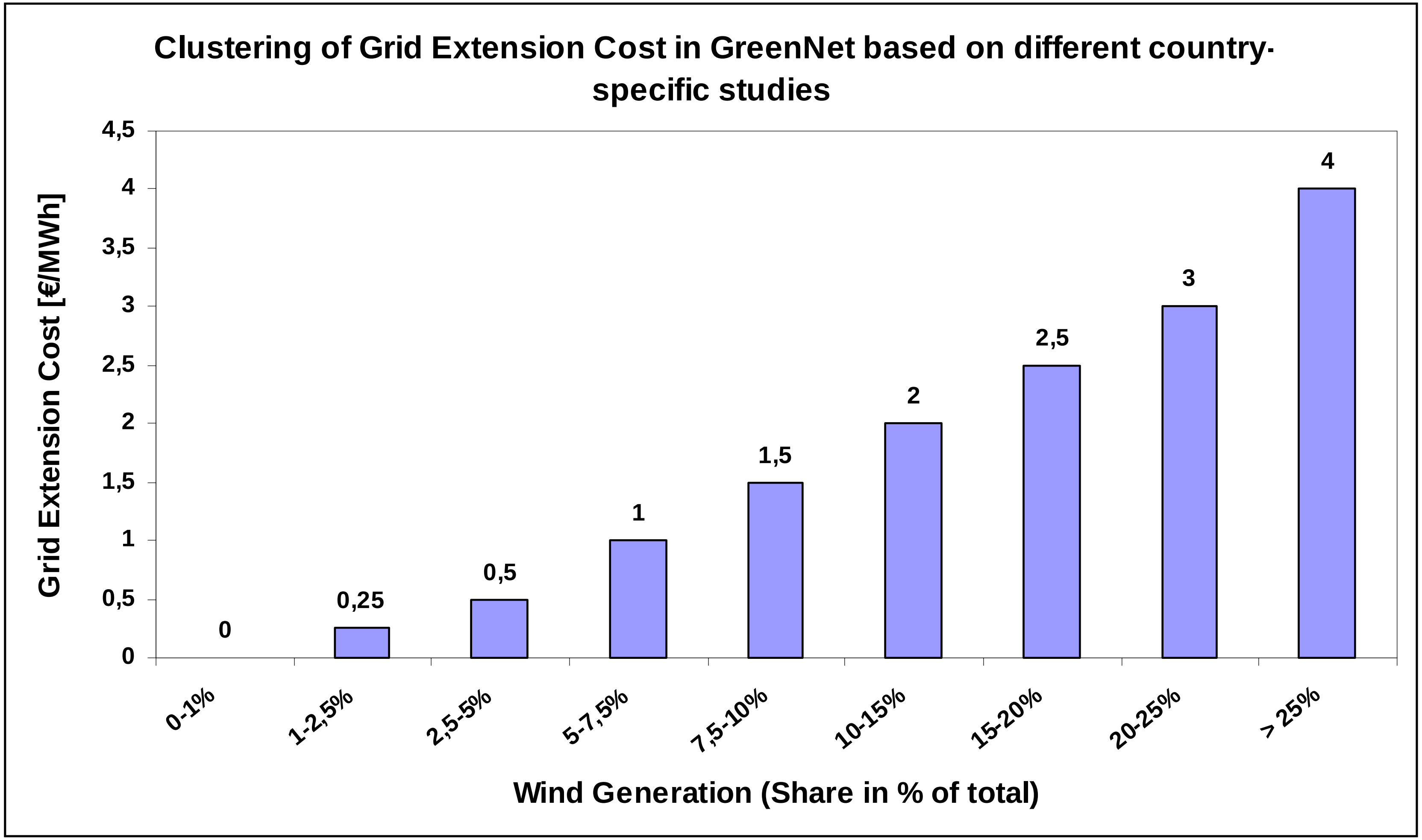
4. Additional Grid Extension Cost

- Unbundling: Grid upgrade/extension requirements, measures as well as corresponding cost have to be allocated to the regulated „natural monopoly", the grid!
- Therefore, grid upgrade/extension cost are not subject to cost allocation in electricity generation and/or system operation.
- Socialisation of grid upgrade/extension cost has to take place in the grid regulation process via transmission and distribution charges/tariffs
- Country-specific studies based on comprehensive load flow analyses exist estimating requirements and cost for large-scale wind integration (see table below)
- Difficult to allocate cost for wind integration only (also increase in conv. generation due to demand increase; grid extension requirements for power trading, etc.)

Empirical Data on Grid Extension Cost allocated to Wind based on Country Studies

Grid Extension Cost in €/MWh	Wind generation (Share in % of total)													Reference
	1,3%	1,8%	2,1%	2,9%	6,4%	8,1%	9,0%	14,1%	16,0%	16,1%	16,6%	20,0%	30,0%	
Belgium I	0,1													van Roy et al (2003)
Belgium II		0,2												van Roy et al (2003)
Austria I			0,3											Consentec et al (2003), EEG (2003), Haidvogl (2001)
Austria II				0,3										Consentec et al (2003), EEG (2003), Haidvogl (2001)
Austria III					0,4									Consentec et al (2003), EEG (2003), Haidvogl (2001)
France						1,6								Verseille (2003)
Germany I							1,0							Fuchs (2003)
Poland I								1,4						Janiczek et al (2003)
Germany II									2					Elässer (2003)
Poland II										1,6				Janiczek et al (2003)
Netherlands											1,6			t Hooft (2003)
UK I												3,3		ILEX / UMIST (2002)
UK II													4,7	ILEX / UMIST (2002)

Modeling additional grid extension cost allocated to wind in Green*Net*



5. Conclusions

- Wind (onshore, best sites with high wind speeds) with $LTMC_{Wind}$ = 37 €/MWh (w/o system operation cost) already competitive with CCGT if gas prices increase slightly (assuming $LTMC_{CCGT,2004}$ = 35 €/MWh)!
- Additional cost for system operation (balancing cost, capacity cost for system security) allocated to intermittent wind generation are…
  …around 5% (i.e. 2-4 €/MWh) of $LTMC_{2004}$ of wind for small wind penetrations (< 10%)
  …up to 10% (i.e. 5-6 €/MWh) of $LTMC_{2004}$ of wind for high wind penetrations (> 20%)
- Additional system operation cost are composed of 1/3 balancing cost and 2/3 capacity cost
- Germany high cost are not respresentative: (i) only isolated analyses of parts of E.ON's & VE's transmission grids but not the entire German grid, (ii) inefficiency due to four different balancing market zones, (iii) strategic behaviour of E.ON & VE (i.e. publishing high numbers) in the amendment process of the new Renewable Law, etc.
- Short-term: Improved forecasting tools can further mitigate intermittency of wind and have the potential to halve system operation cost
- Long-term: Market re-design focusing on flexible loads on the demand-side -> system operation cost allocated to intermittency of wind go towards zero!

EU-Project + Simulation Software Green*Net*

„Pushing a Least Cost Integration of Green Electricity Into the European Grids“ (www.greennet.at)

Contact:

Dr. Hans Auer
Energy Economics Group (EEG)
Vienna University of Technology
Email: auer@eeg.tuwien.ac.at
Tel. +43-1-58801-37357