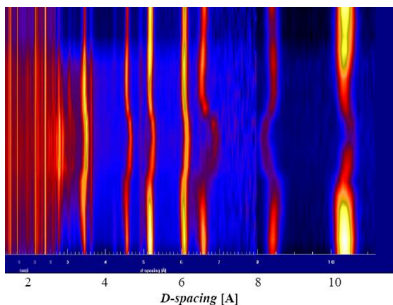


The implication of renewable power variation for large scale energy storage

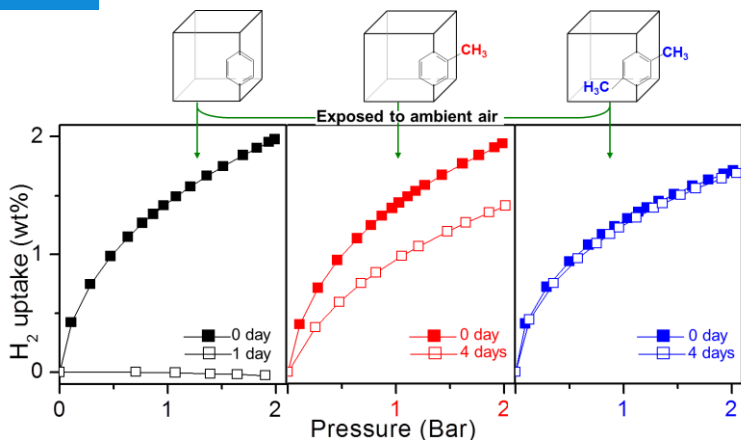
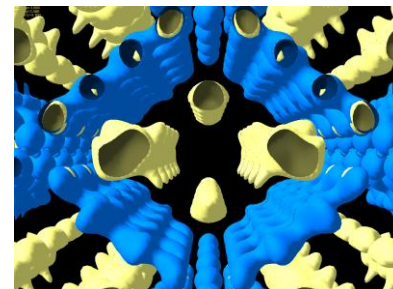
Fokko Mulder
Delft University of Technology
Faculty of Applied Sciences

f.m.mulder@tudelft.nl



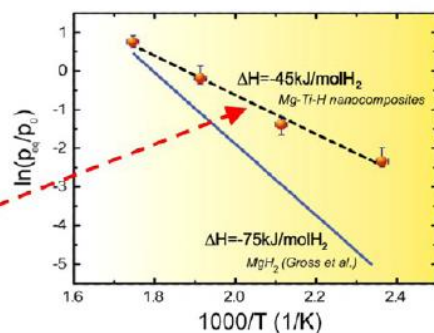
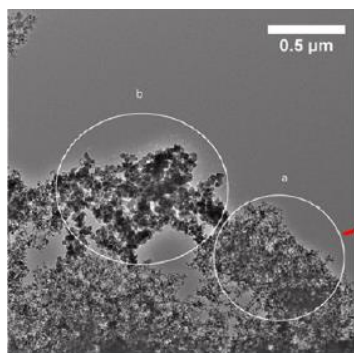
H₂ Gas storage: MOF's

J. Phys.Chem C 114 (2010) 10648



H₂ Gas storage: water stable MOF's

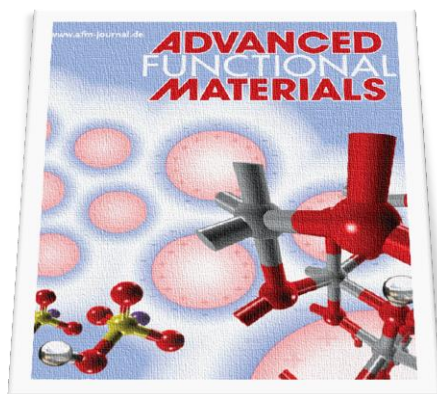
Chem. Comm. 47 (2011) 5244



Destabilisation of MgH₂:

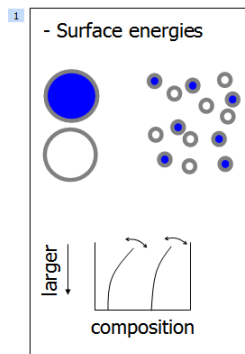
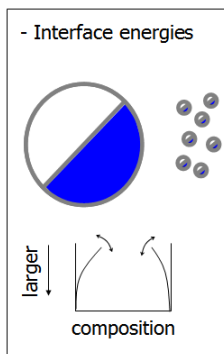
J. Phys. Chem. C 2012

J. Am. Chem. Soc. 2013



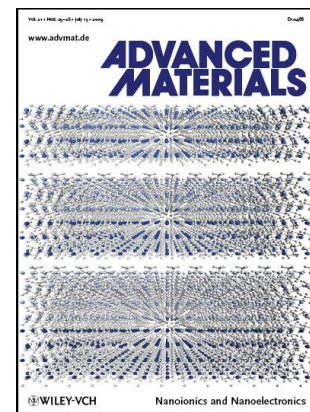
Nanoionics: solid state electrolytes

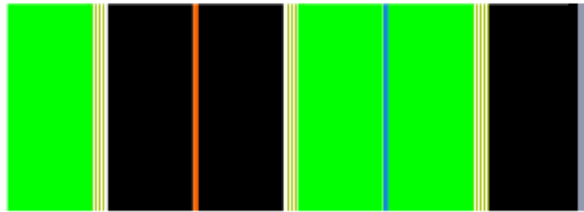
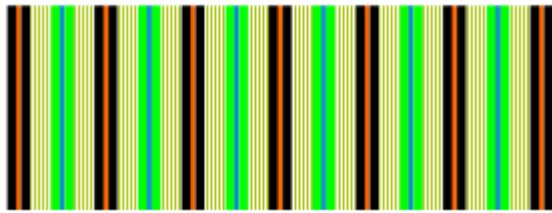
Adv. Funct. Mater. 2010 & 2011



Impact of nanostructuring on Li battery materials

JACS 2005, 2007, 2009, 2011,
Adv.Mat. 2009
Nature 2002, Acc Chem. Res. 2013





High effective energy density
of Li battery + 100%

WO Patent 2,013,012,334

Adv. Ener. Mat. 2013, El.Chem.Comm. 2013

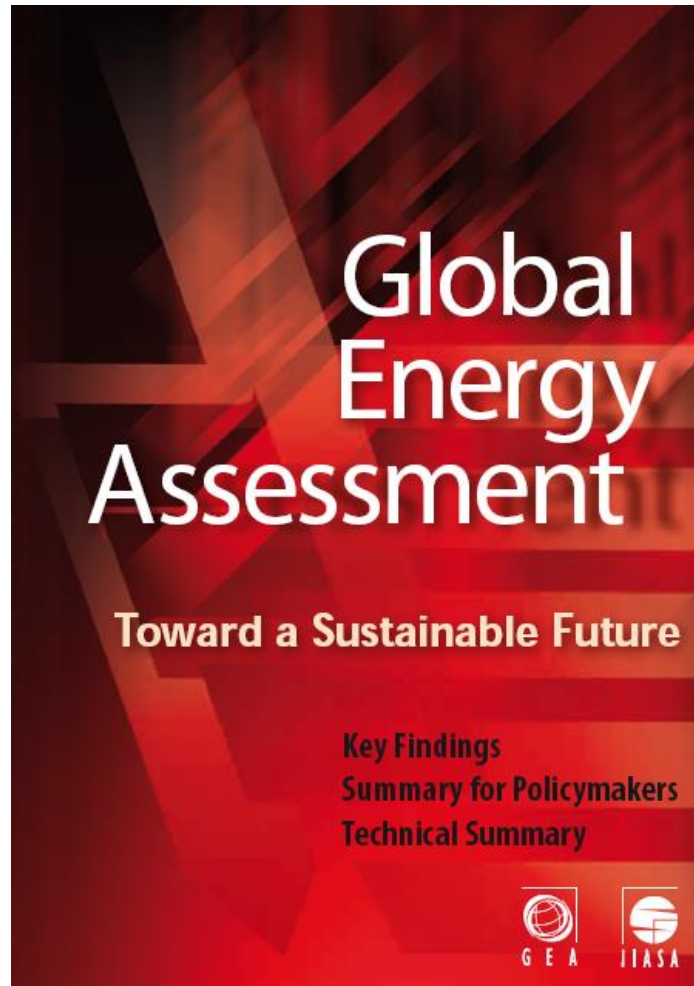
General TU Delft:

- Energy as a main research area
- 5 times winner of 3000 mile
World Solar Challenge



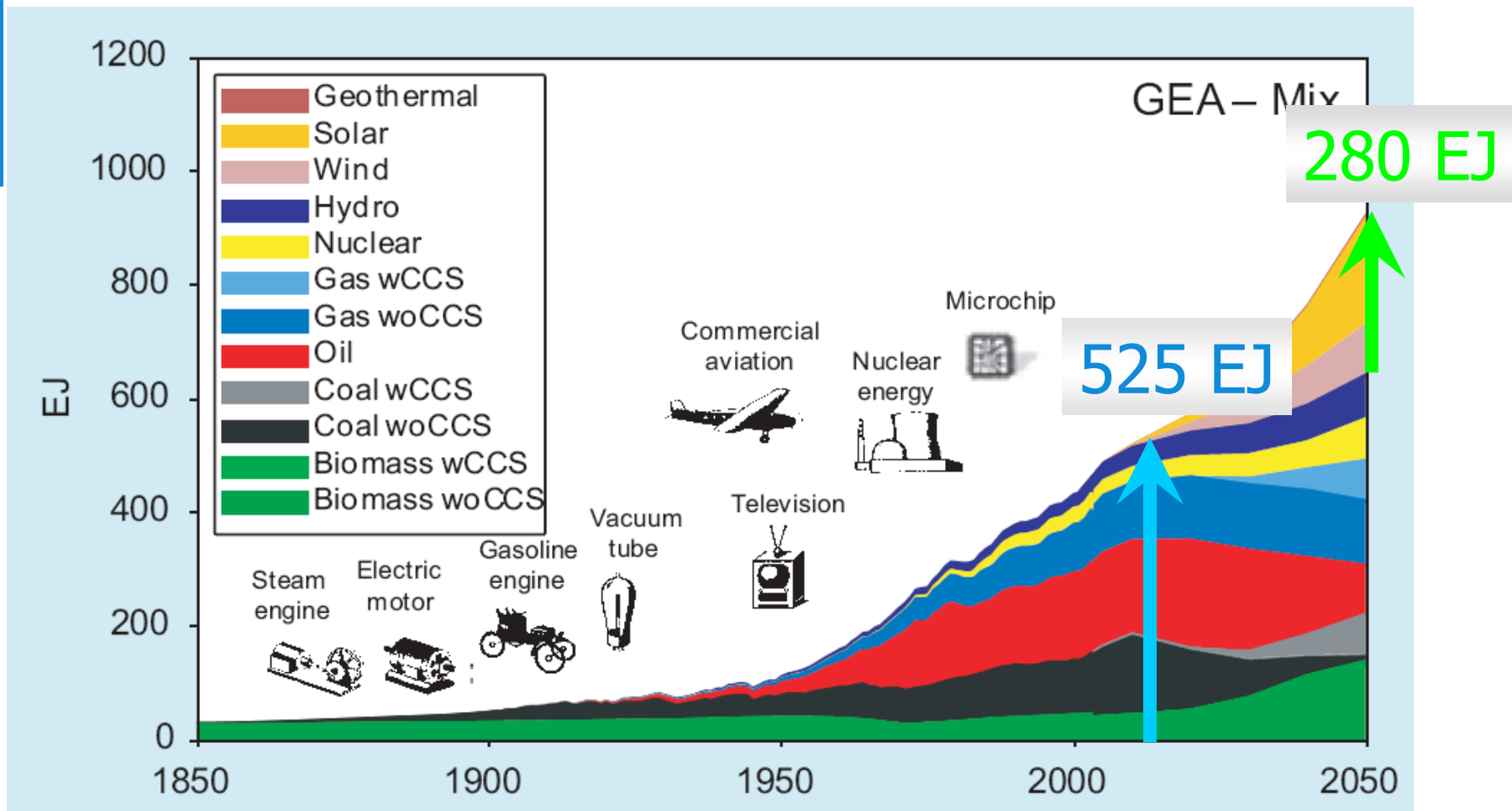
How to get to a number for the future scale for energy storage?

Start from a scenario

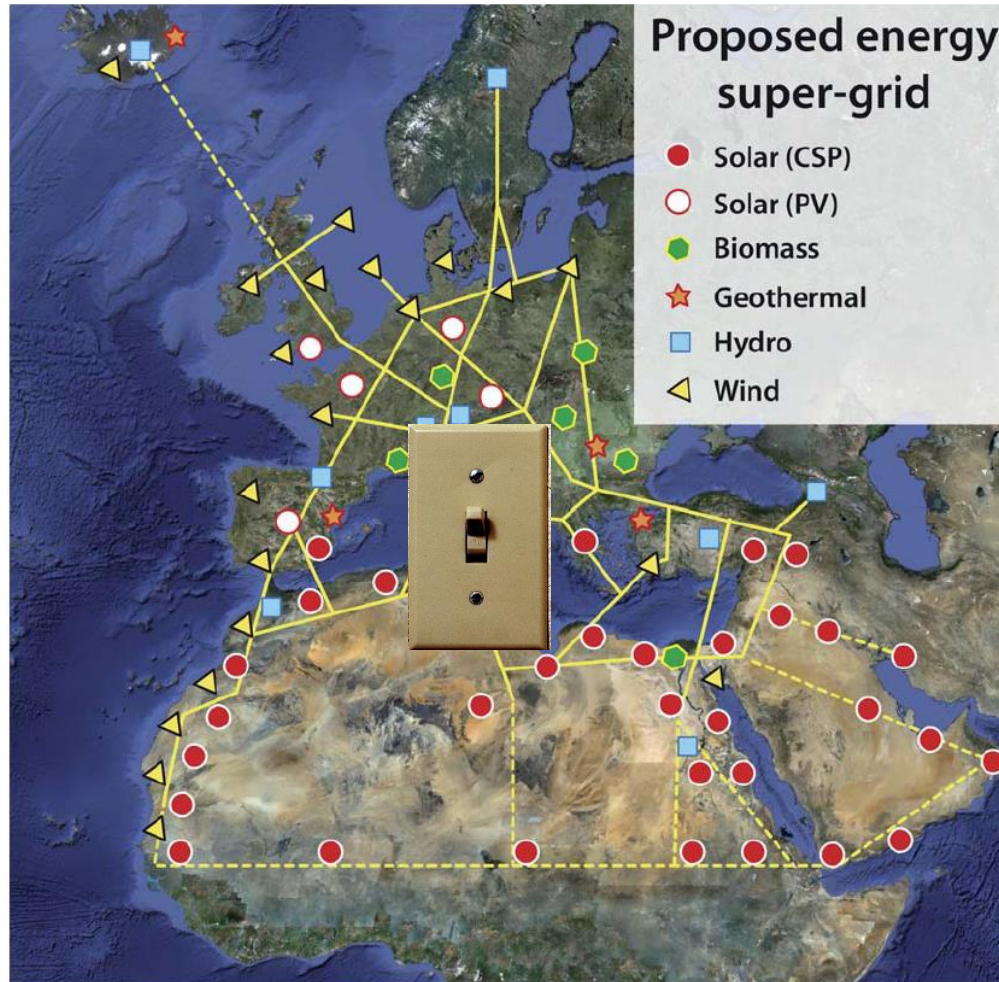


2012

World energy use; Global Energy Assessment 2012



Renewables...



Light switch
on continents!

(day/night and
summer/winter)

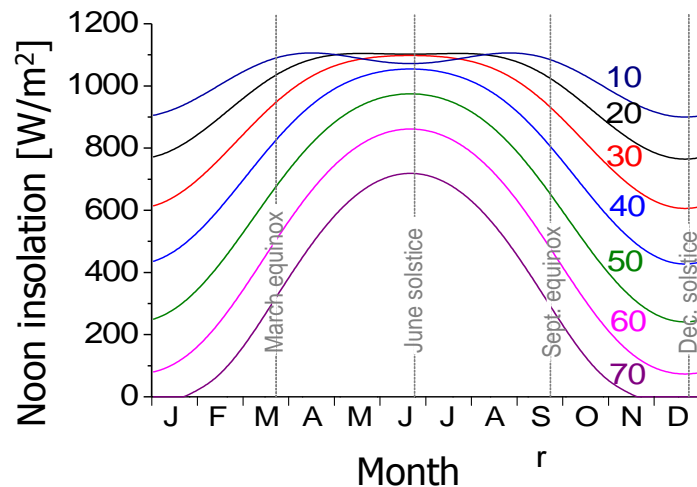
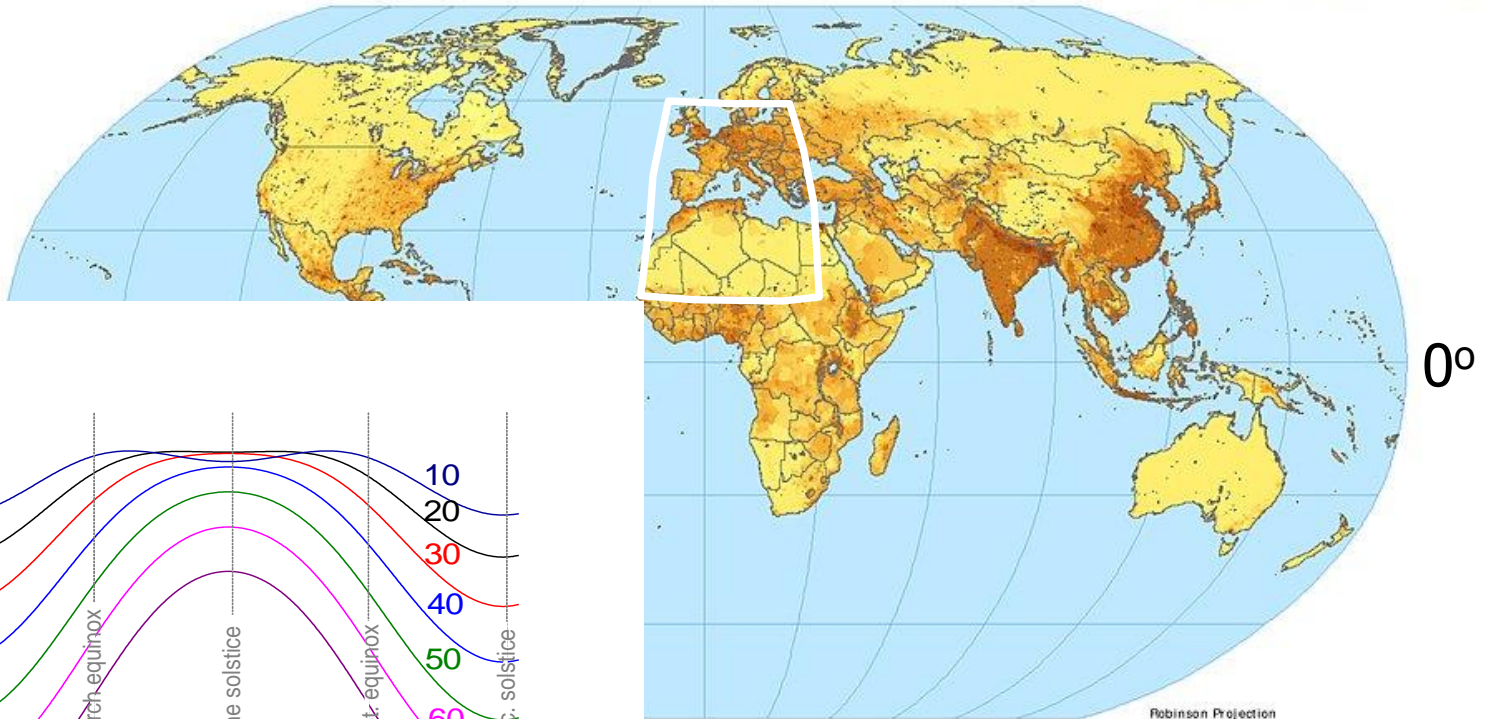
DESERTEC plan

0°

Most people live on the Northern hemisphere above 20°

Population Density

Global

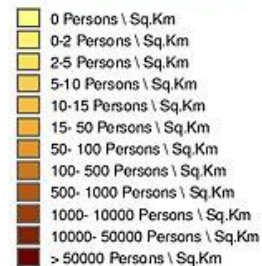


below. Source Information: <http://sedac.ciesin.columbia.edu/gpw/>



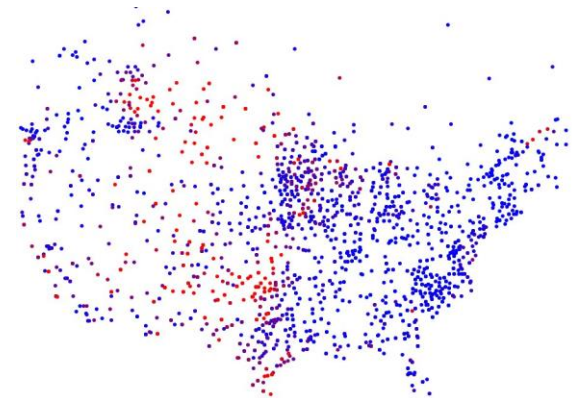
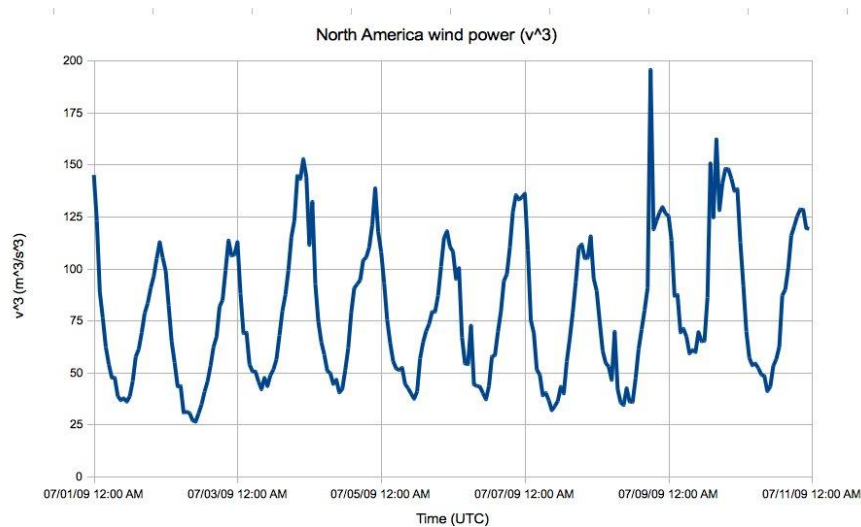
Copyright 2007, The Trustees of Columbia University in the City of New York.
Source: Center for International Earth Science Information Network (CIESIN),
Columbia University. Population, Landscape, and Climate Estimates (PLACE).
Further information available at: <http://sedac.ciesin.columbia.edu/PLACE/>

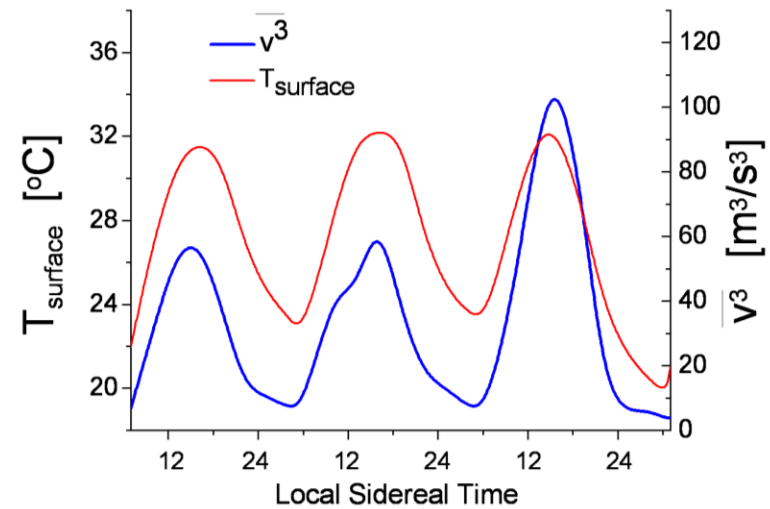
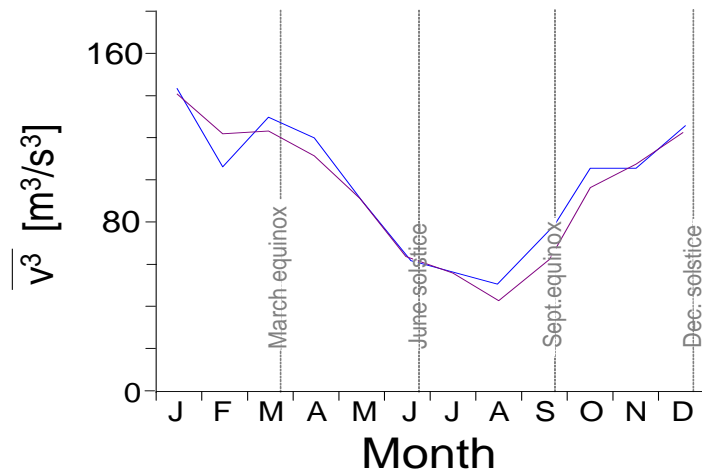
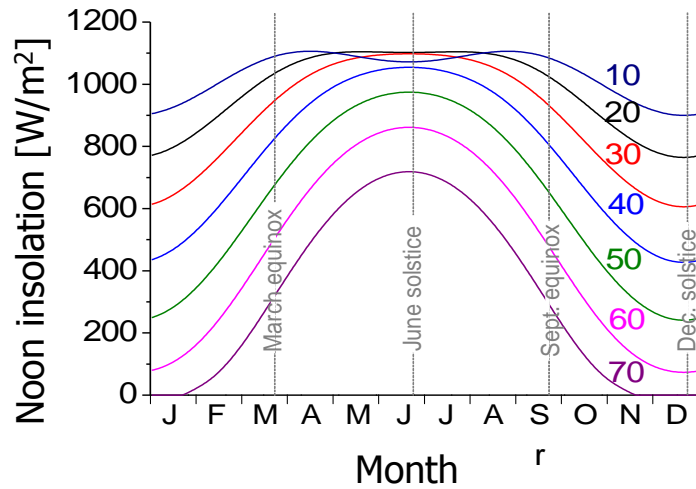
Population Density 2000



Publish Date: 03/19/07

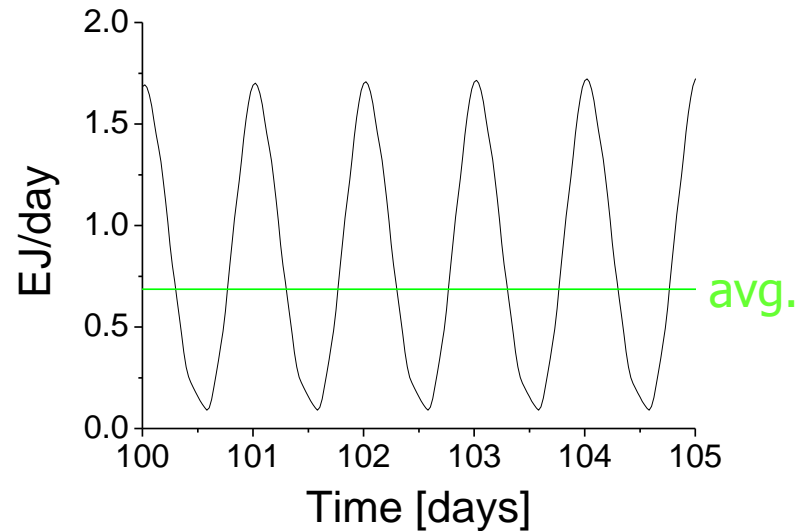
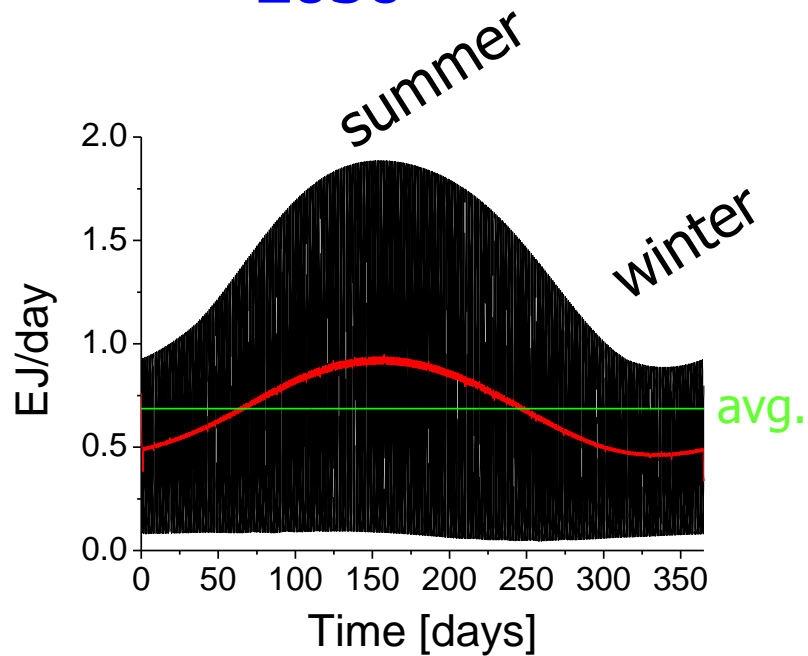
Large area still shows large wind power fluctuations



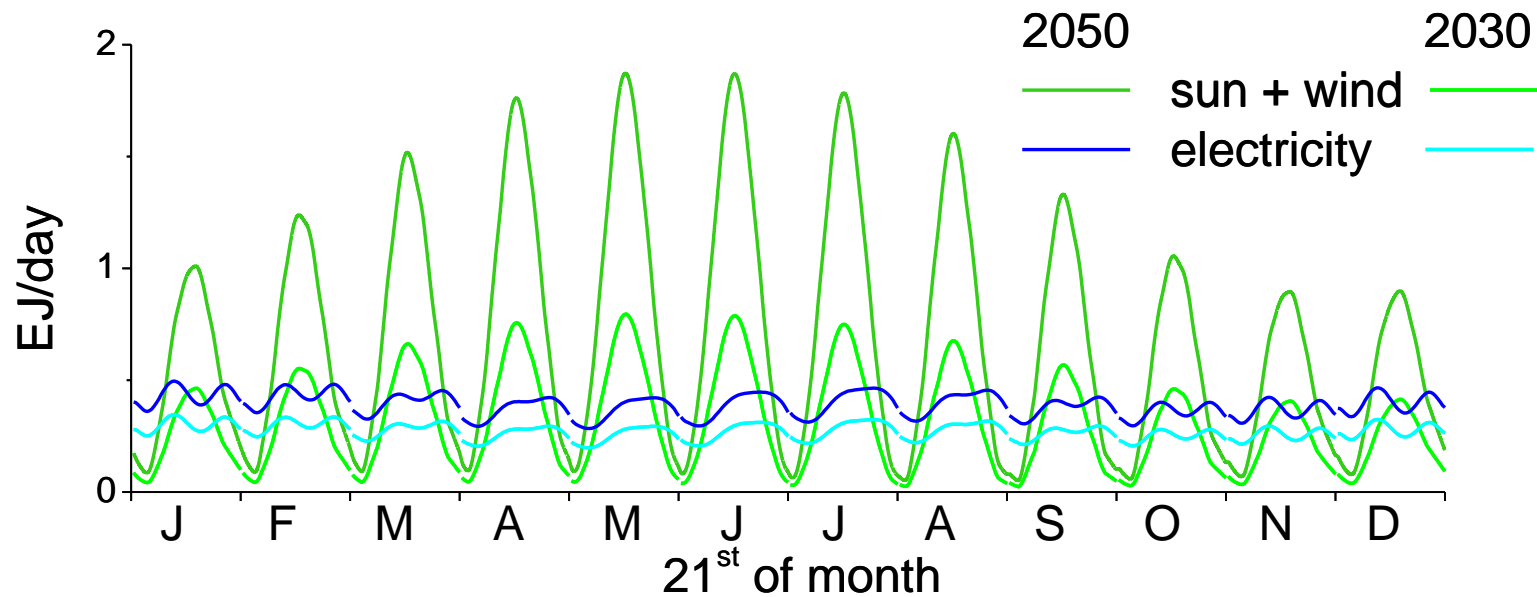


Varying output of renewables on an extended grid

2050



Future sun + wind compared to electricity use

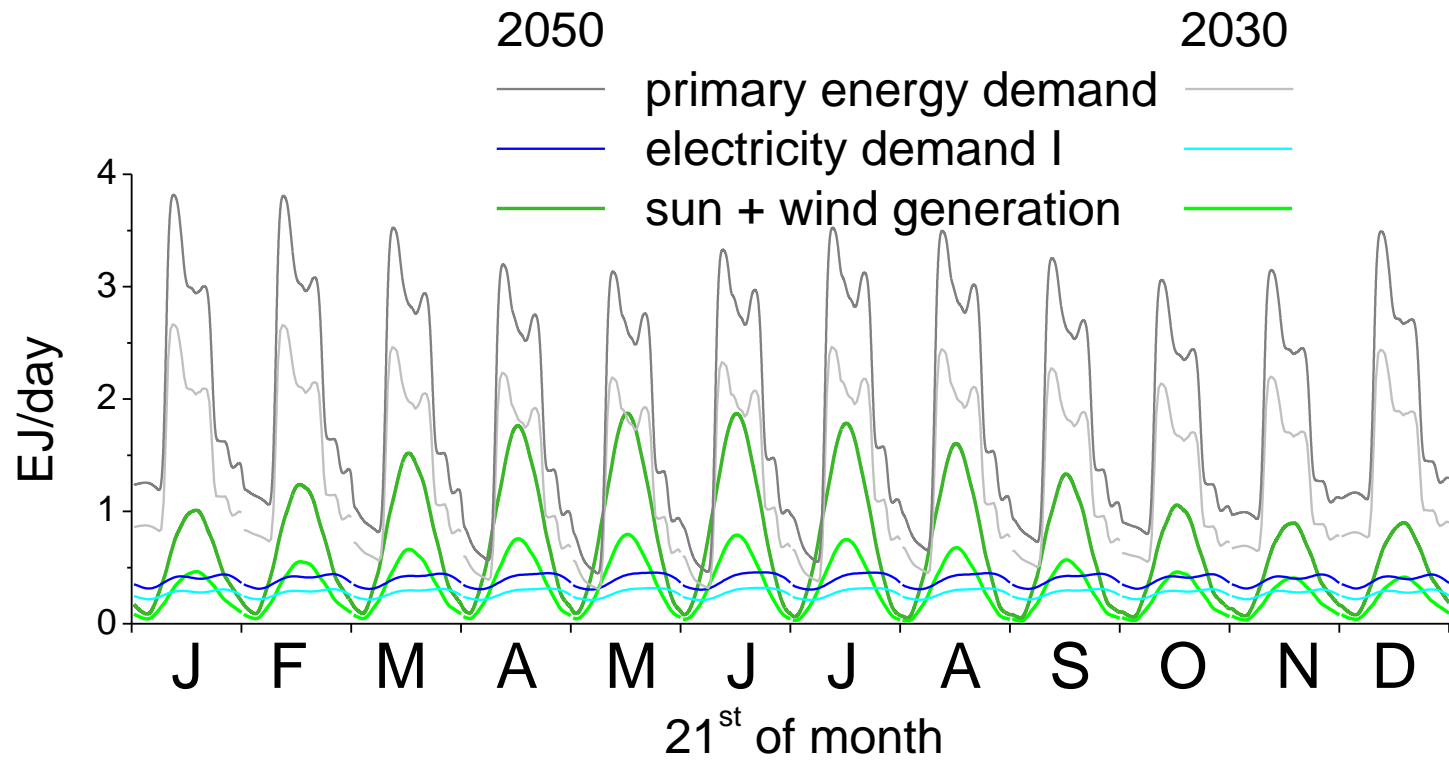


Renewable **peak power** becomes large compared to **peak use**

Did I miss something?

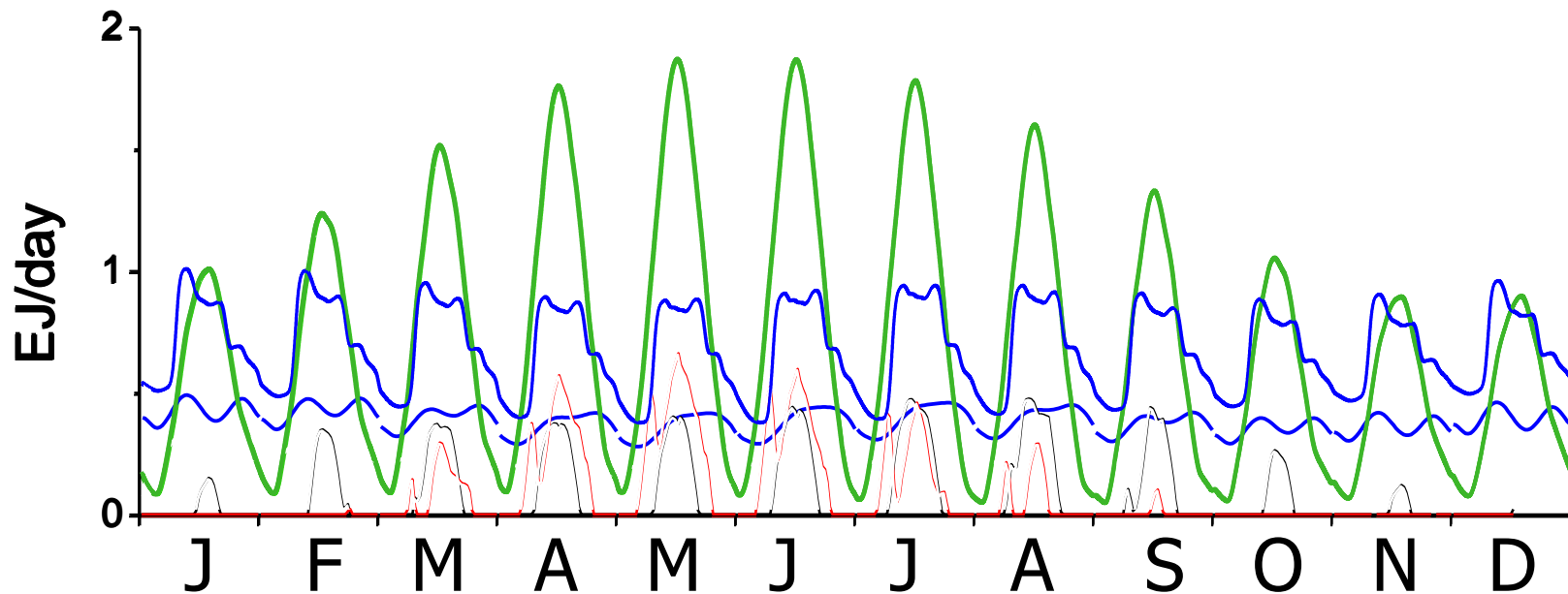


Electrification
Load shifting
Energy storage!



What to do with too much electricity?

- use electricity for more applications (EV, heating,...)
- match supply & demand by **long**/short term storage

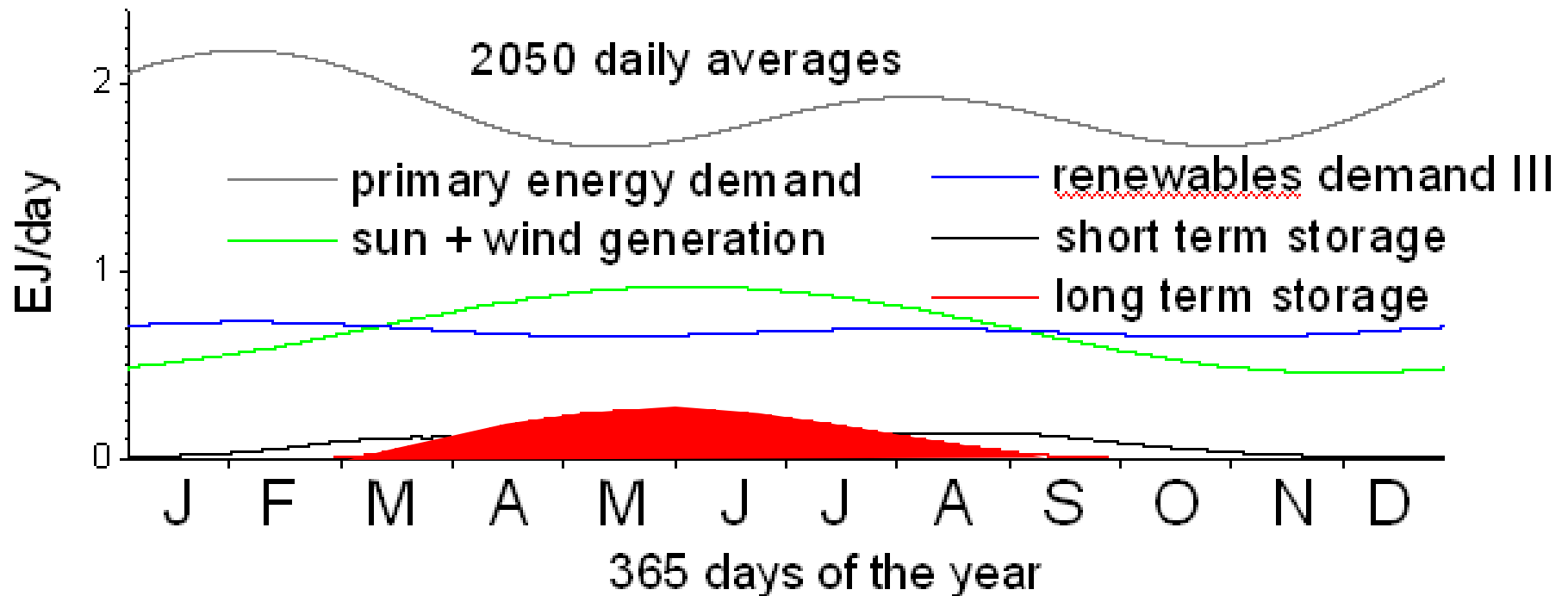


2050:

Short term: 0.2 EJ

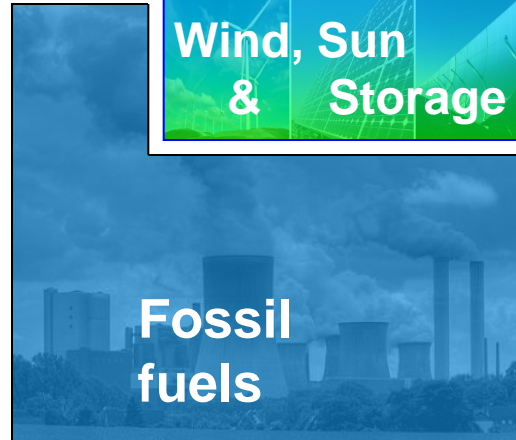
NL ~ 44 kWh/house

Daily averages...

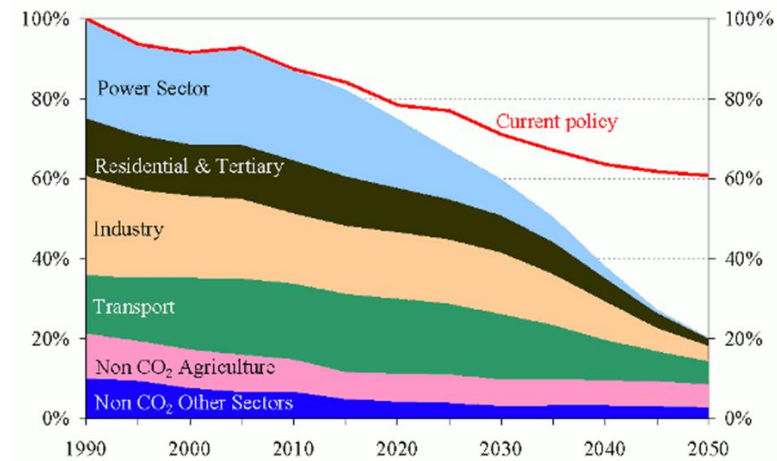


2050:
Short term: 0.2 EJ
NL ~ 44 kWh/house

2030: 2050:
10 EJ = 29 EJ =
2800TWh 8000TWh



Note EU Roadmap:
-80% CO₂ in 2050

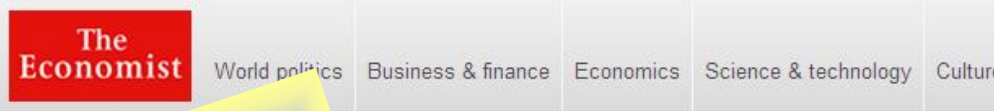


Price effects in Germany during the day:



- Reducing daily price for renewables
 - Reducing daily price for fossile power
 - High investments in parallel infrastructure
- Deteriorating earnings at higher cost (for all)

Large scale energy storage is required for economic renewable energy implementation



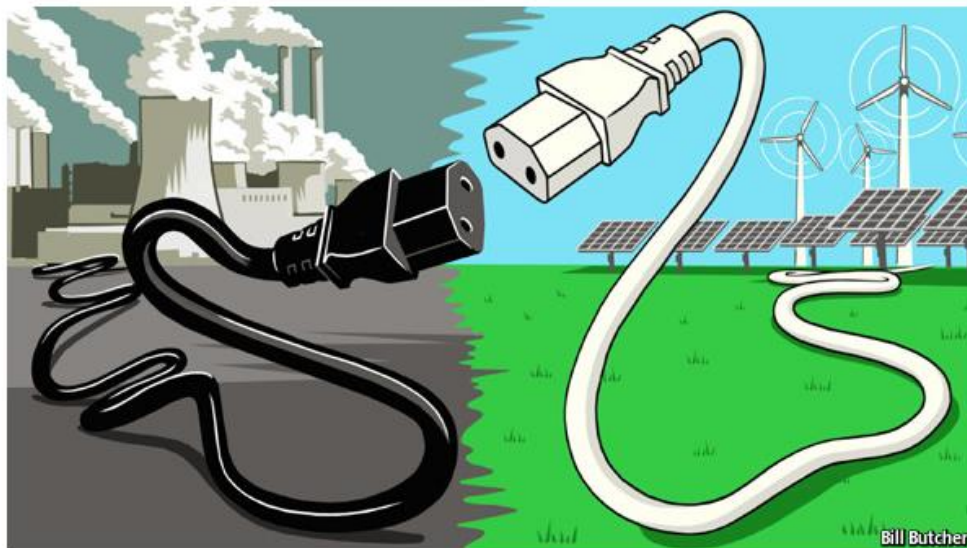
European utilities

How to *gain* half a trillion euros

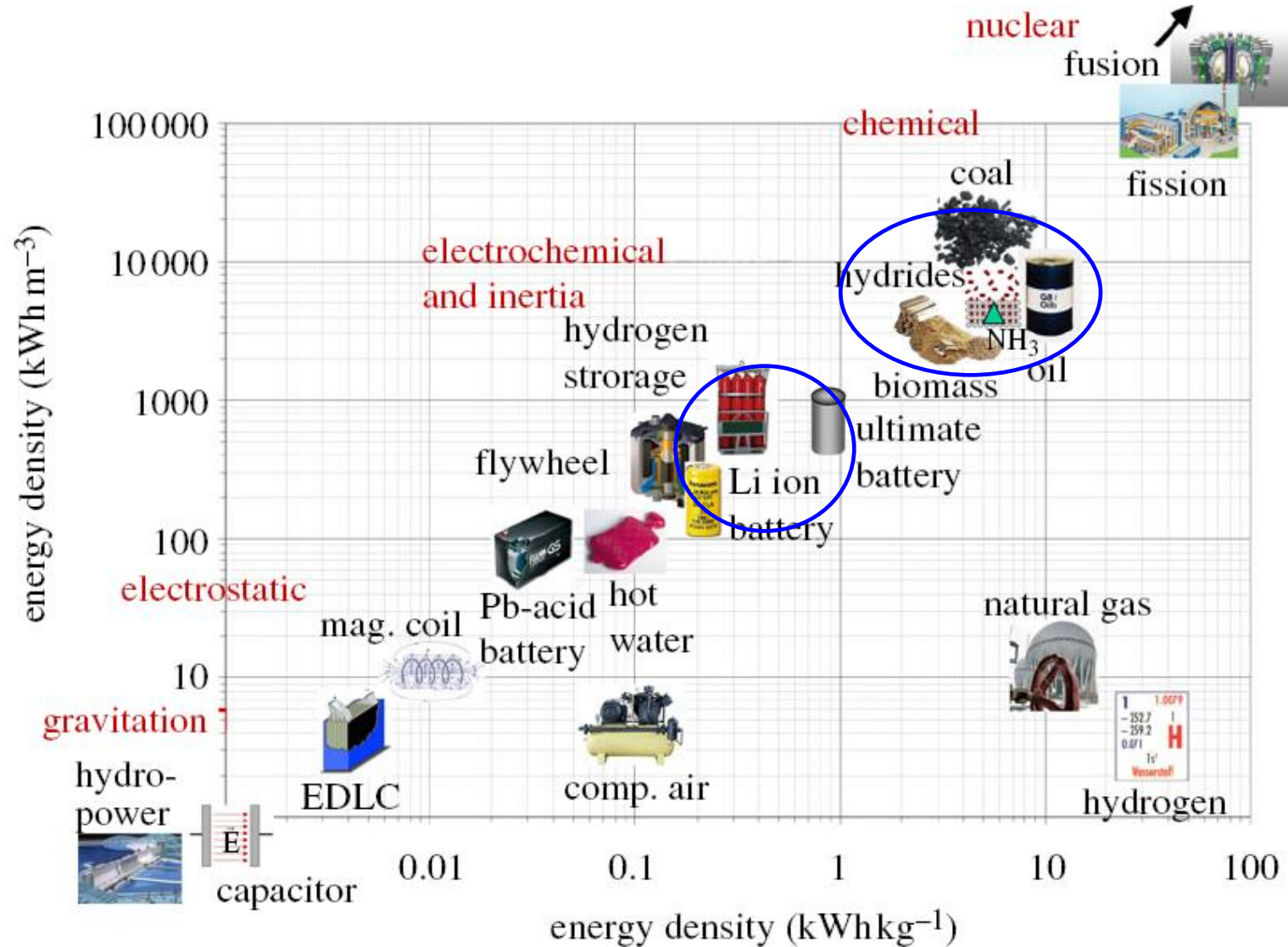
Europe's electricity providers face an existential threat

Oct 12th 2013 | From the print edition

Like 6.6k Tweet 635



Energy densities of storage technologies



Solutions for large EJ scale energy storage?

	capacity EJ scale	efficiency $e^- \rightarrow e^-$	Long term	Short term
Hydropower	--	++ _{0.8²}	-	++
Compressed air	--	+ _{0.75²}	-	++
Batteries	-	++ _{0.85²}	--	++
Hydrogen under- ground storage	(+)	-/-- _{0.65²x0.85²}	(++)	+
NH ₃ (l)	++	-- _{0.3x0.65}	++	+
C _n H _m O _p	++	--- CO ₂ from air?	++	+

Research,
geology?

Storage options for large scales: to be developed (!)

- batteries
 - For the short term only (low J/€)
 - Requires long life, cheap batteries
- H_2
 - Requires large scale storage method itself
 - Can partially be fed in gas-grid
(max 10% ~5GW in Germany, limited compared to current 22GW PV record)
- $C_kH_nO_m$
 - Synthetic conventional fuels
 - Requires a carbon source
- NH_3
 - Is already produced & stored at large scale, but not from renewables.
 - In industrial environment only (safety).
 - Low efficiency
- heat
 - Conversion losses may be recovered as heat, CHP

Preferably abundant elements!

Periodic Table of the Elements

Electronegativity

<http://chemistry.about.com>

©2010 Todd Helmenstine

About Chemistry

1A	2A																	8A
1	2																	2
H	He																	no data
3	4																	10
Li	Be																	Ne
0.99	1.57																	no data
11	12																	18
Na	Mg																	Ar
0.93	1.31																	no data
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
0.82	1.00	1.36	1.54	1.63	1.66	1.55	1.83	1.88	1.91	1.90	1.65	1.81	2.01	2.18	2.55	2.96	3.00	
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
0.82	0.95	1.22	1.33	1.6	2.16	1.9	2.2	2.28	2.20	1.93	1.69	1.78	1.96	2.05	2.1	2.66	2.6	
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	
Cs	Ba	Lanthanides	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
0.79	0.89		1.3	1.5	2.36	1.9	2.2	2.20	2.28	2.54	2.00	1.62	2.33	2.02	2.0	2.2	no data	
87	88	89-103																
Fr	Ra	Actinides																
0.7	0.89																	

*** Elements > 104 exist only for very short half-lives and the data is unknown.***

Lanthanides

Actinides

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1.10	1.12	1.13	1.14	1.13	1.17	1.2	1.2	1.2	1.22	1.23	1.24	1.25	1.1	1.27
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
1.1	1.3	1.5	1.38	1.36	1.28	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	no data

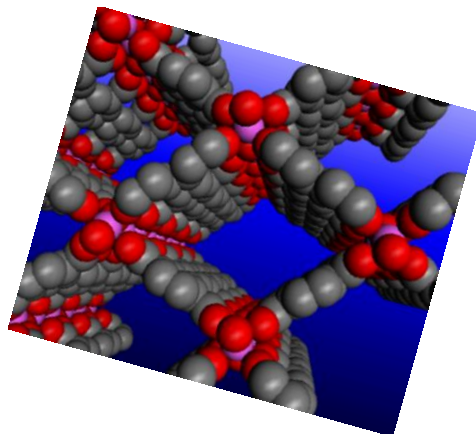
Acknowledgements

- **TU Delft:** Wouter Borghols, Vincent Verhoeven, Gijs Schimmel, Lucas Haverkate, Winkee Chan, Deepak Singh, Anna Grzech, Sarita Singh, Ignatz de Schepper, Jouke Heringa, Lambert van Eijck, Tobias Pfeiffer, Andreas Schmidt-Ott, Stephan Eijt, Marnix Wagemaker, Erik Kelder, Joop Schoonman
- **ISIS (Oxford, UK):** Laurent Chapon, Winfried Kockelmann, Ron Smith
- **U Nijmegen:** Ernst Van Eck, Arno Kentgens
- **ILL (Grenoble, France):** Mark Johnson
Mohamed Zbiri
- **ANSTO (Menay, Australia):** Don Kearley
- **And others**

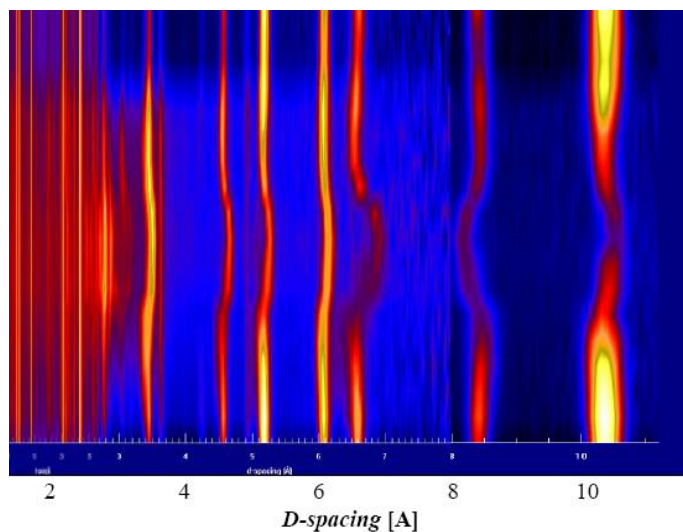


DISE

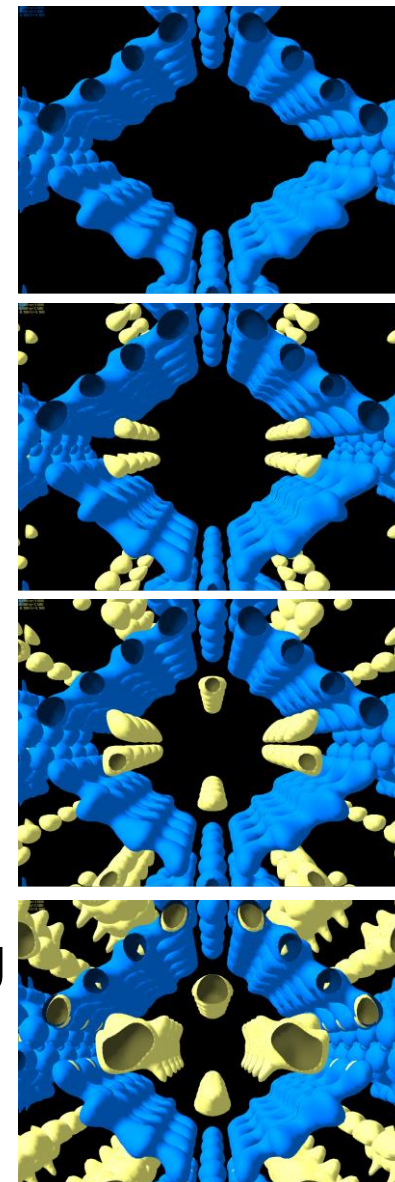


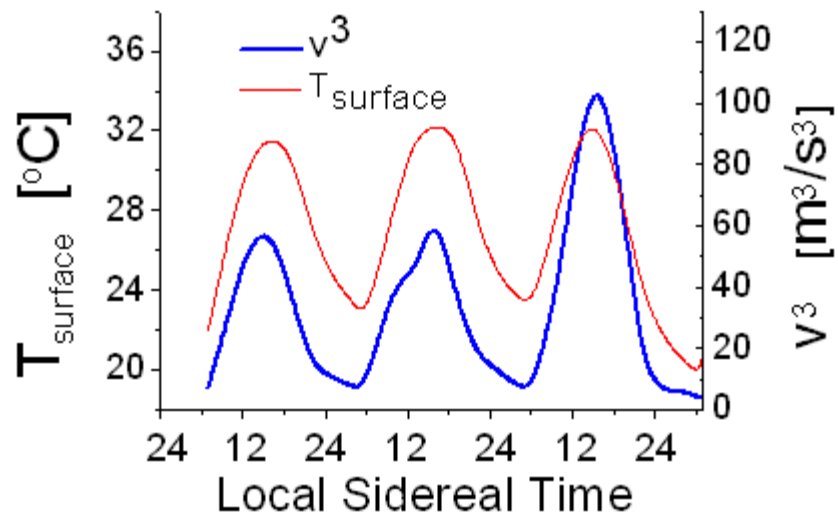
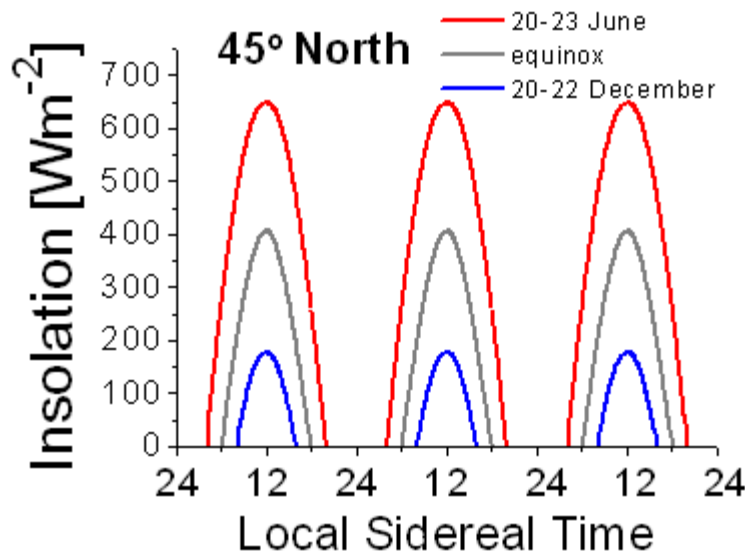


Neutron diffraction measurements 



Images of the
inside of the
material, visualizing
the hydrogen





Solar power:
Large variations
during the day.
Large difference
between seasons

Wind power $\sim v^3$:
Also large variations
during the day:
wind is driven by
surface temperature
(this becomes visible for very
large grid, e.g. $3000 \times 3000 \text{ km}^2$)