reflex
Analysis of the European Energy System

REFLEX WP3 Overview and first results

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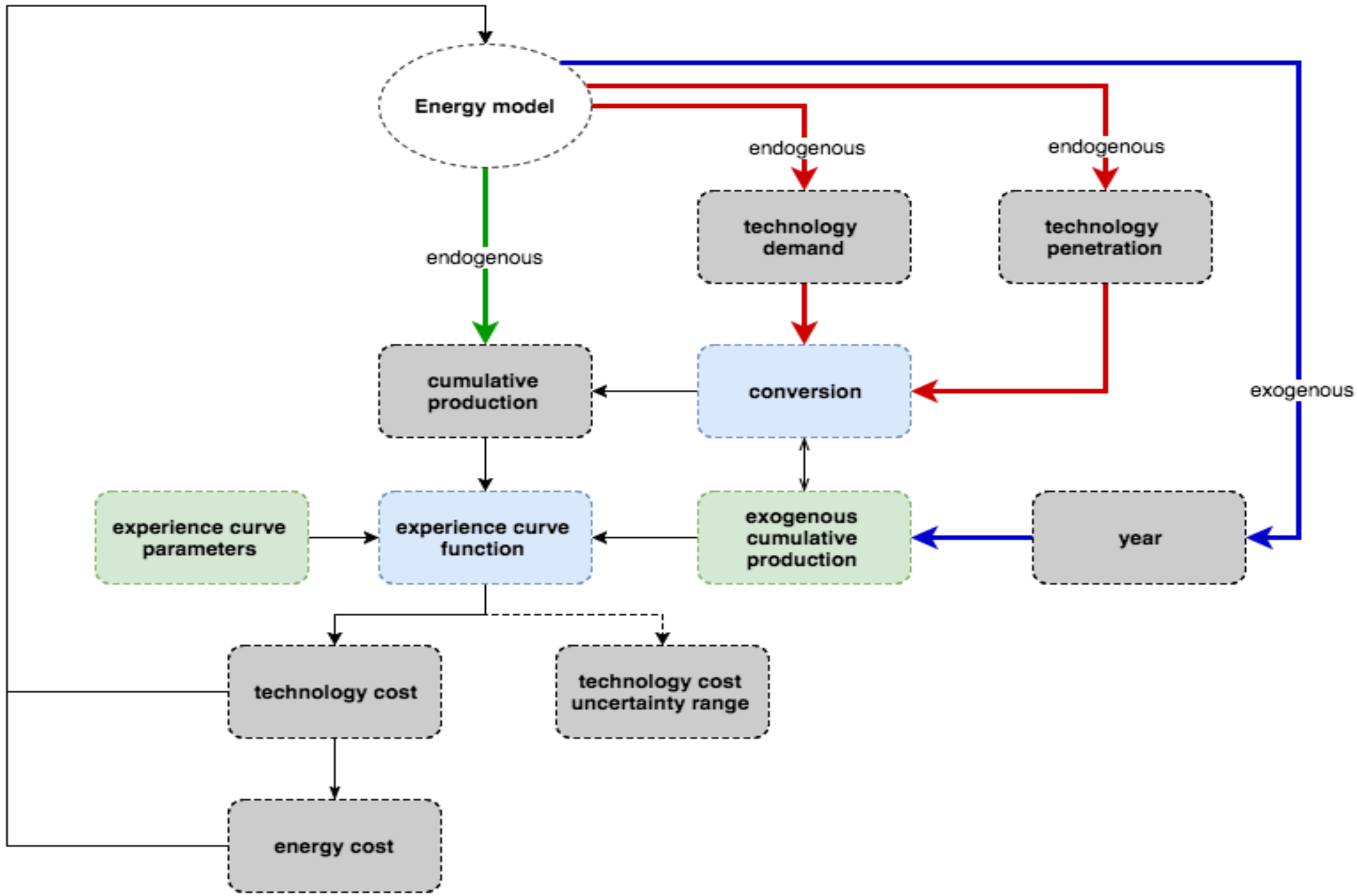
REFLEX expert workshop “**Technological Learning in the Energy Sector**”
Karlsruhe, 8 November 2017

Objective of the Work Package on Experience Curves

Develop and implement experience curve models into the sectoral models of other WPs

- Identify most relevant energy technologies in the electricity, heat and transport sector (supply, demand, storage)
- Collect empirical data on installed capacity and cost development of these technologies
- Devise/update experience curves for these technologies
- Incorporate experience curves into the various energy models to enable endogenous modeling of technological developments and cost reductions
- Where possible take into account (statistical) uncertainty of devised learning rates
- Where possible decompose experience curves to account for e.g. input material prices or available geographical potential (multi-level experience curves)

Experience Curve Model Implementation in Reflex



Aims of this workshop

- To present intermediate results of the Reflex project to external experts (mainly in the morning session) and to get feedback, e.g. on additional data sources or interpretation of results
- To discuss methodological assumptions and issues encountered both within the project and in general by the experts (mainly in the afternoon session)
- To discuss new application areas of the experience curve methodology, e.g. on ex ante environmental impact assessment
- To explore the interest from external experts to also contribute to the project

Technologies included and data availability so far

Sector	Technology	Data availability	Experience Curve
E supp	Onshore wind		(y)
	Offshore wind		(y)
	PV		y
	Biogas/Bioenergy		
	CCGT		
	CCOT		
	Coal + CCS		
	Lignite + CCS		
	Gas + CCS		
	OCGT		
	OCOT		
E stor	Li battery		y
	RF battery		y
	A-CAES		
P2X	Electric boiler		
	Electrode boiler		
	Power-to-H2		y
	Power-to-Methane	Proxy H2, bottom-up	
	Power-to-Methanol	Proxy H2, bottom-up	
Transport	BEV (battery pack)		y
	HEV (battery pack)		y
	PHEV (battery pack)		
	FCV (battery pack)		y
Other	Air conditioning		y
	Heat pumps		y
	CHP		
	micro-CHP		

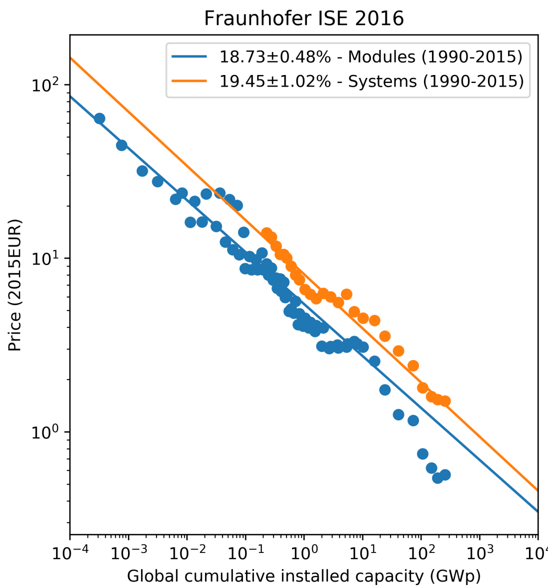
- Data + curves
- Data
- No data
- Not possible

First results - overview

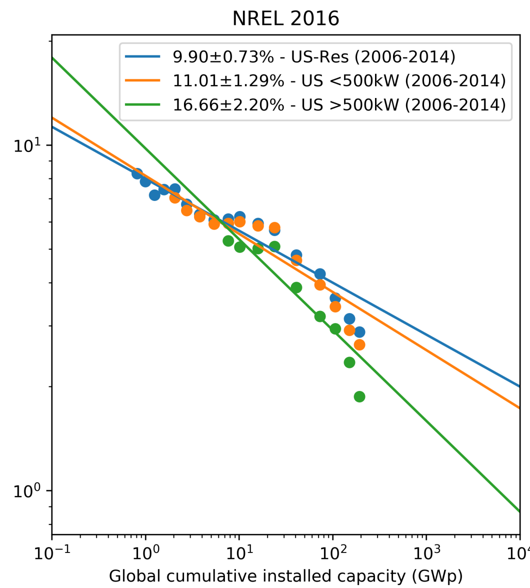
- Electricity-supply
  - Photovoltaics
  - Onshore wind
  - Offshore wind
- Power-to-H_2

First results: Photovoltaics

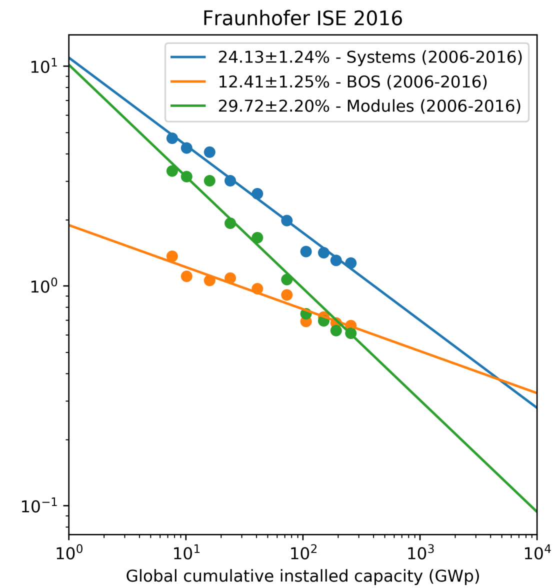
Modules / systems



Systems



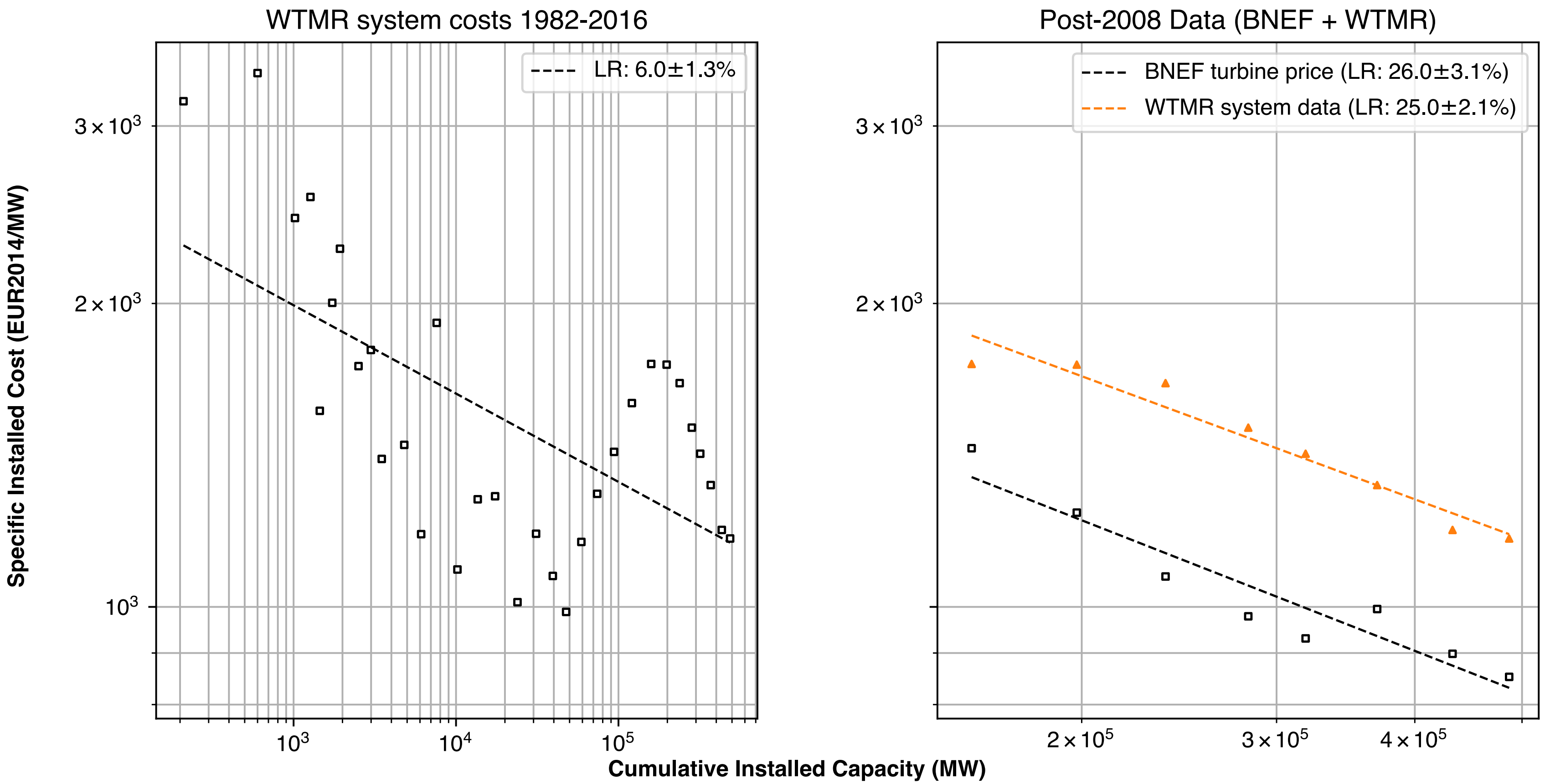
Modules/systems/BOS 2006-2016



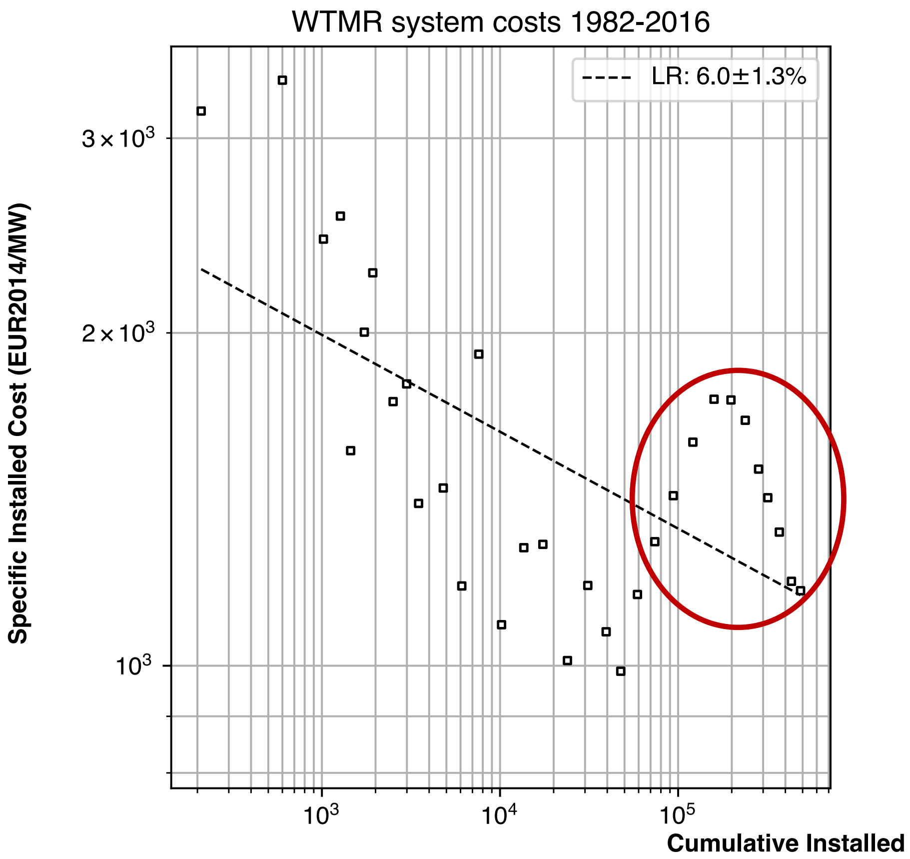
First results: Photovoltaics

- Time horizon has significant effect on estimated learning rate
- Contribution of BOS has increased to around 50% of system costs now (from ~20%)
- We will probably use separate learning curves for BOS and modules
- We will use the long term trends for modules ("learning" between 2006-2016 was probably a shake-out effect)

First results – Wind onshore, farms and turbines



First results – Onshore Wind



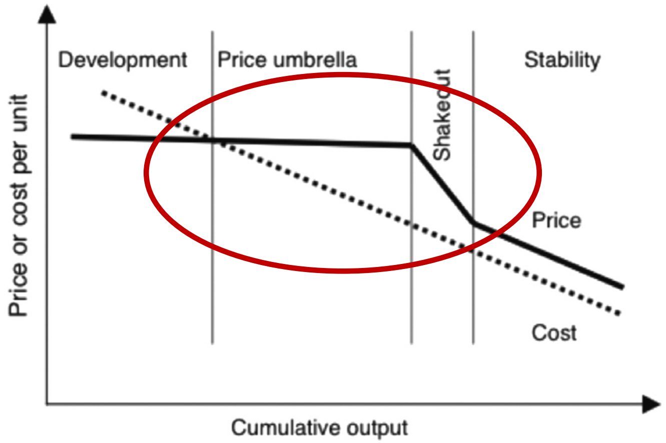


Fig. 1. Development of costs and prices of emerging technologies (Boston Consulting Group, 1968).

First results – Onshore Wind, discussion (1/2)

- Dataset going back to before 2008 show minimum around 2000-2002, followed by sharp increase up to 2008, explained by*
  - Increase in input prices (material, energy, labor)
  - Increased profitability (demand > supply)
  - Increased cost for warranty provisions
- Prices of 2016 have still not returned to 2002 minimum
- Current price trends are too limited to assess whether Post-2008 reflects the “new” market or is fluctuation like 2000-2008s (learning rate of 25-26% too high)

*(Moné et al, 2017 in Wiser et al., 2017)

First results – Onshore Wind, discussion (2/2)

- Costs shown here refer to turnkey system costs (and turbine prices) but do not account for:
  - Changes in O&M costs (decrease over time ?)
  - Changes in capacity factors (increase over time)
- A more appropriate functional unit would be EUR/MWh,as this would include these improvements
- -> we are currently looking into US data

First results – Onshore Wind, summarising

Cost per kW based on, either:

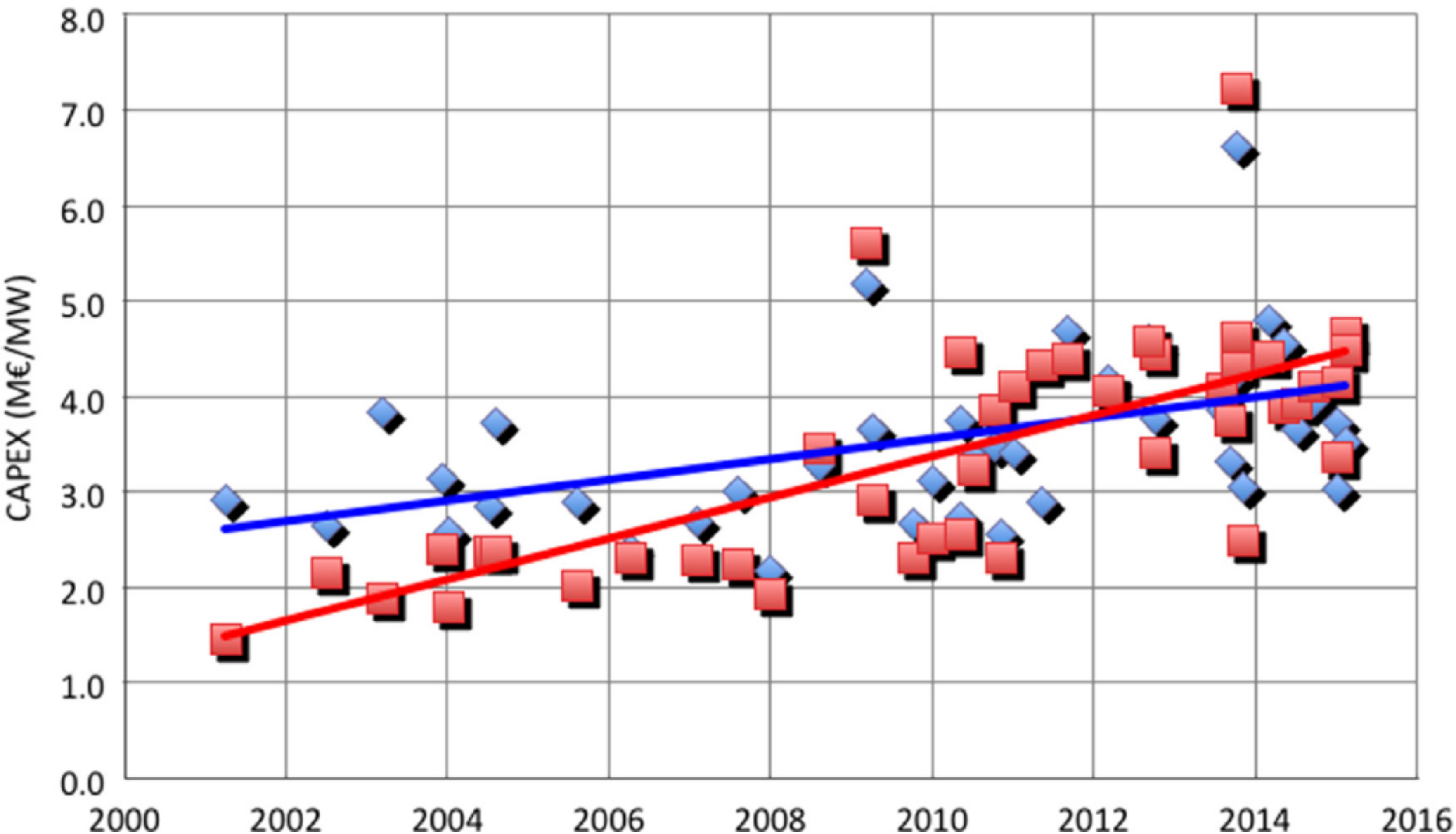
- o 6% learning rate based on 1980-now
  - Likely too low
- o Optimistic learning rate based on 1980-2002
  - How to account for (limited) geographical potential onshore?
  - Translation to EUR/kWh (capacity factor, O&M)
  - Discrepancy between current costs and modeled 2017-20?? costs

First results – Wind, offshore farms Europe

- Data: 56 offshore farms in Europe (UK, DE, NL, DK)
- Capacity and installed system costs
- Coupled with global installed wind capacity (GWEC)
  - Separate for on- and offshore
- Presented here:
  - Raw data, visualised per country
  - Annual (capacity)weighted average

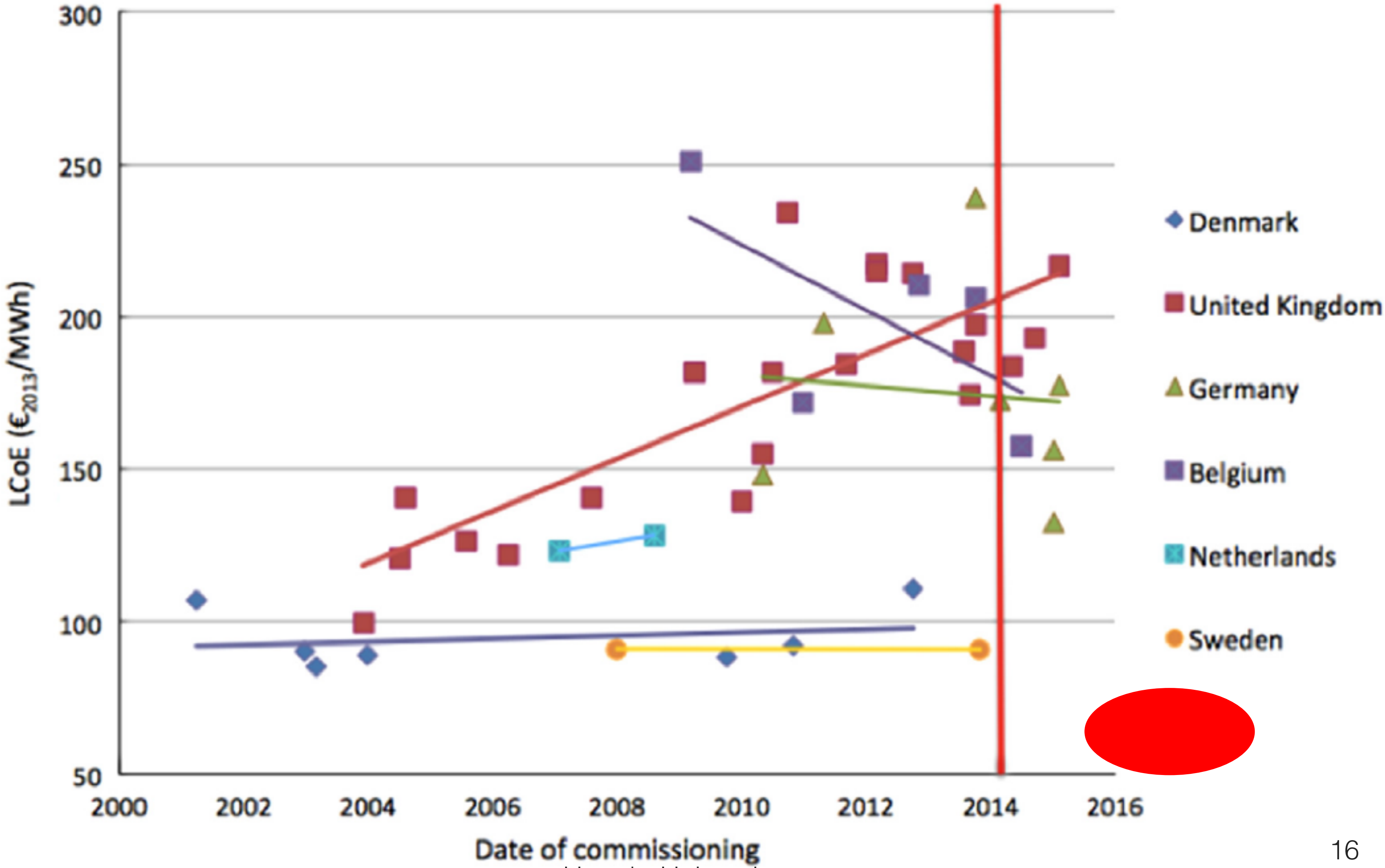
Offshore wind farm CAPEX, corrected for water depth and distance to shore (blue diamond)

source: Voormolen et al. (2016)

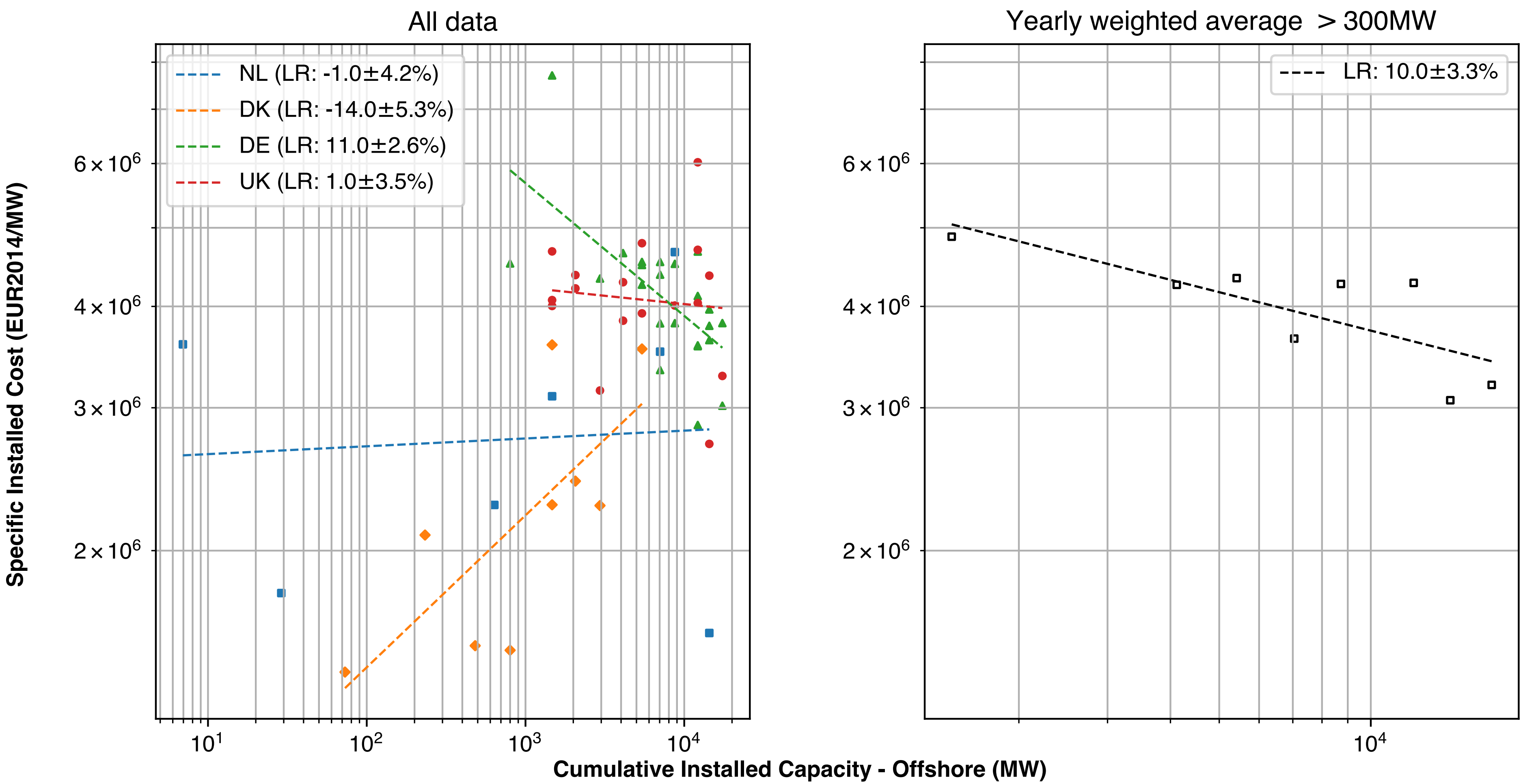


Offshore LCOE trends varying strongly per country

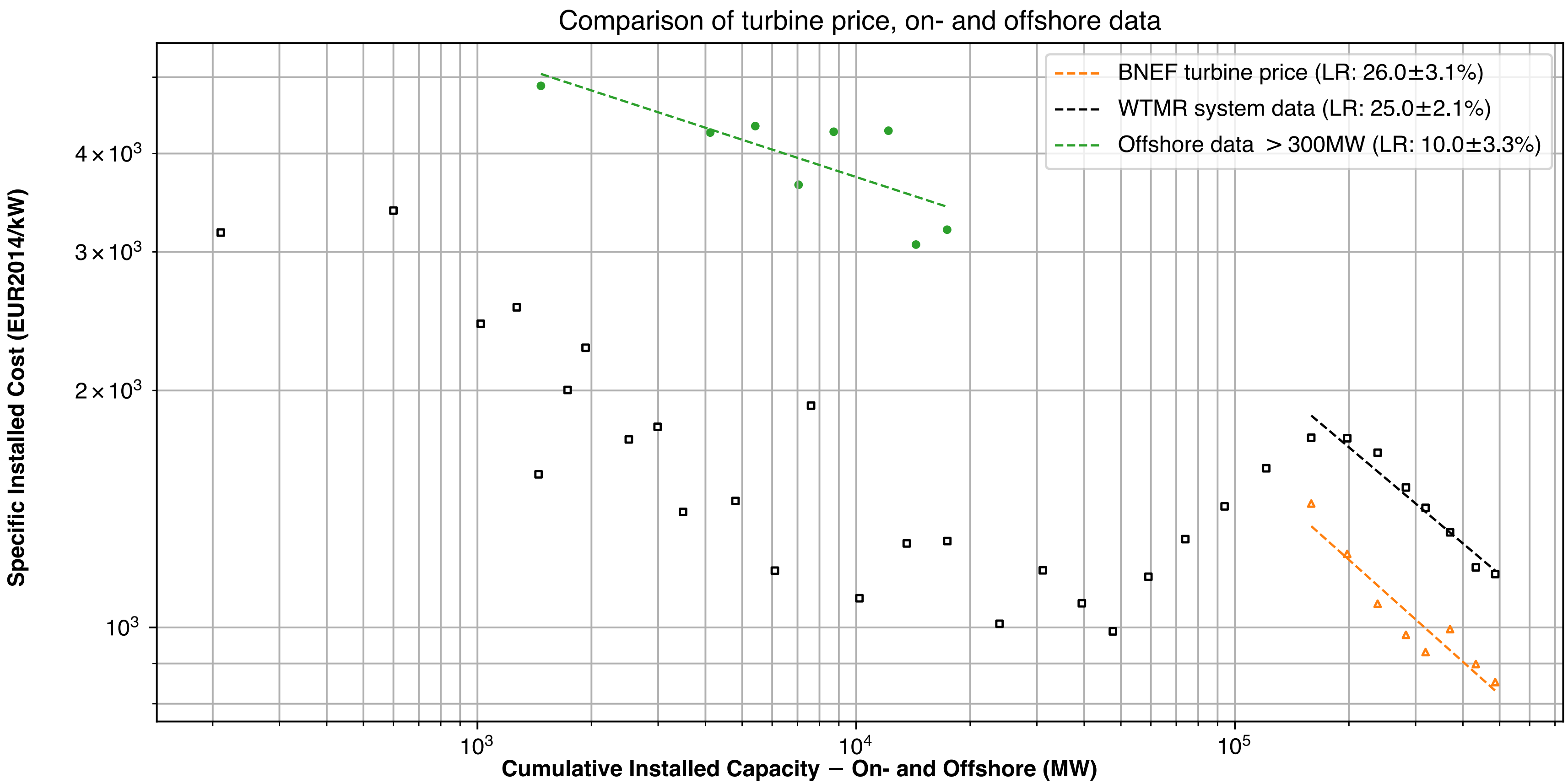
source: Voormolen et al. (2016)



First results – Wind, offshore farms, Europe



First results – Wind, comparison on/offshore, turbines



First results – Offshore wind

- Data is very much scattered (very different farms from 1990-now)
- Only for >300MW farms of last years a learning rate of 10% is observed for EUR/kW
- Pre-2016 trends of LCOE show increase, even when correcting for distance-to-shore and commodity prices
- 2016/2017 show drastic decrease of EUR/MWh
- Also for offshore geographical potential gives constraints
- Grid connection costs (can) optimise in future
- So what now?
  - Experience curve do not seem suitable at the moment
  - Use exogenous estimates

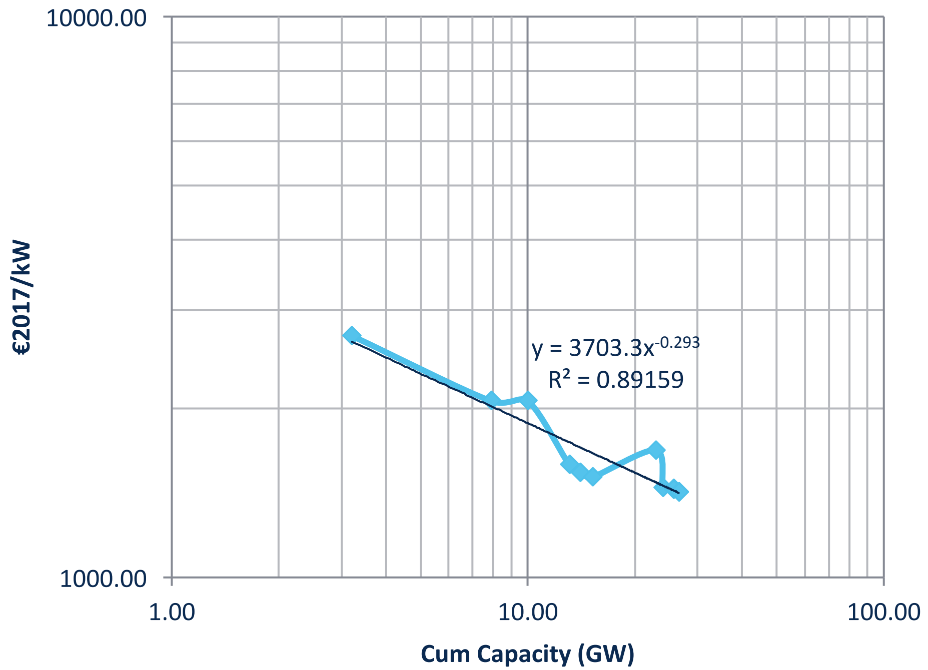
First results – Alkaline Electrolysis, data collection

	Scale	Timeframe	Functional unit	Sources
Capacity	Global	1956-2016	Cumulative GW	1) Schmidt, Hawkes, Gambhir, Staffell (2017), *The future cost of electrical energy storage based on experience rates,* Nature Energy *2)*Cox & Williamson (1977), *Hydrogen:Its technology and Implications.* *3)* Caprioglio, P., *Prosepects fro a hydrogen economy.* Energy Policy, September 1974, Elsevier Scientific Publishing Company, Amsterdam, 1974 4)Hoffman, P., *Tomorrow's Energy,* MIT Press, Cambridge, Massachusetts, 2001. 5) Kelly, J.H., *Hydrogen Energy Syste,ms Technology Study.* International Journal Hydrogen Energy, Vol1, pp 199-204, Pergamon Press Ltd., Great Britain, 1976
System cost		1956-2016	€2017/kW	1)Schmidt, Hawkes, Gambhir, Staffell (2017), *The future cost of electrical energy storage based on experience rates,* Nature Energy 2) Bogers ,1975. *Waterstof als energiedrager,* TNO 3) Hammerli (1984), *When will electrolytic hydrogen become competitive?* International Journal of Hydrogen Energy, 1984 4) Altener (2004), *Market Potential Analysis for Introduction of Hydrogen Technology in Stand –Alone Power Systems.* 5) Kuckshinrichs,W., Ketelaer, T. Koj, J.C; (2017). *EconOMIC Analysis of Improved Alkaline Water Electrolysis.* Frontiers in Energy Research, doi: 10.3389/fenrg.2017.00001

First results – Alkaline Electrolysis

- Presented here are stack costs (EUR/kW),
- Depending on the model we might need, e.g: EUR / kg H_2
  - Electricity price 75% of total cost
- Ambition to also assess the development of specific electricity consumption (kWh/ kg H_2)

LR 18.3%

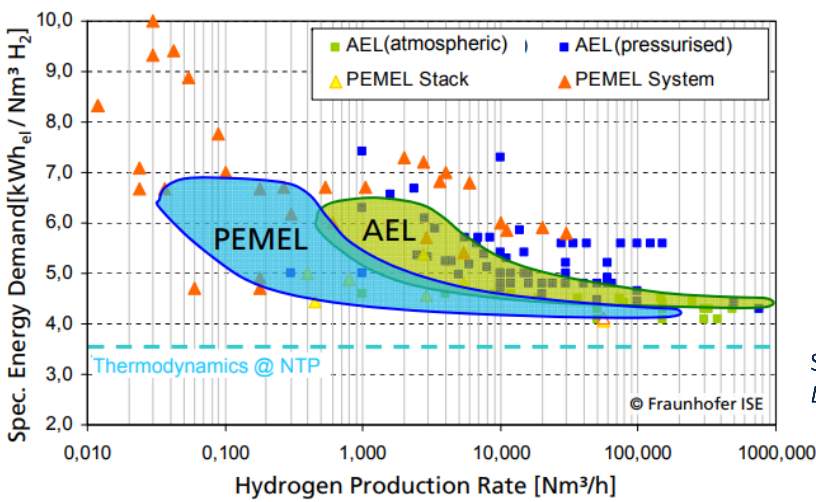


First results – P2H Discussion

- Alkaline vs PEM
- SEC (kWh/kg H_2)
- E.g. (Alkaline electrolysis):
  - 2011: 50 kWh/kg
  - 2015: 46 kWh/kg
  - 2020 (expected) : 44.7 kWh/kg

Alkaline		PEM
	Advantages	
Well established technology		High current densities
Non-noble catalysts		High voltage efficiency
Long-term stability		Good partial load range
Relative low cost		Rapid system response
Stacks in the MW range		Compact system design
Cost effective		High gas purity
		Dynamic operation
	Disadvantages	
Low current densities		High cost of components
Crossover gases		Acidic corrosive environment
Low partial load range		Possibly low durability
Low dynamics		Commercialization
Low operational pressures		Stacks below MW range*
Corrosive liquid electrolyte		

Source: Koponen,J.,(2015). *Review of water electrolysis technologies and design of renewable hydrogen production systems.* Lappeenranta University of Technology



Source: Smolinka, T.,(2014). *Water Electrolysis: Status and Potential for Development.* Fraunhofer-Institut für Solare Energiesysteme ISE

Set-up for this afternoon

- Three parallel sessions
  - Experience curves methodology
  - Model implementation
  - ECs and Environmental Impact
- Aims of these sessions:
  - Discuss current/new general methodological issues related to the use of experience curves / how to implement in energy & other models / discuss suitability to assess future environmental impacts
  - Discuss specific issues encountered in the Reflex project

  - => Scoping session for relevant topics for new book on experience curves

Further time planning and intended outcomes

- Implementation of experience curves in a number o the sector-specific models within the REFLEX consortium over the next 6 months
- Comprehensive report on experience curves for specific technologies in May 2018
- Dedicated book on experience curves in mid 2019

Program for today

Plenary Sessions
Wednesday, 8th November 2017, 09:00 – 12:30
Room: 418
Chair: Dominik Möst

Time	Topic
08:45	**Registration**
09:00	**Welcome and introduction** General introduction of the REFLEX project (Dominik Möst, TUD) REFLEX WP3 Overview (Atse Louwen/Martin Junginger, UU)
09:20	**Experience Curves for Electricity Storage Technologies** Oliver Schmidt (Imperial College)
09:50	**Experience Curves for DSM technologies** Ulrich Reiter or Martin Jakob (TEP Energy)
10:20	**From learning curves for current technologies to new & emerging technologies** Uwe Remme (IEA)
10:50	**Coffee Break**
11:20	**Case study: application of experience curves in the ASTRA transport model** Stephanie Heitl (Fraunhofer ISI)
11:50	**Experience Curves for Assessment of Environmental Impact** Atse Louwen (Utrecht University)
12:15	**Quantum Modelling of the Learning Curve – achievements and prospects** Clas-Otto Wene (Wenergy)
12:30	**Lunch break**

Program for today

Parallel Sessions Wednesday, 8th November 2017, 13:30 – 16:20			
Time	**Experience Curves Methodology** Chair: Martin Junginger (UU)	**Model Implementation** Chair: Theresa Müller (TUD)	**Environmental Impact** Chair: Atse Louwen (UU)
13:30	**One vs Two-factor Experience Curves** Noah Kittner **Markets, spillover and radical innovations** Thomas Martinsen (NMBU)	**Model Implementation** Theresa Müller (TUD) Tobias Fleiter (Fraunhofer ISI)	**Experience Curves for Future Environmental Impact Assessment** Atse Louwen (UU) **Lifecycle Inventory Updating for Future Environmental Impact Assessment** Mary Fuss / Lei Xu (KIT-ITAS)
14:30	**Coffee break**		
14:45	**Discussion**	**Discussion**	**Discussion**
16:00	**Wrap up and closing (UU)**		
16:20	End of workshop		

Some practical issues for today

- Three parallel sessions
  - Experience curves methodology- Room 418
  - Model implementation – Room 16
  - ECs and Environmental Impact Room 511

Please sign the participants list – we need it

Lunch

Have a great workshop

I look forward to all discussions

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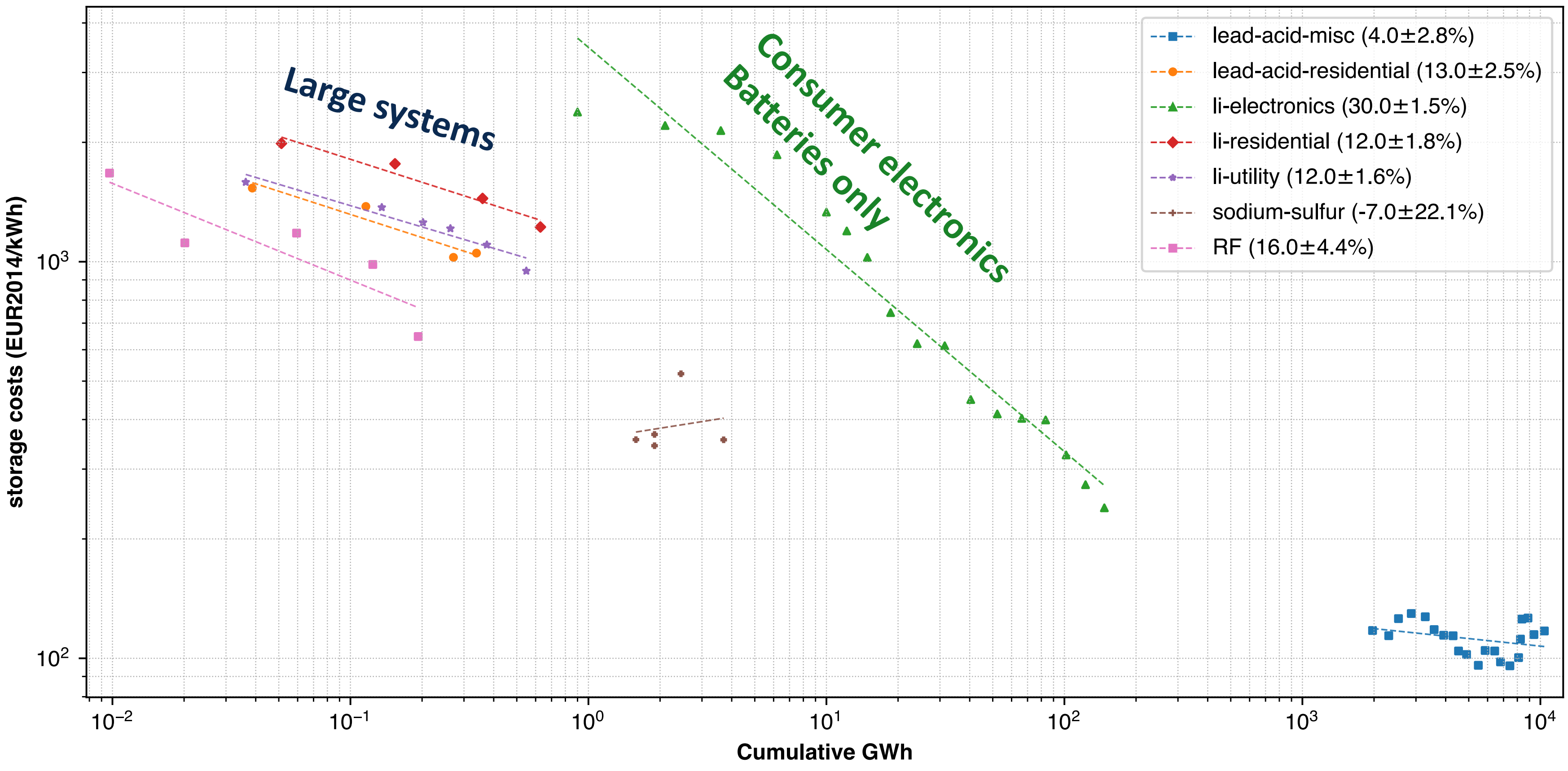
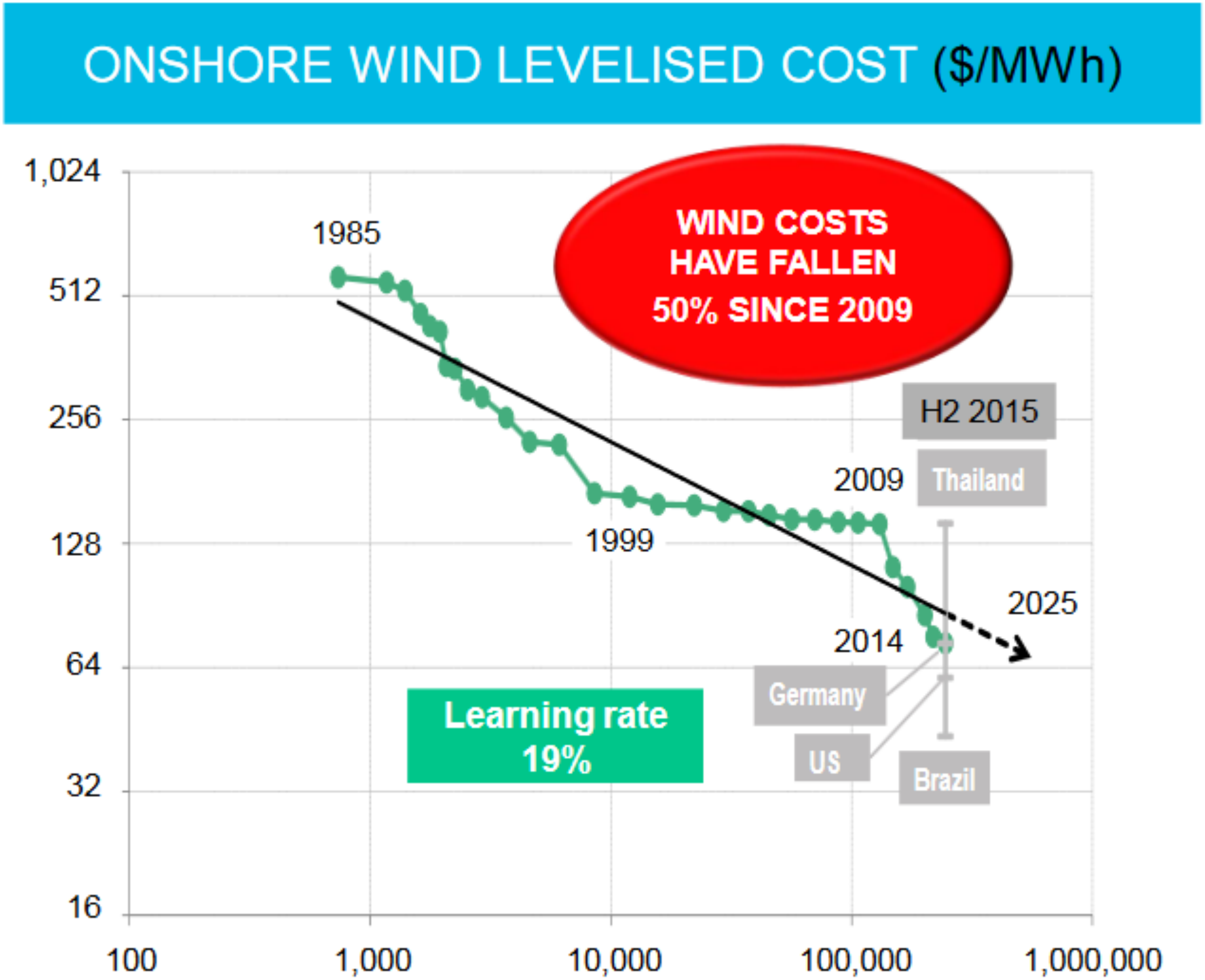
Back Up

First results – Electricity storage



Wind onshore - electricity

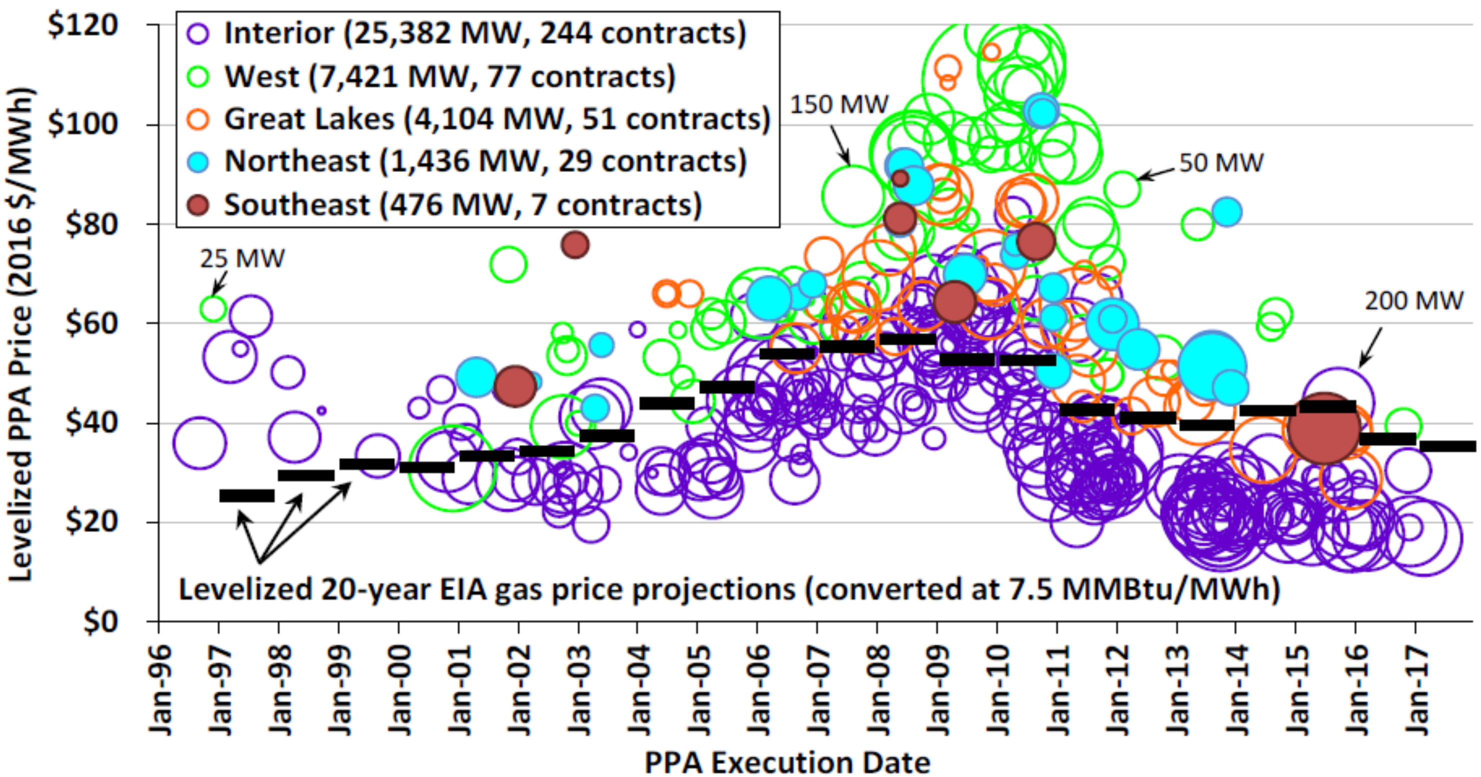


Note: Pricing data has been inflation corrected to 2014. We assume the debt ratio of 70%, cost of debt (bps to LIBOR) of 175, cost of equity of 8% Source: Bloomberg New Energy Finance

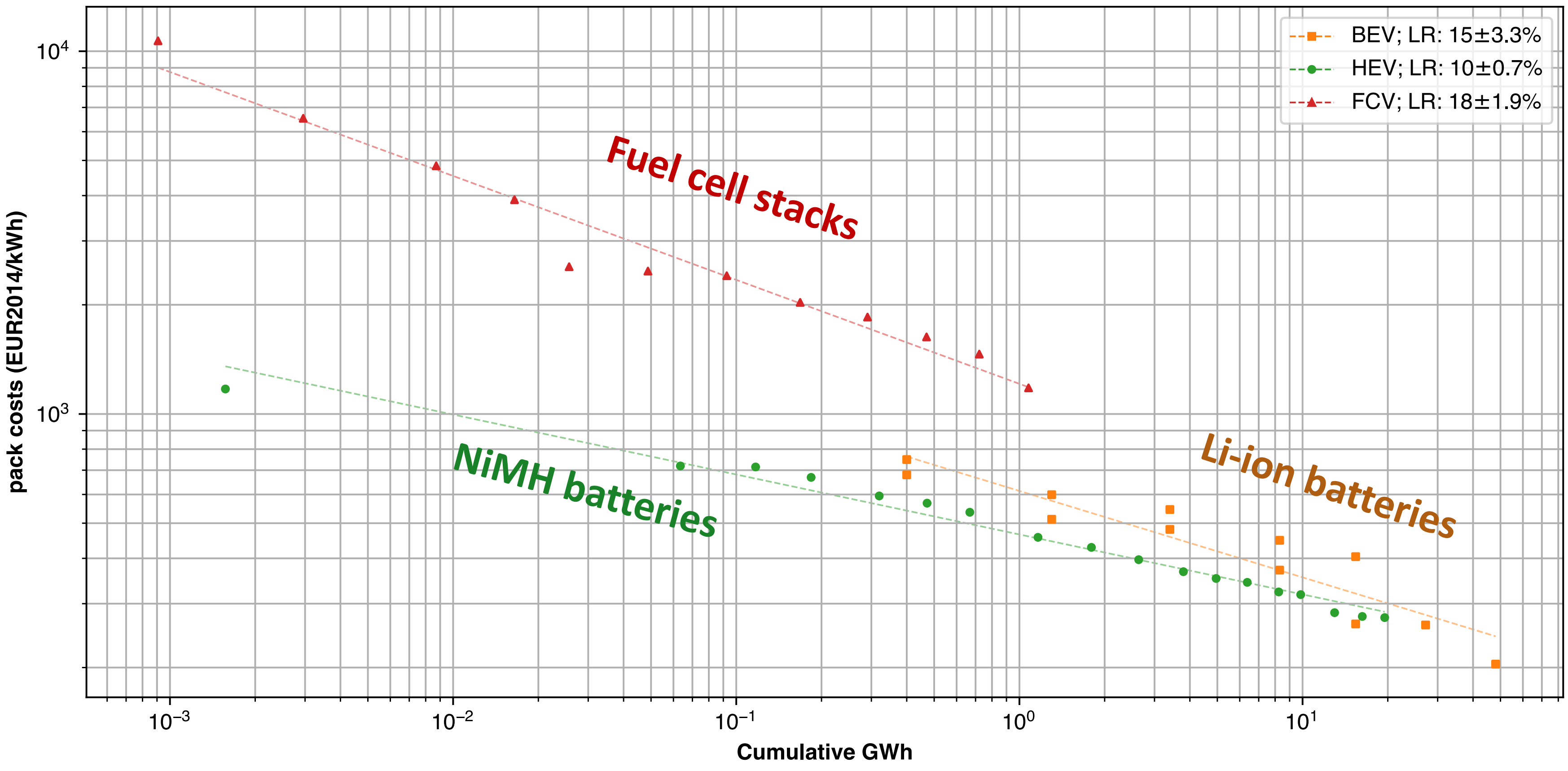
Wind onshore - electricity

Wind Power Price Trends

Wind PPA Prices Very Low, Competitive with Levelized Fuel Cost of a Gas Plant



First results – BEV/HEV battery packs, FC stacks

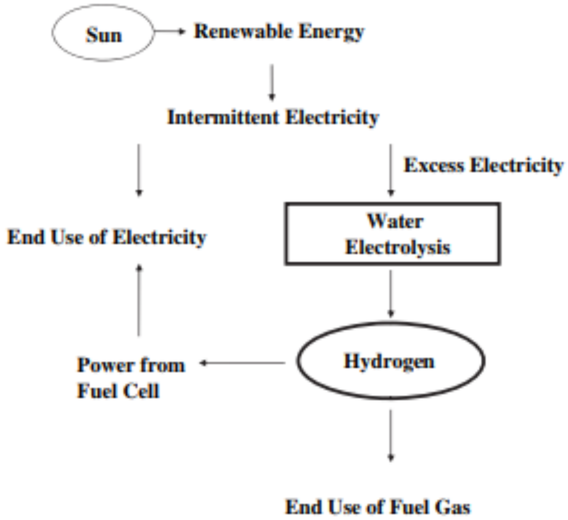


First results, Storage and Vehicle Packs

- Majority of data from Schmidt et al., 2017
- Minor updates performed, could do more updates for certain datasets
- In general nice trends for batteries
- No clear scale effect, e.g.
  - Li-ion for electronics << home/utility storage
  - But: home and utility storage learn at same rate but different price levels
- No specific data for PHEV battery packs
- Supply (capacity) > Demand:
  - Do current cost trends reflect production costs, or shakeout?

First results – Power to Hydrogen

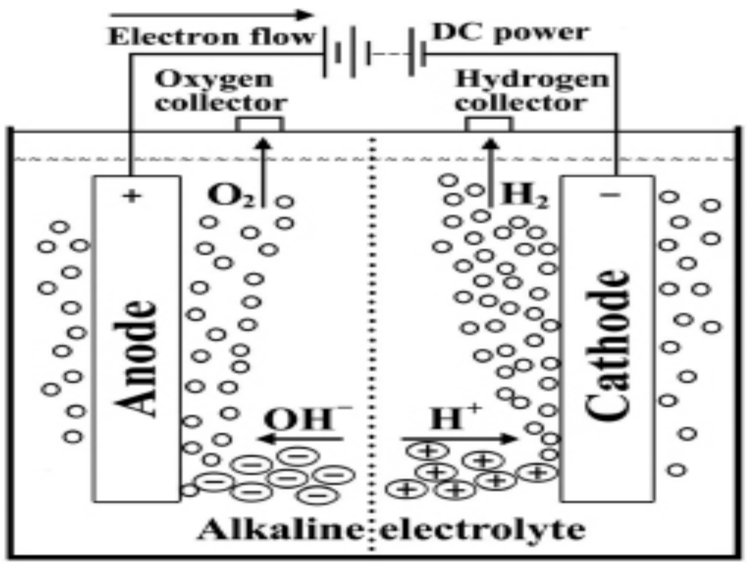
- Concept



Source: Zeng & Zhang, (2010) *Recent progress in alkaline water electrolysis for hydrogen production and applications*

First results – Alkaline Electrolysis

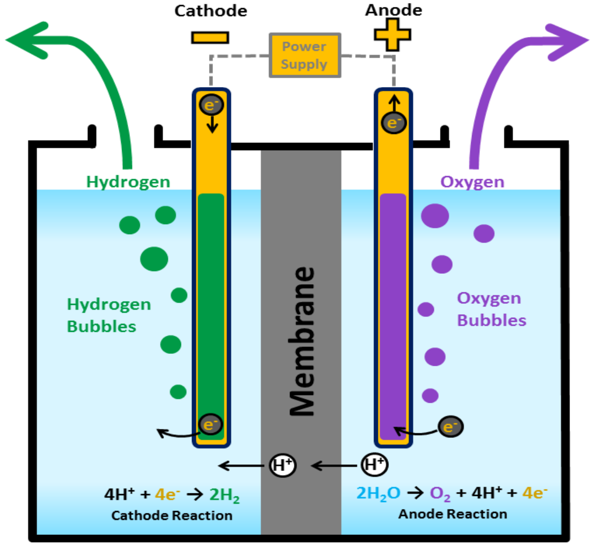
- KOH electrolyte
- Cathode: $2H_2O + 2e^-$ ⟶ $H_2 + 2OH^-$ (E^0 = - 0.83V)
- Anode: 2OH ⟶ ½ $O_2 + H_2O$ +2 e^- (E^0 = 0.40V)
- Overall: H_20 ⟶ H_2 + ½ O_2 (E_0 = -1.23V)
- Operational temperature: 50 – 90 ^{0}C
- Pressure: 1-30 bar



Source: Santos, Sequeria, Figueiredo, (2013); *Hydrogen production by alkaline electrolysis*

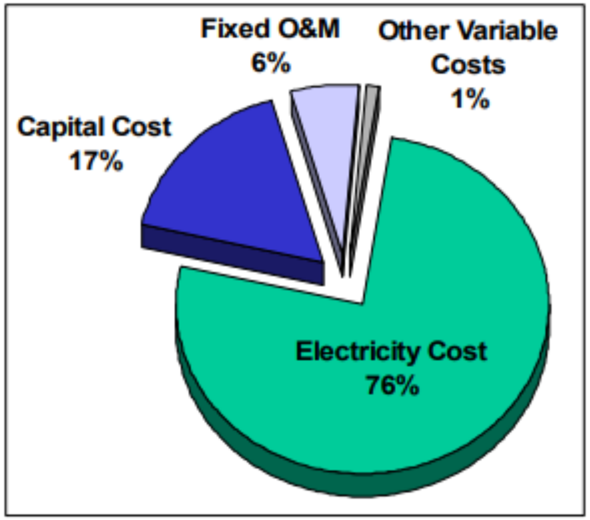
First results – Polymer Electrolyte Membrane (PEM)

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.
- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.
  Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
  Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$
- Pressure up to 200 bar
- Temperature: 20 – 100 ^{0}C



First results – P2H Cost breakdown (Alkaline Electrolysis)

- Capital cost
  - Stack Capital cost
  - BOP Capital cost
  - Indirect Capital cost and replacement cost



Source: NREL (2009); *Current State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*

First results – Alkaline Electrolysis Experience Curve

input values						
Production to storage			inflation rate 2017 (USD)			USD € exchange rate
kW	kWh		2003	2015		
1	10		33%	3,30%		0,85

	P(x)=AX^-b	
A	3703	
b	0,293	
ER	18.3%	ER= 1-(2^-b)