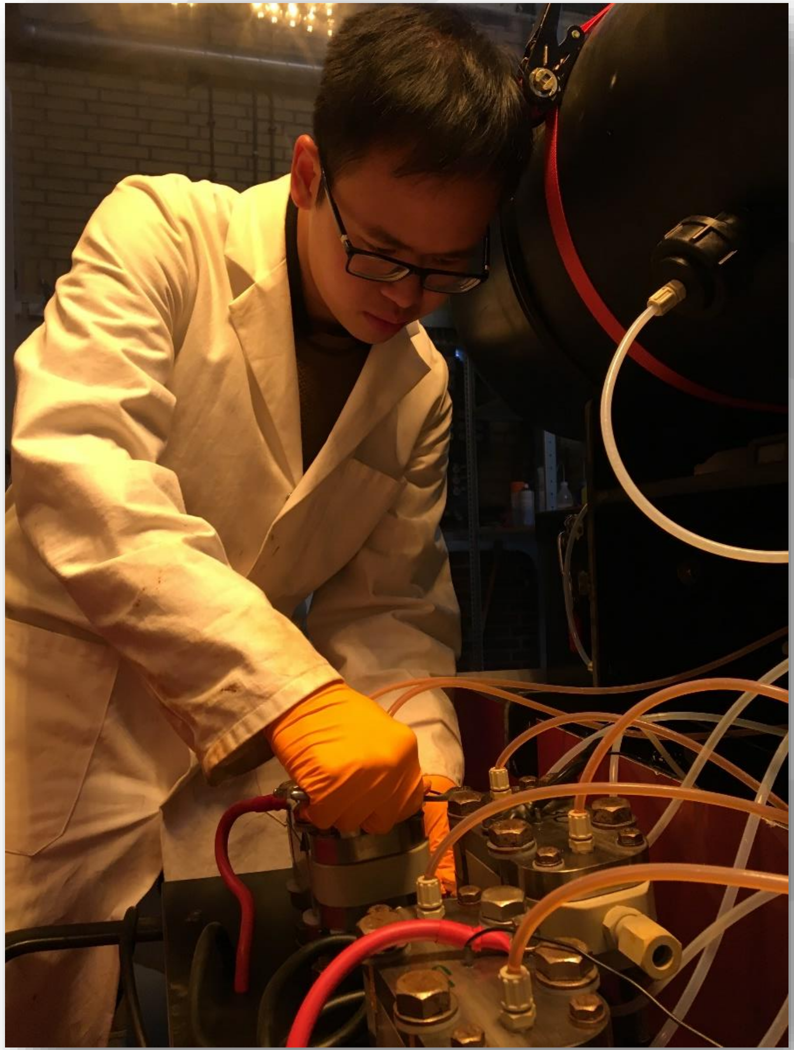
KIVI Engineering Society

Afdeling Elektrotechniek

The Hydrogen Bromine Flow Battery



Wiebrand Kout, CTO, Elestor BV

ELESTOR electricity storage

The energy transition paradox

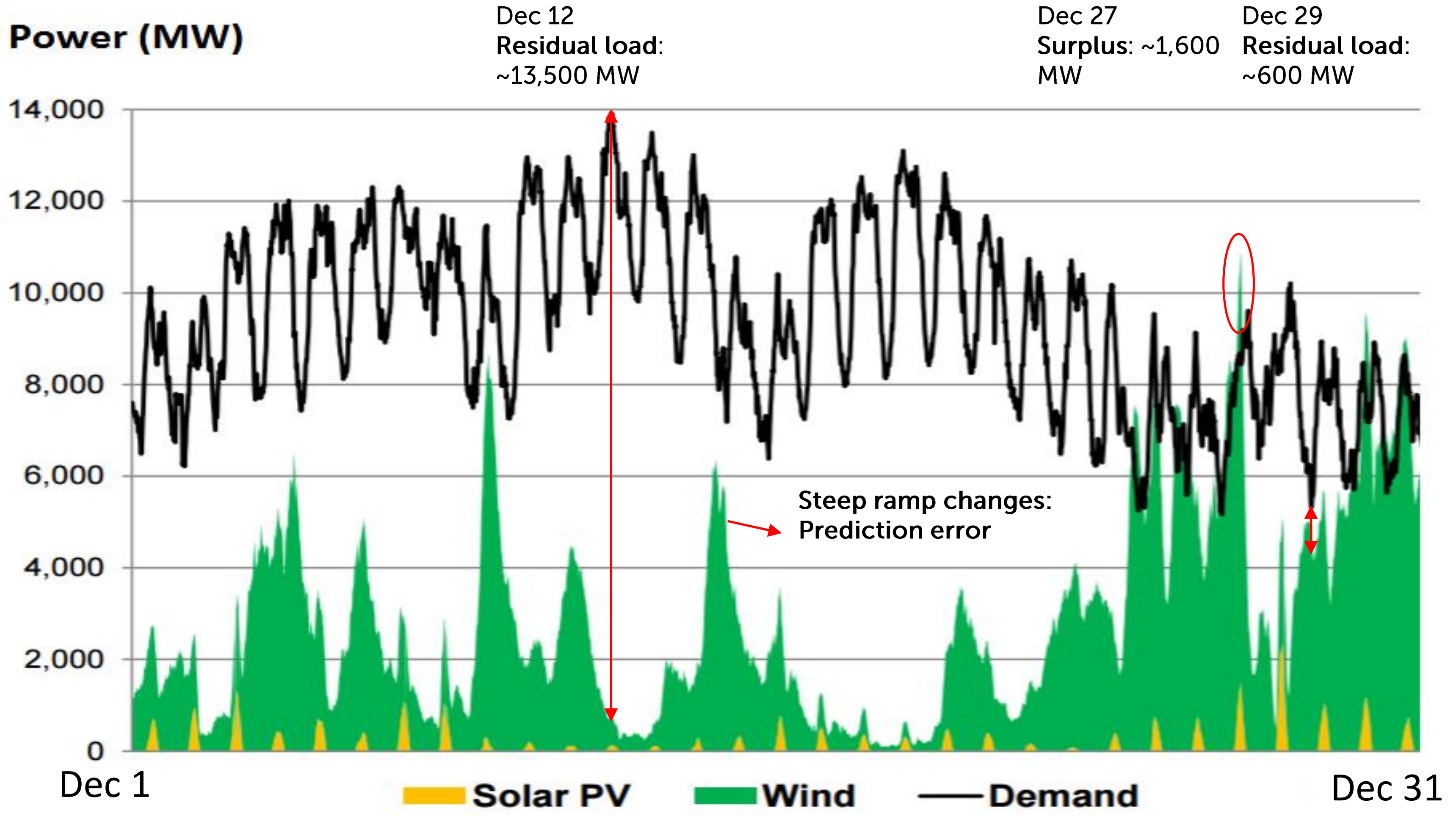
3,9 * 10^26 W

Then… What is the problem?!

Clean energy sources are abundant available …

… and the technologies have been developed to generate all the electricity

The energy transition paradox



Germany, December 2016

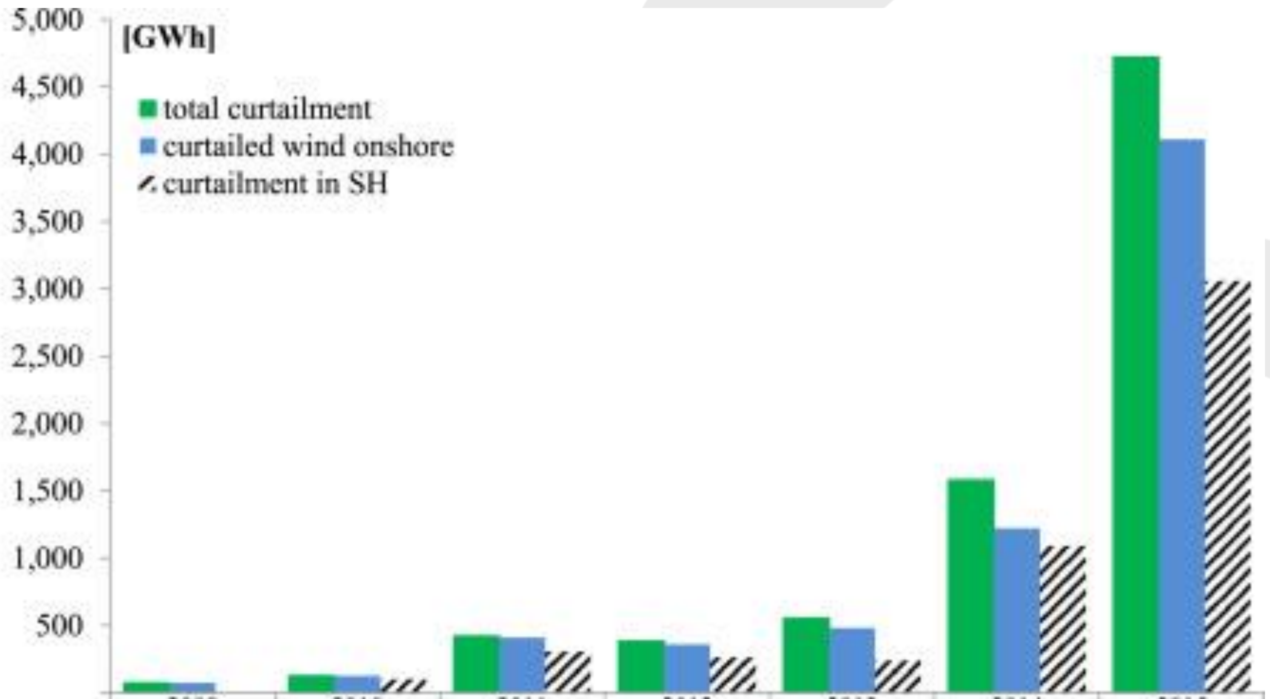
Source: SBC Energy Institute

The energy transition paradox

A further increase of the installed base of renewable energy systems will result in:

- *Larger grid-instability problems*
- *Exponential growth of curtailment*

→ Fossil power plants remain
→ Negligible CO_2 reduction
→ Energy transition frustrated



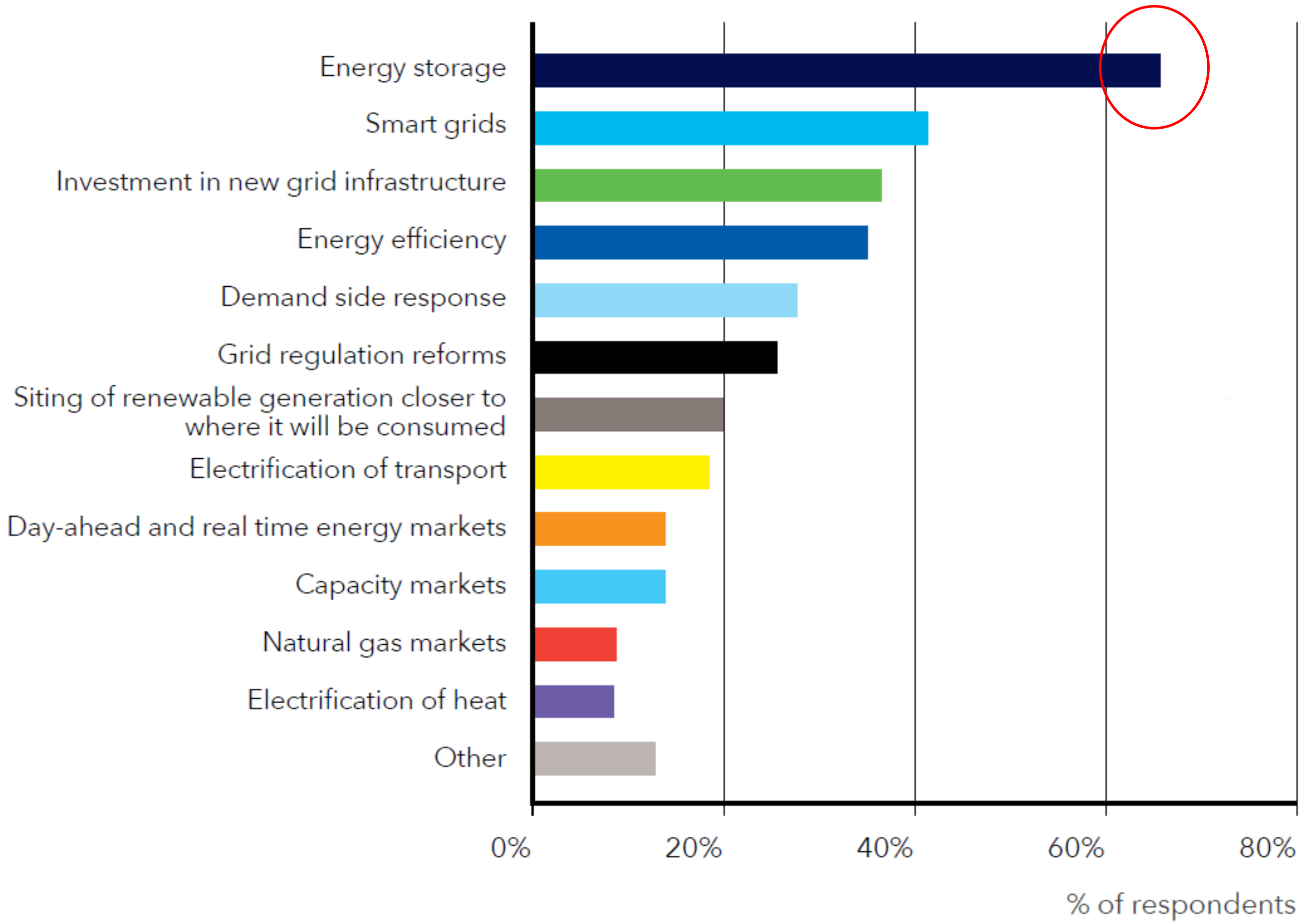
[GWh]	2009	2010	2011	2012	2013	2014	2015
total curtailment	74	127	421	385	555	1,581	4,722
curtailed wind onshore	73	125	410	358	480	1,221	4,110
curtailment in SH		100	308	262	239	1,092	3,055

Source : Renewable energy curtailment: A case study on today's and tomorrow's congestion management. Authors: Hans Schermeyer, Claudio Vergara, Wolf Fichtner

In 2015 about 4.7 TWh (2.9% of total generated) was curtailed (cost 478 M€)

Awareness

Survey : *"Which are most important changes of interest for integrating a high share of renewables (70% by generation) in a cost-effective way ?"*

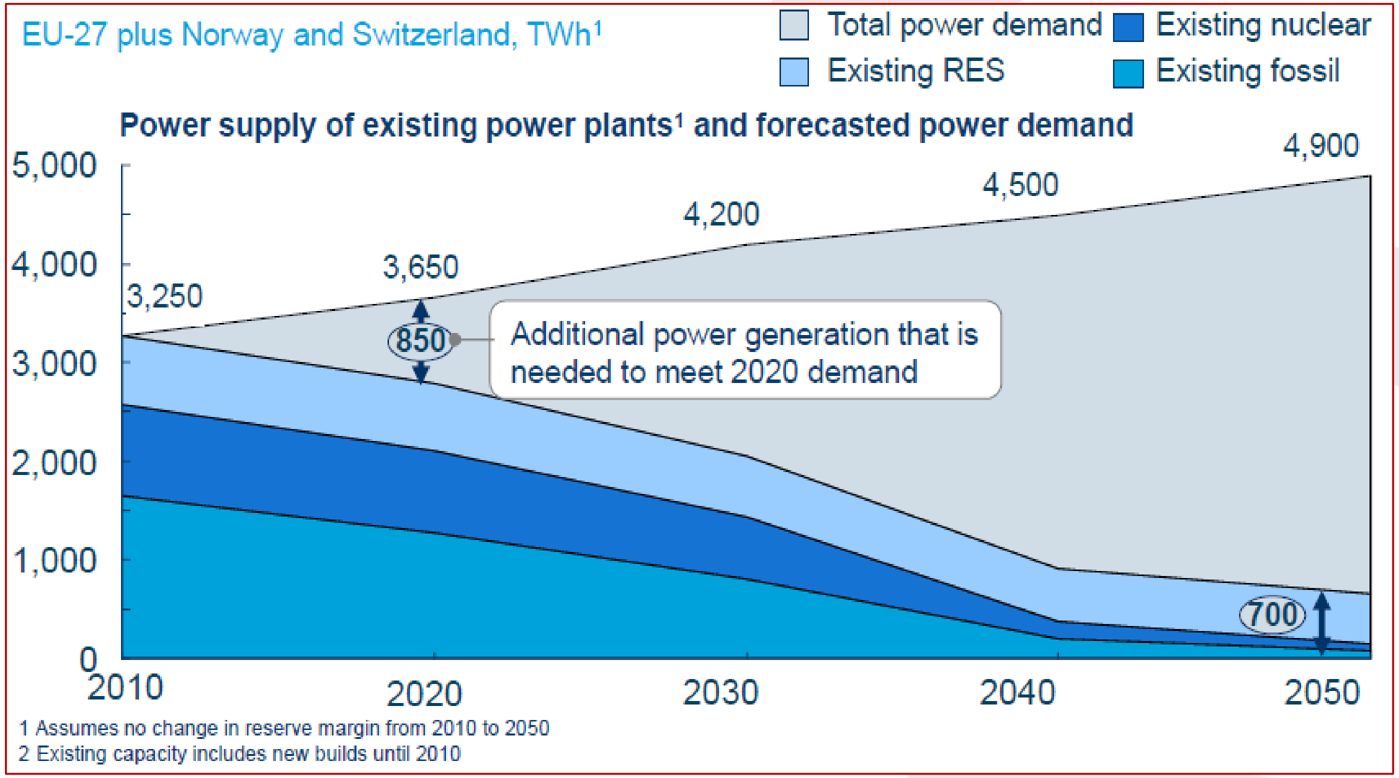


Two-thirds out of 1,665 respondents

The market for storage systems (1)

- European Climate Foundation (outlook in 2014) :

  "By 2020 a yearly additional capacity of 850 TWh will be required, most of which will have to be covered by renewable energy sources to meet the targets for reduction of CO_2 emission"

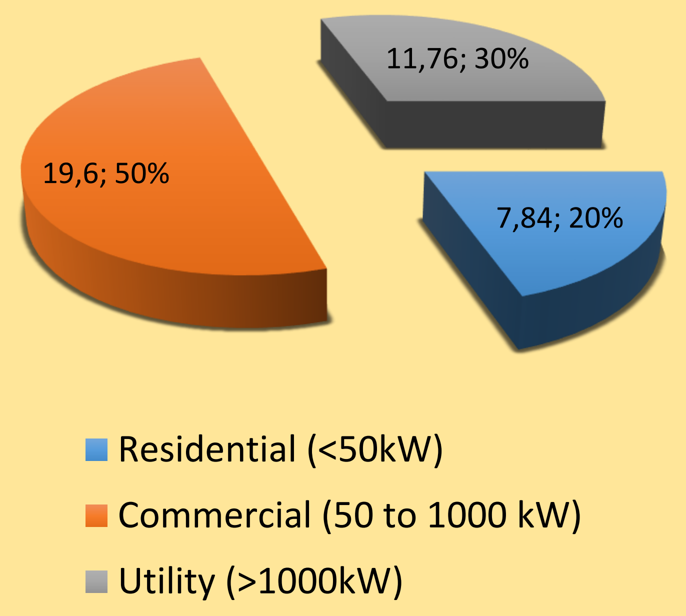


→ Renewable energy sources will continue to show massive growth figures - for decades

→ Similar magnitudes for growth can be expected for storage systems

→ Prior predictions are almost always too conservative !

The market for storage systems (2)



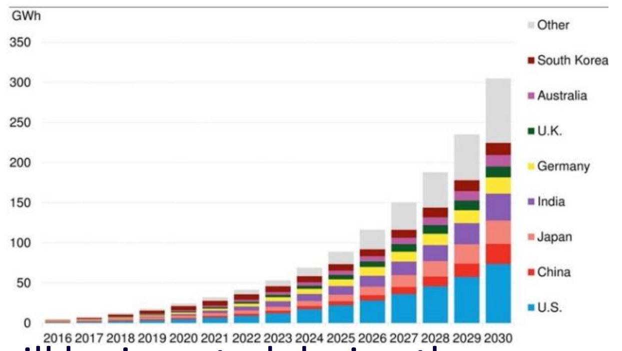
2025 EU-27 electricity storage TAM by segment [B€]

- Bloomberg New Energy Finance (BNEF) :

Energy storage market to double six times by 2030

21 November 2017, source edie newsroom

The global energy storage market looks to mirror the rapid growth the solar industry experienced between 2000 and 2015, with a new Bloomberg New Energy Finance (BNEF) report predicting that the energy storage market will double six times by 2030.



BNEF predicts that > $100bn will be invested during the next 15 years in the energy storage market

The energy transition paradox

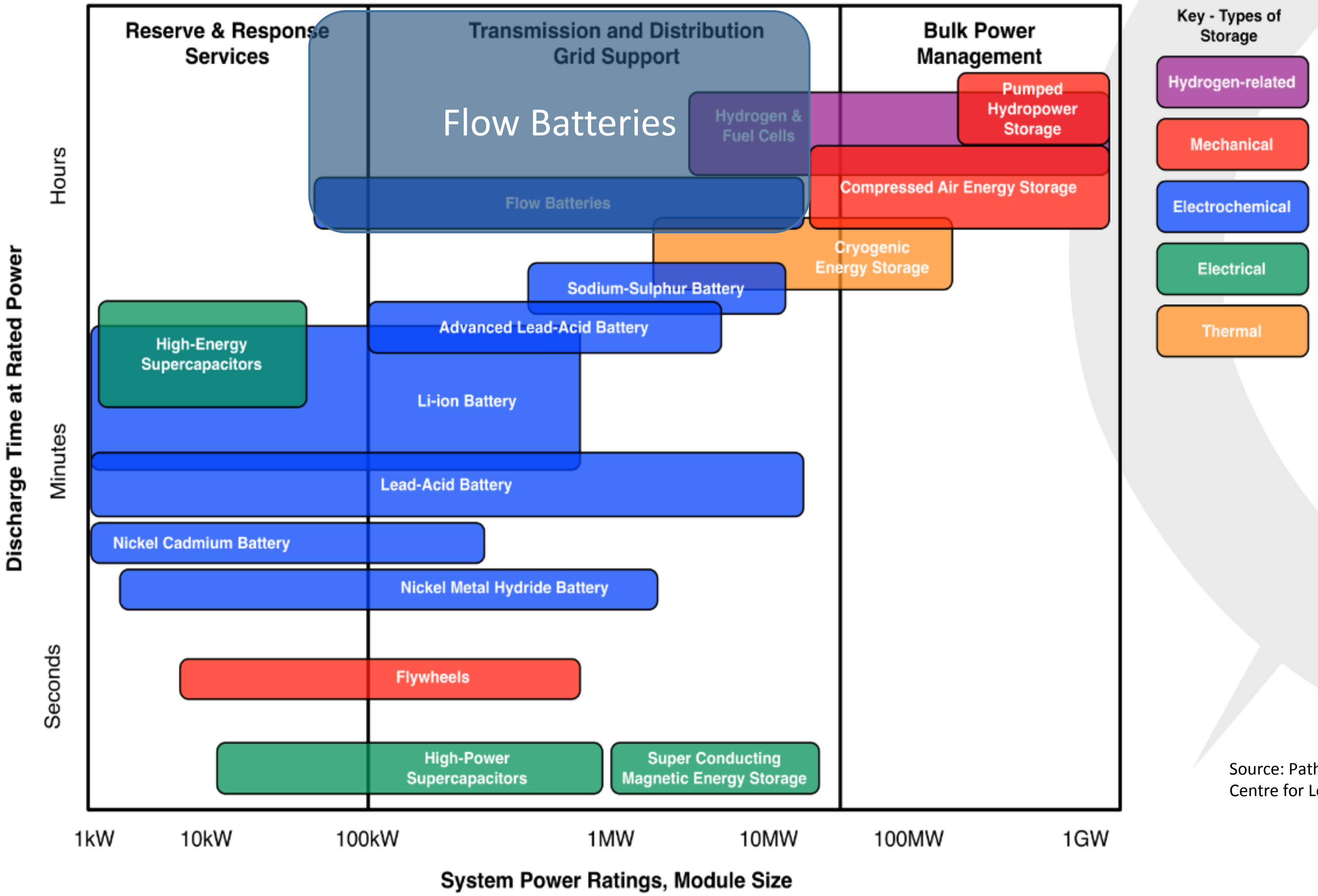
KIVI-EL, 24 januari 2018

Electricity storage technologies are available in many form

Then… What is the problem?!

… and the suppliers are there!

Electricity storage techniques and applications



Source: Pathways for energy storage in the UK", Centre for Low Carbon Futures, 2012

It's all about 'Storage Cost per kWh'

$$\text{Storage Cost per kWh} = \frac{\text{Total costs during life}}{\text{Total energy during life}} = \frac{\text{Capital investment [€] + Maintenance costs [€]}}{\text{Lifetime [cycles] * } \underline{\textit{Usable}} \text{ Capacity [kWh] * Efficiency [\%]}}$$

- The result is referred to as the 'Levelized Cost of Storage', or LCoS

→ Says what it **really costs** to store 1 kWh of energy

→ Enables **objective comparison** of different storage technologies

→ Determines business case **profitability** in combination with trade :

* LCoS > ~€ 0,07 per kWh → Storage is a Cost factor

* LCoS < ~€ 0,07 per kWh → Storage is a Business model

→ The LCoS is decisive for the market adoption of a storage technology

Lithium Ion batteries

High energy density, suitable for portable & EV applications

A

- High
- Fast r
- High
- Scala

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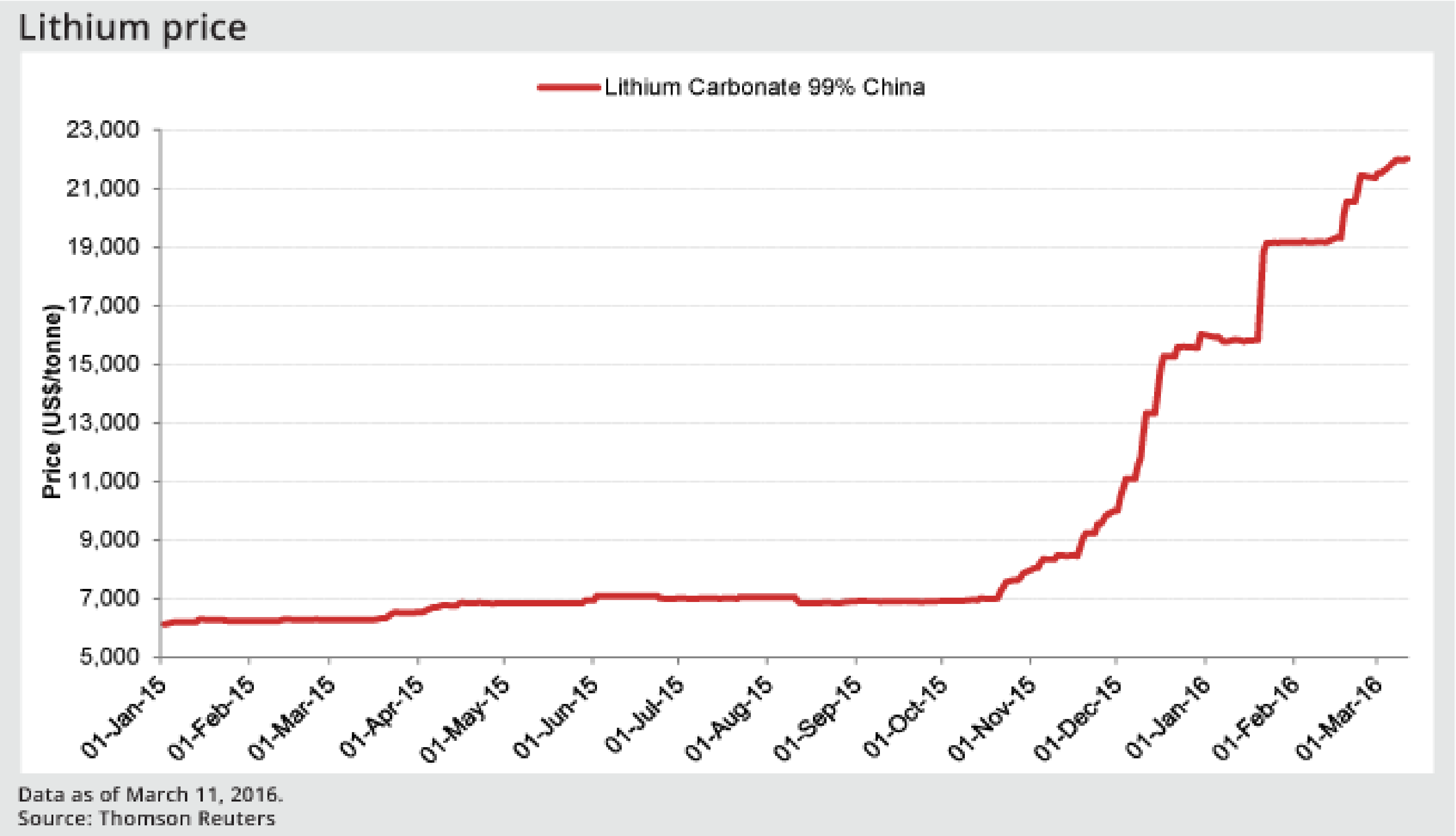
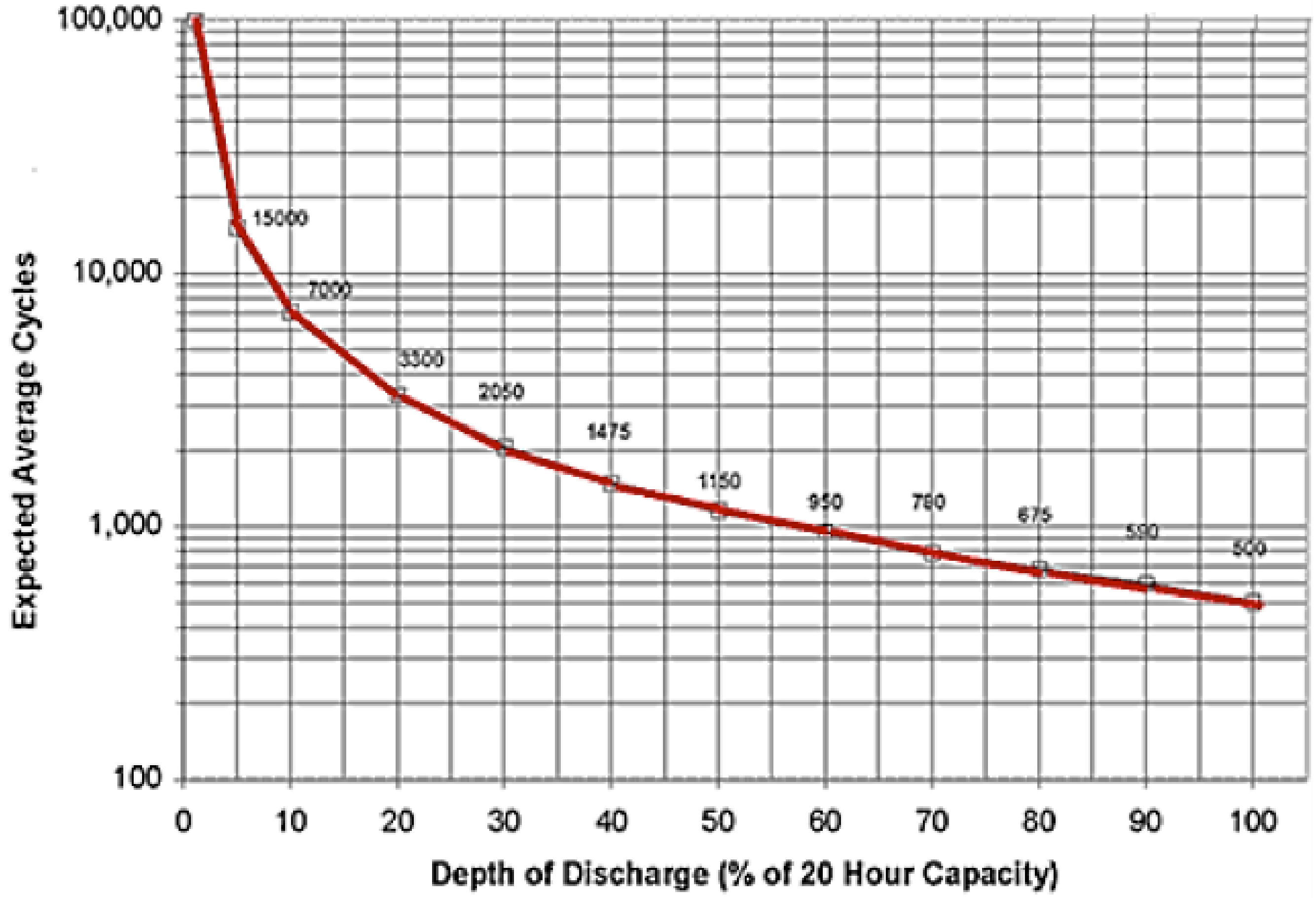


Lifetime and Depth of Discharge (DoD)

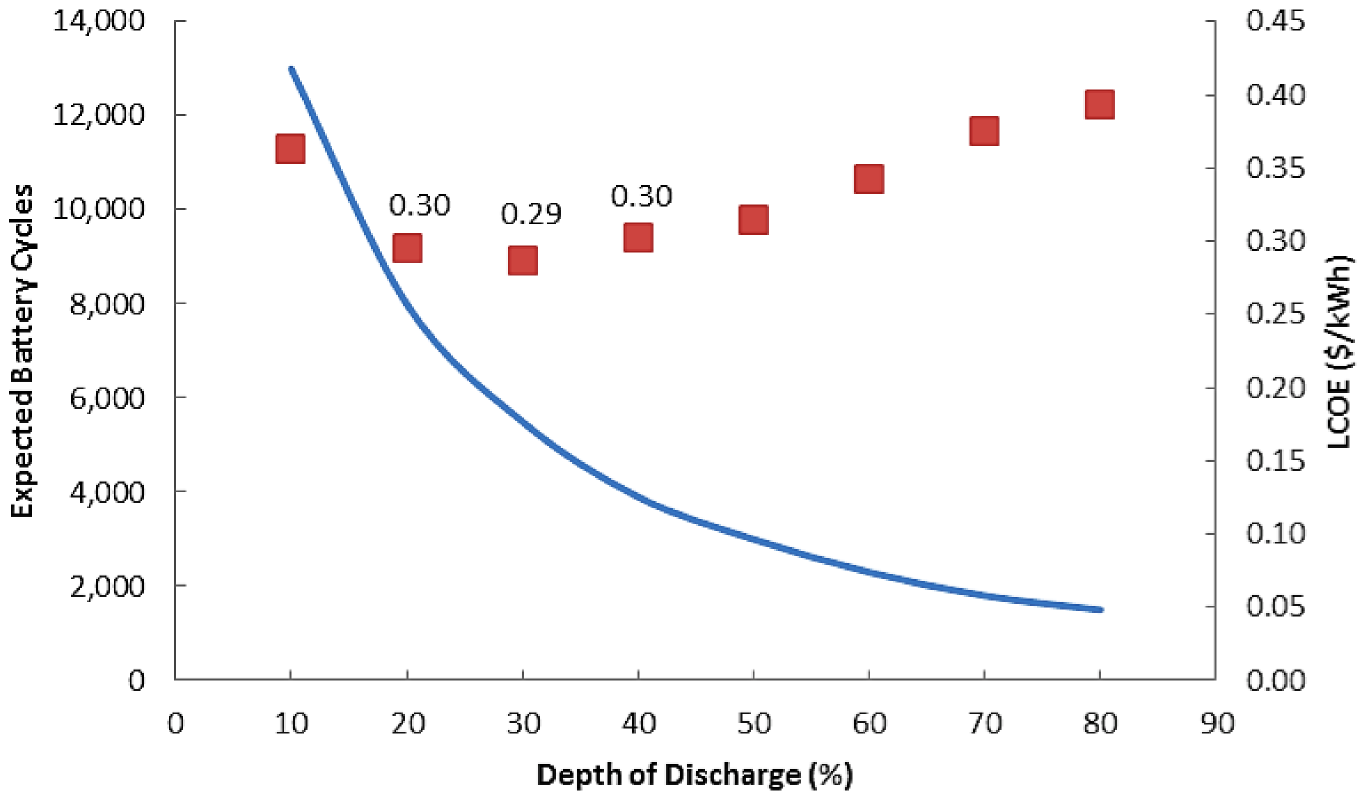


Cycle Lifetime = f(DoD)

Source: Levelised cost of storage: A better way to compare battery value *by* JOHN RODRIGUEZ *on MAY 23, 2017, in* USEFUL SOLAR TOOLS AND RESOURCES, BATTERIES & ENERGY STORAGE

LCoS and DoD

Example: Lead acid



Source: Levelised cost of storage: A better way to compare battery value *by* JOHN RODRIGUEZ *on MAY 23, 2017, in* USEFUL SOLAR TOOLS AND RESOURCES, BATTERIES & ENERGY STORAGE

Flow Batteries on the rise …

"Another promising storage technology that deserves more investment is called a flow battery."

From: "Energy Innovation –Why we need it and how to get it." 30/11/2015

University of California
Berkeley
Haas School of Business

"Solution : HBr Flow Battery"

From: "Hydrogen Bromine Flow Battery for Grid Scale Energy Storage"

"Vanadium redox fuel cells is one of the coolest things I've ever said out loud"

From: Presidential roundtable discussion at Cleveland State University

IFBF The International Flow Battery Forum™

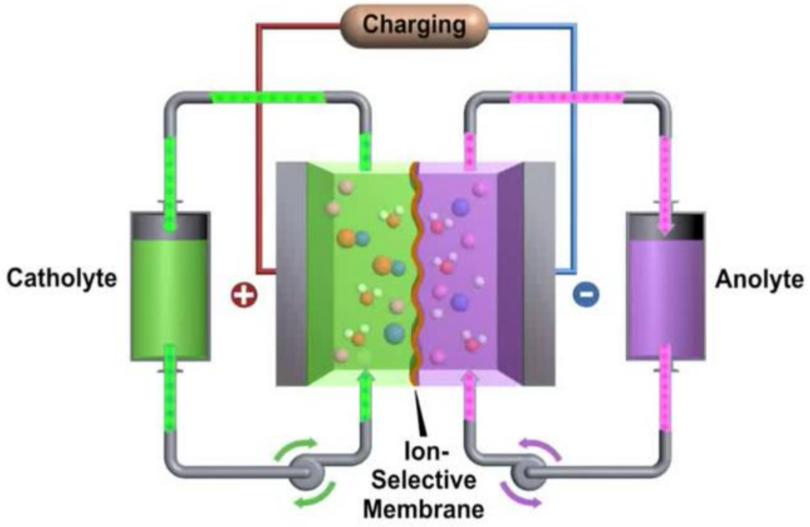
"The 8th International Flow Battery Forum (Manchester) brought together 212 delegates from 24 countries"

Working principle

- A (redox) flow battery is a rechargeable battery, consisting of 2 reservoirs and an ion-selective membrane

- The active materials:
  - Are contained within the system
  - Circulate in their own respective area
  - Are separated by the membrane

- Ion exchange occurs through a membrane



Movie by : Pacific Northwest National Laboratory (PNNL) S&T

Power and Capacity are not coupled:

- Membrane surface area → Power [kW]
- Active material volumes → Capacity [kWh]

Flow battery types

A wide range of chemistries has been investigated:

Chemistry	Cell voltage (V)	Power Density (W/m^2)
Hydrogen - Lithium Bromate	1,10	15.000
Hydrogen – Bromine	1,07	8.000
Iron – Tin	0,62	<200
Iron – Titanium	0,43	<200
Iron – Chrome	1,07	<200
Vanadium – Vanadium	1,40	3.500
Sodium – Bromine	1,54	800
Zinc – Bromine **	1,85	1.000
Lead – Acid **	1,82	1.000
Zinc – Cerium **	2,43	2.500

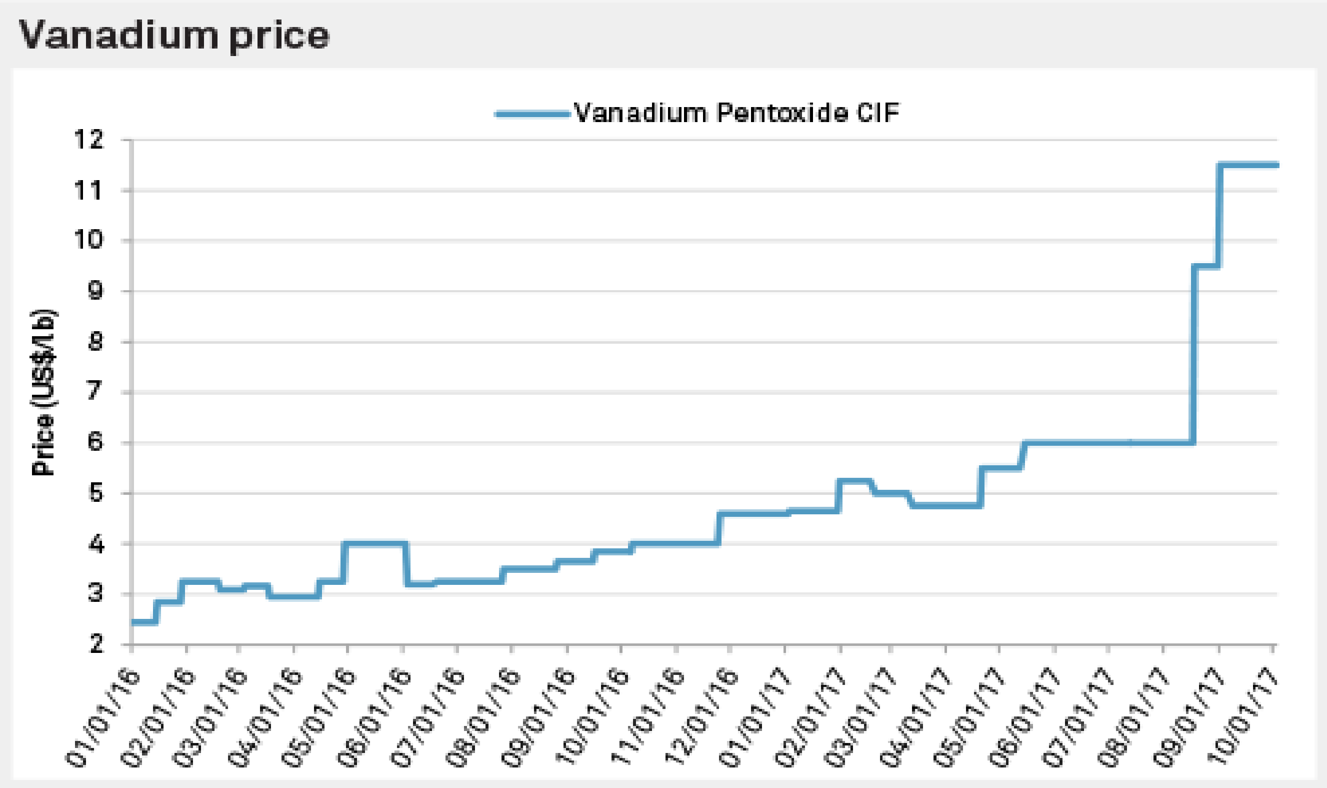
But, only a few chemistries qualify for commercialisation

*** By definition, these configurations are so-called 'Hybrid Flow Batteries'.*
Since 1 of the reactive components is deposited as a solid layer, the battery capacity is limited by the surface area of the electrode

All Vanadium Flow Batteries (VFB)

Reliable and simple energy storage system

- Indepe
  power
- Fast re
- Scalab
- Minim
- Long li



Data as of Oct. 4, 2017.
Source: Thomson Reuters

antages

- lensity
- ancillary parts
- m cost

Hydrogen Bromine Flow Batteries (HBFB)

High power-low cost flow batteries

Advantages

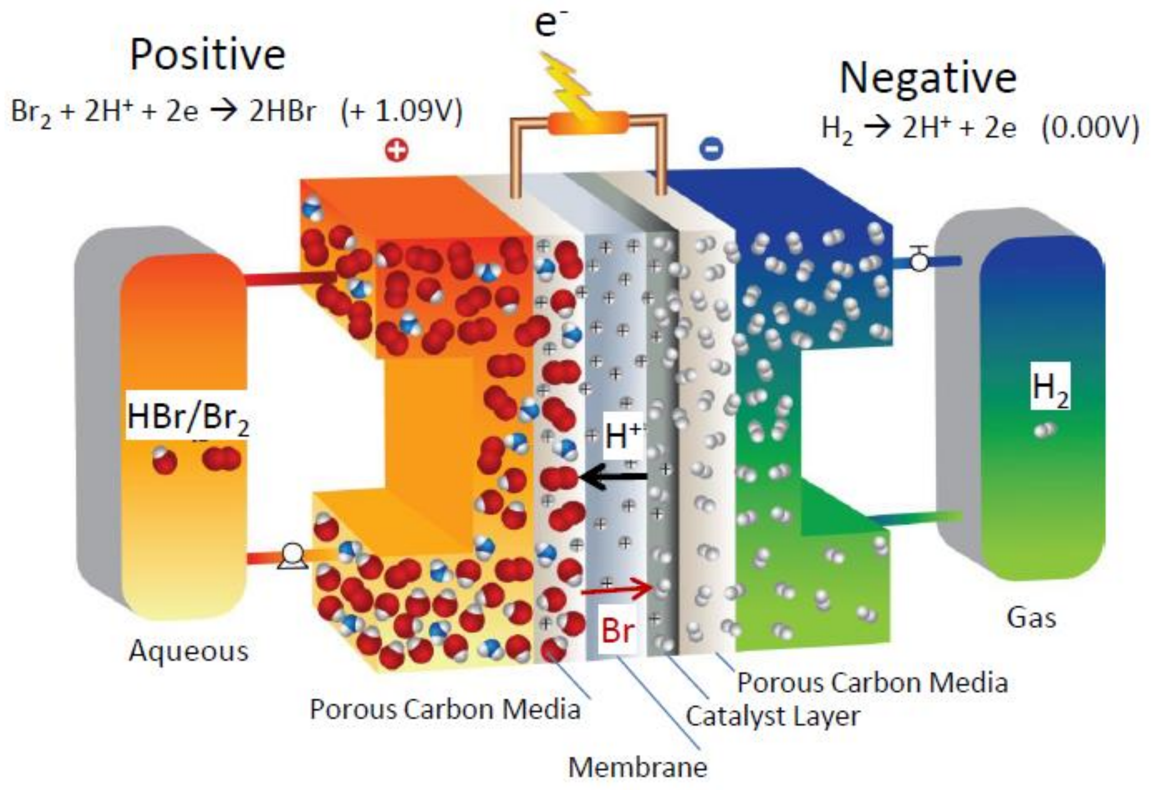
- High power density
- Easy to manufacture
- Low active materials cost
- Active materials can be fully recycled

Disadvantages

- More complex two phases system
- Environmental & technical concerns regarding the electrolyte solution

The Hydrogen Bromine Flow Battery (HBFB)

High power, low-cost system



Picture courtesy of Dr. M. Tucker

$$H_2 + Br_2 \underset{\text{discharge}}{\overset{\text{charge}}{\leftrightarrows}} 2\,HBr + \text{electrical energy}$$

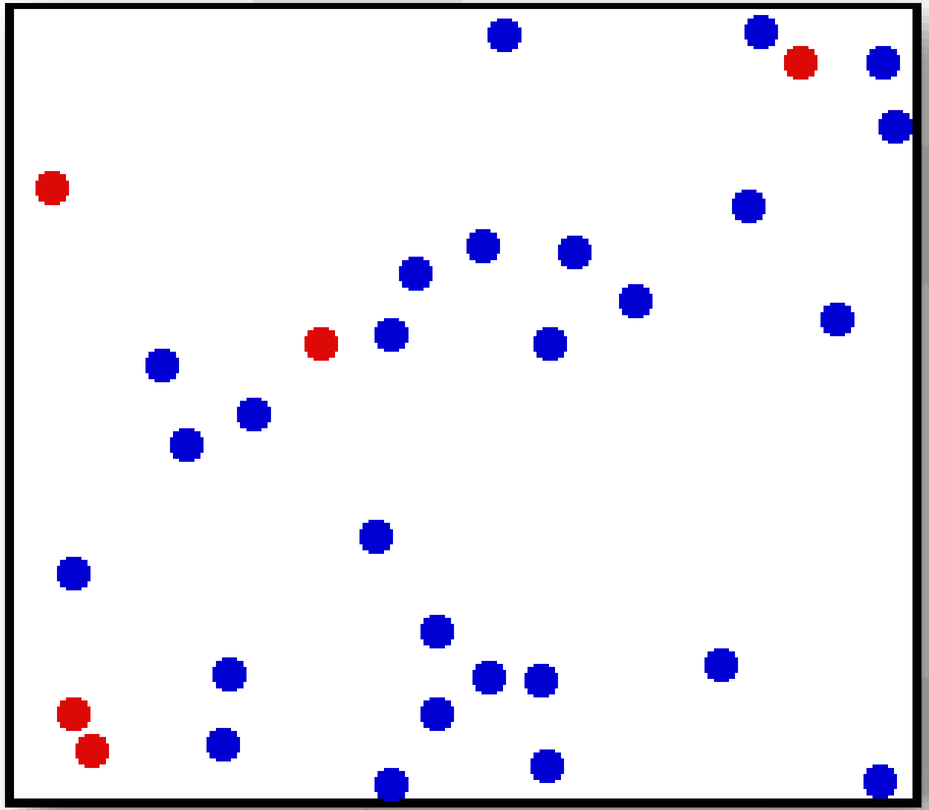
Technology	HBFB	VFB
Power density (W/cm^2)	0.80	0.35
Energy density (Wh/kg)	30-65	15-25
Material cost ($/kWh)	<20	300

Reduces the Levelized Cost of Storage to an absolute minimum: < € 0.05 per kWh

Technology Fundamentals

- The high reactivity of Bromine enables fast switching from charge to discharge and vv
- Switching times of HBr storage systems are typically in the order of tens of milliseconds

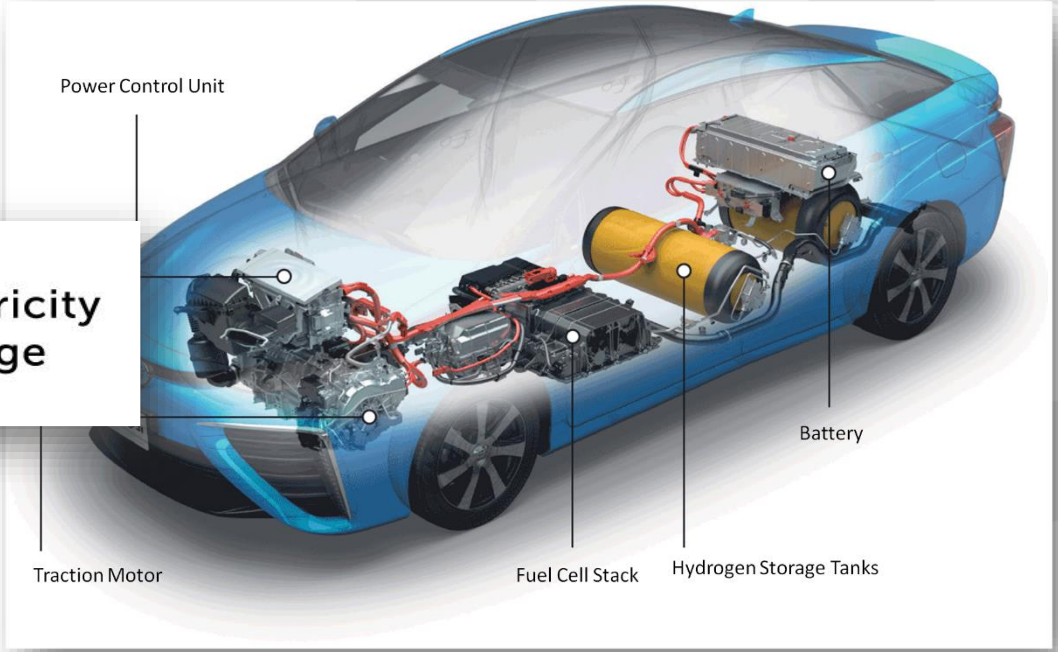
→ The HBr chemistry is ideal for electricity storage applications



Safety

- Safety measures for 1) Bromine and for 2) Hydrogen are individually known
- Zinc-Bromine batteries & Hydrogen vehicles have been proven
- Combination & Scale are new !

ELESTOR electricity storage

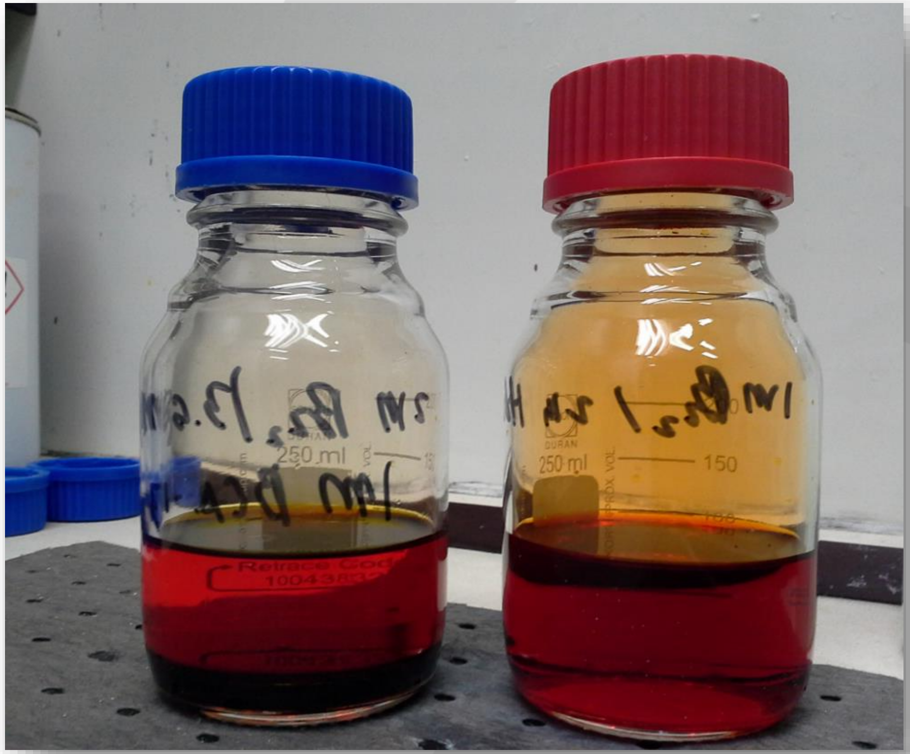


About bromine

- Bromine can be found all over the world
  - → abundant availability
  - → Very low cost
- 3 independent safety regimes in parallel
  - Mechanical : Double-walled reservoirs, submerged in neutralizing agent
  - Chemical : Complexing Agent
  - Electronic : H_2 / Br_2 / Pressure Sensors Smart Measure & Control
- Close cooperation with ICL-IP, world's largest supplier of Bromine

ICL Where needs take us

→ **Approval received from the Dutch authorities**



With Without

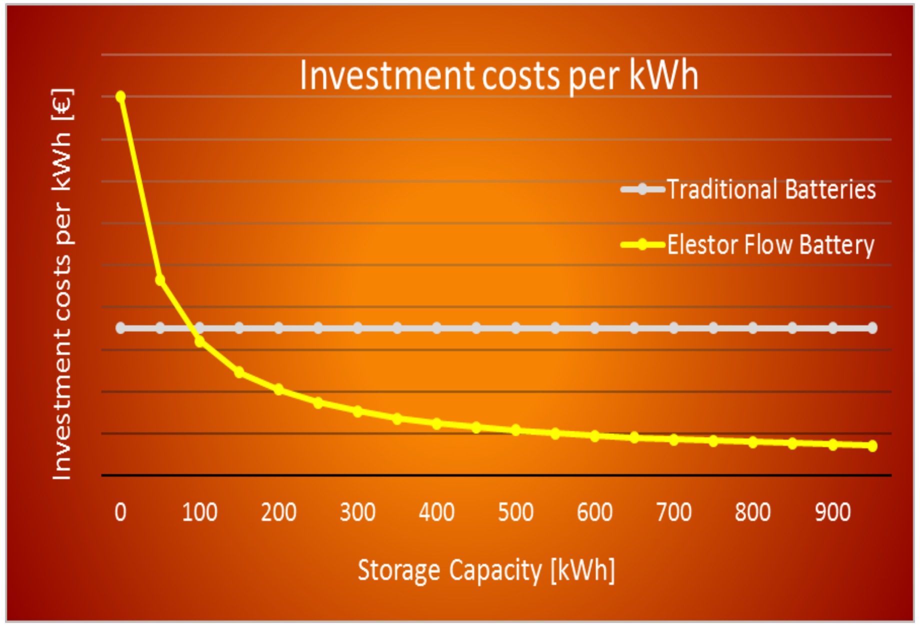
'Complexing Agent'

CAPEX and LCoS

- <u>CAPEX</u>

  Is *<u>not</u>* a constant figure in €/kWh :

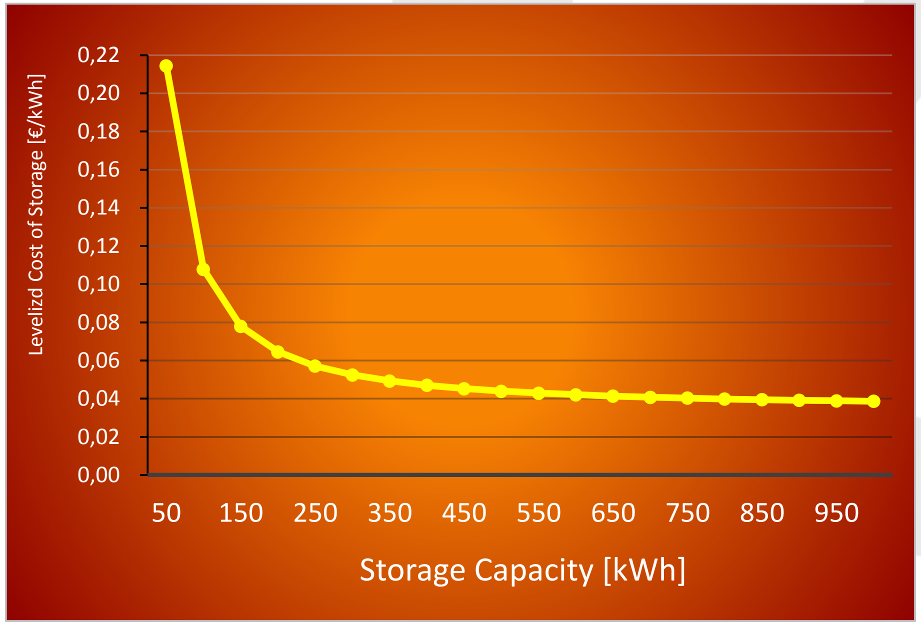
  - Low capacity → hardware costs dominant
  - High capacity → active material costs dominant



CAPEX [€/kWh] @ 100 kW storage power

- <u>Levelized Cost of Storage (LCoS)</u>

  - An LCoS < € 0,05 / kWh is reached beyond a Power:Capacity ratio of about 1:3
  - In below example : at 100 kW / 300 kWh

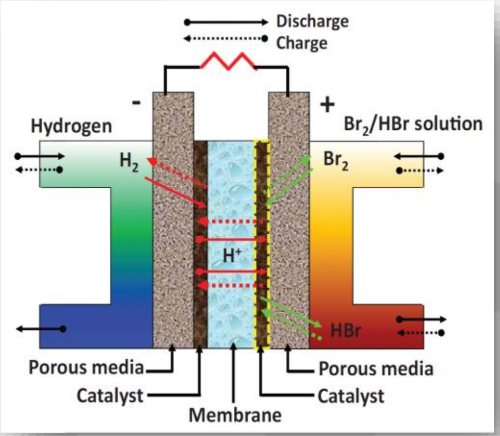


LCoS [€/kWh] @ 100 kW storage power

The keys to low storage costs - summary

1) The intrinsic features of the Flow Battery concept

- Power [kW] and Capacity [kWh] not coupled
- Long lifetime (10,000 cycles)
- No fundamental degradation (→ no loss of capacity)
- Maximum 'Depth of Discharge', without affecting lifetime
- No self-discharge
- Upgradable, servicable
- Ultra short reaction times
- High power density



2) The choice for hydrogen & bromine

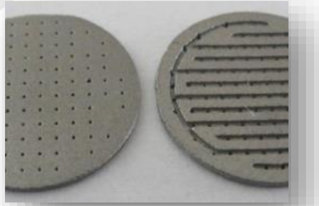
- Abundant available, thus low cost
- Active materials can be fully recycled
- Safety assured by several protocols

3) Elestor's patented system design

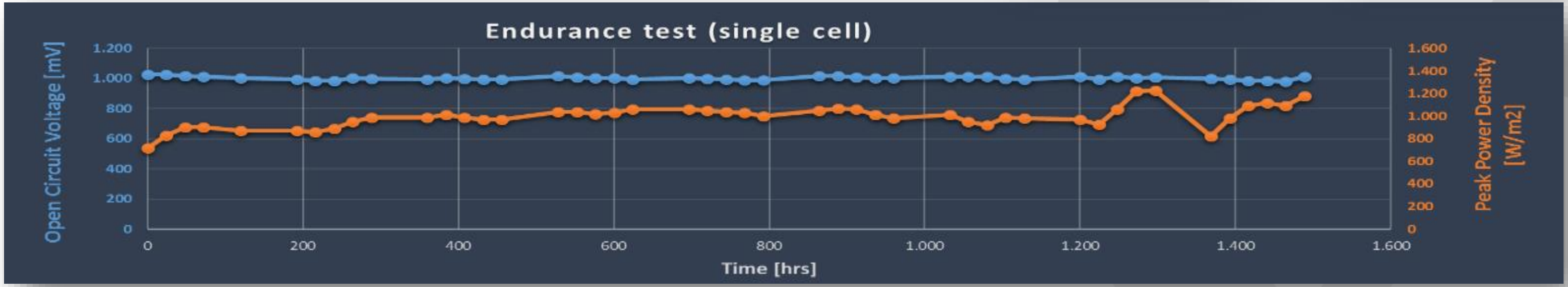
- Simplified and robust
- Easy to manufacture, in large quantities

Roadmap (1)

- <u>Jun 2015</u> First working HBr flow cell in Europe demonstrated



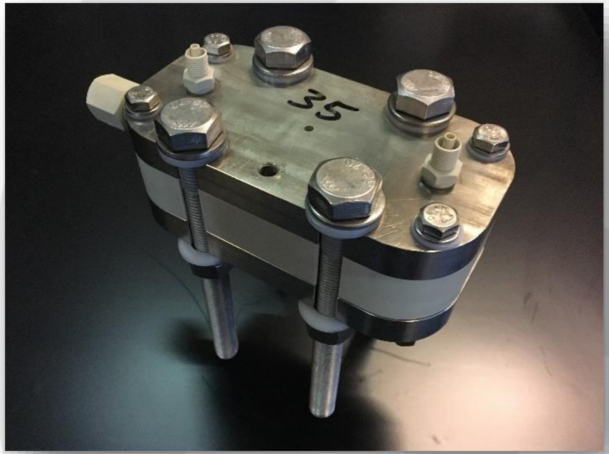
- <u>Today</u> Over 30 stacks tested > 20.000 testing hours



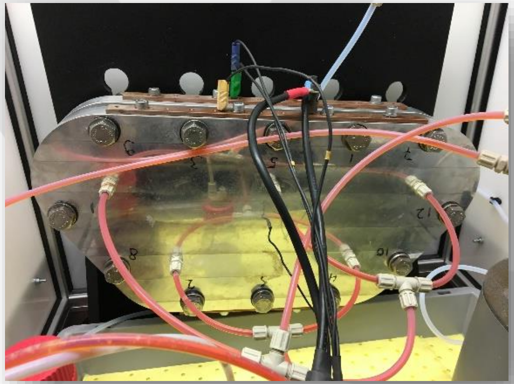
- <u>Nov 2016</u> First pilot (GEN1)
  - Witteveen+Bos, Deventer
  - Working under real conditions
  - Connected to office, PV and grid
  - Cooperation with ECN and HAN University of Applied Sciences

Roadmap (2)

- <u>2017</u> GEN2 pilots
  - Installed in NL + UK (upcoming)
  - Robust & compact version of GEN1
  - Connected to building, PV and grid



- <u>2018</u> 50 kW pilots
  - 4 installation (3x NL, 1x Germany)
  - Locations have been confirmed
  - 1rst installation in Emmeloord (NL) →



- <u>2019</u> Commercial launch
  1rst commercial deal (400 kW / 1,000 kWh) has been signed

Company profile

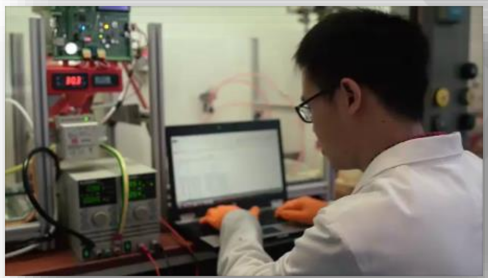
- Founded in 2014, 10 FTEs (2 PhD, 4 MSc, 2 BSc,+ graduates/interns)
- PhD program at Technical University, Eindhoven

  (Membrane Research Group, Prof. Dr. Kitty Neimeijer)
- Hiring PhD candidate under FlowCamp project (Fraunhofer Institute)
- Series A financing closed in Dec 2015, 4 shareholders

  (Inod BV, Dalessi BV, InnoEnergy, Enfuro BV)

- Close cooperations with a.o. :

* Sweco	* ICL-IP, Israel	* Witteveen+Bos
* DNV GL	* Fraunhofer Institute	* ECN
* Alliander	* Technical Universities (Eindhoven & Delft)	



- 2016 : Recognized with several awards (a.o. Jan Terlouw)

  2017 : 'IDTechEx Award', Berlin, for

  'Best Technical Development in Storage Technology'

Summary

1) Customers want RELIABILITY, but renewable energy introduces VARIABILITY and UNCERTAINTY

2) To integrate renewables, the grid needs to become “smarter”

3) Integrating electricity storage to the grid is a solution for the energy transition

4) Several electricity storage technologies are available, but they are either site-specific or, in terms of LCoS, too expensive

5) Cost-effective electricity storage is the missing link of this transition

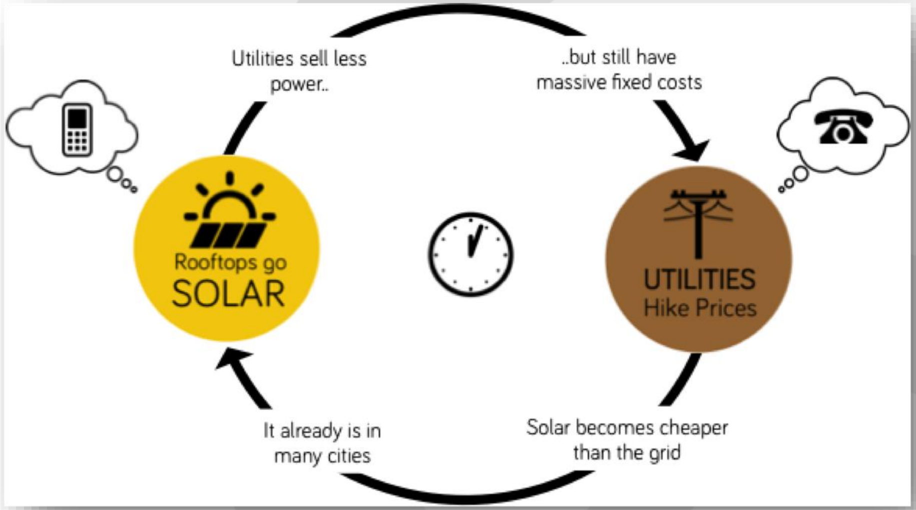
6) Hydrogen Bromine Flow Batteries utilize the cheapest possible active materials and have therefore the potential to reduce the Levelized Cost of Storage to an absolute minimum

7) There are technical challenges, but no fundamental ones

Can't we really do better !?

The Utility death spiral

- €104 Billion write-offs on *assets* by top 12 EU energy companies, since 2010 *[Financial Times, 22nd May 2016]*
- On april 21, 2016 a coal power plant was opened in Rotterdam…



- Sun + Wind + Storage + *IoT* = de-central & sustainable energy
- Neighborhoods and business parks will install microgrids
- Advantages new system:
  - Highly Robust
  - Cheaper
  - Environmentally friendly
  - New business models
- Energy is an emotional subject, full of prejudices about politics, technology and legislation
  - Strong and factual discussions are necessary !

Thank you for your attention !

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“We will make electricity so cheap that only the rich will burn candles”

\- Thomas A. Edison