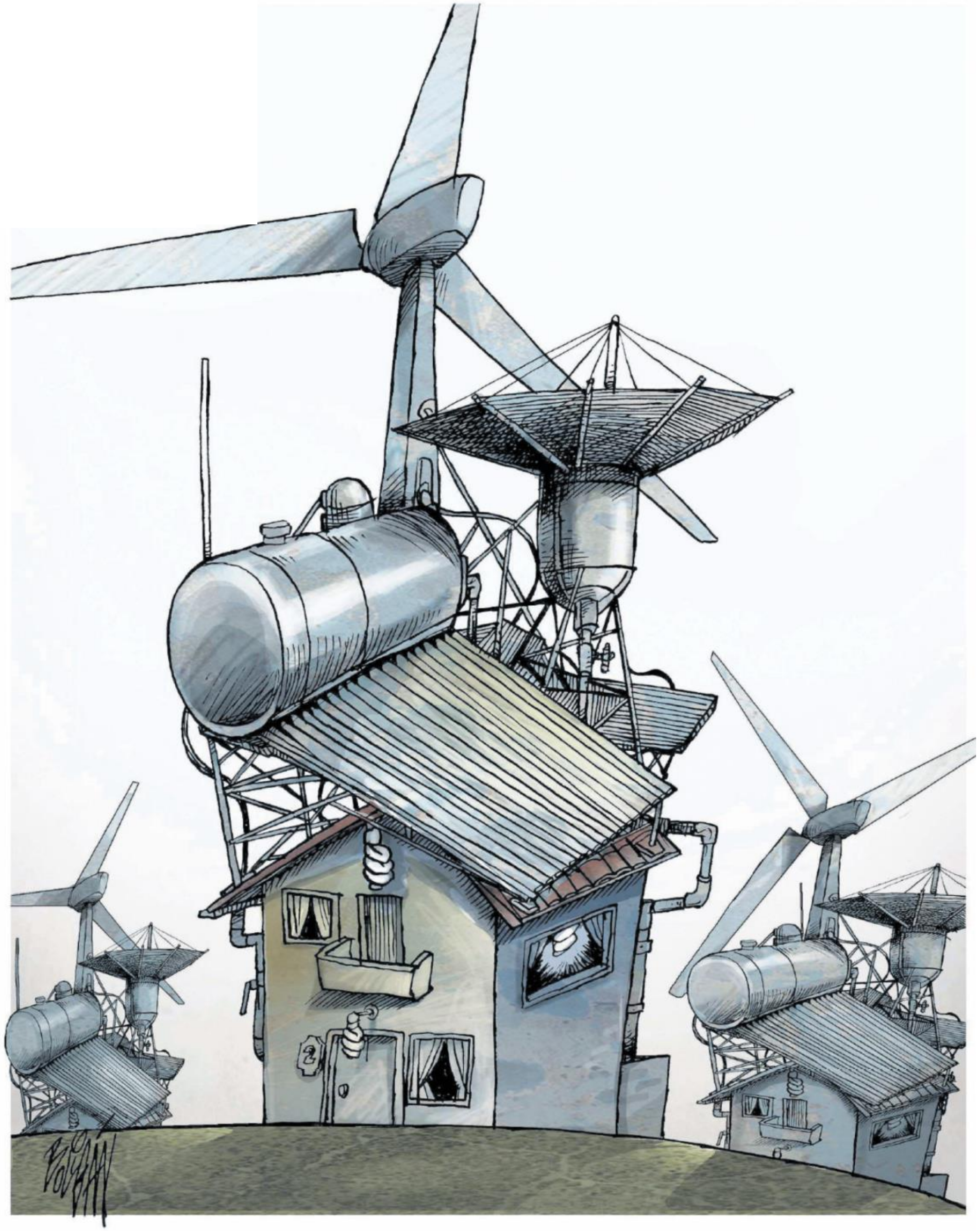

Source drawing: NRC-HB, 19 August 2013

Some remarks on

Climate Change and our Future Energy System

Wim Turkenburg

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Utrecht University
&
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NNV
De Bilt, 29 October 2015

Climate Change & Stranded assets

Carbon budget & CCS

Austria's Pasterze Glacier has retreated hundreds of meters since nations began debating limiting warming to +2°C

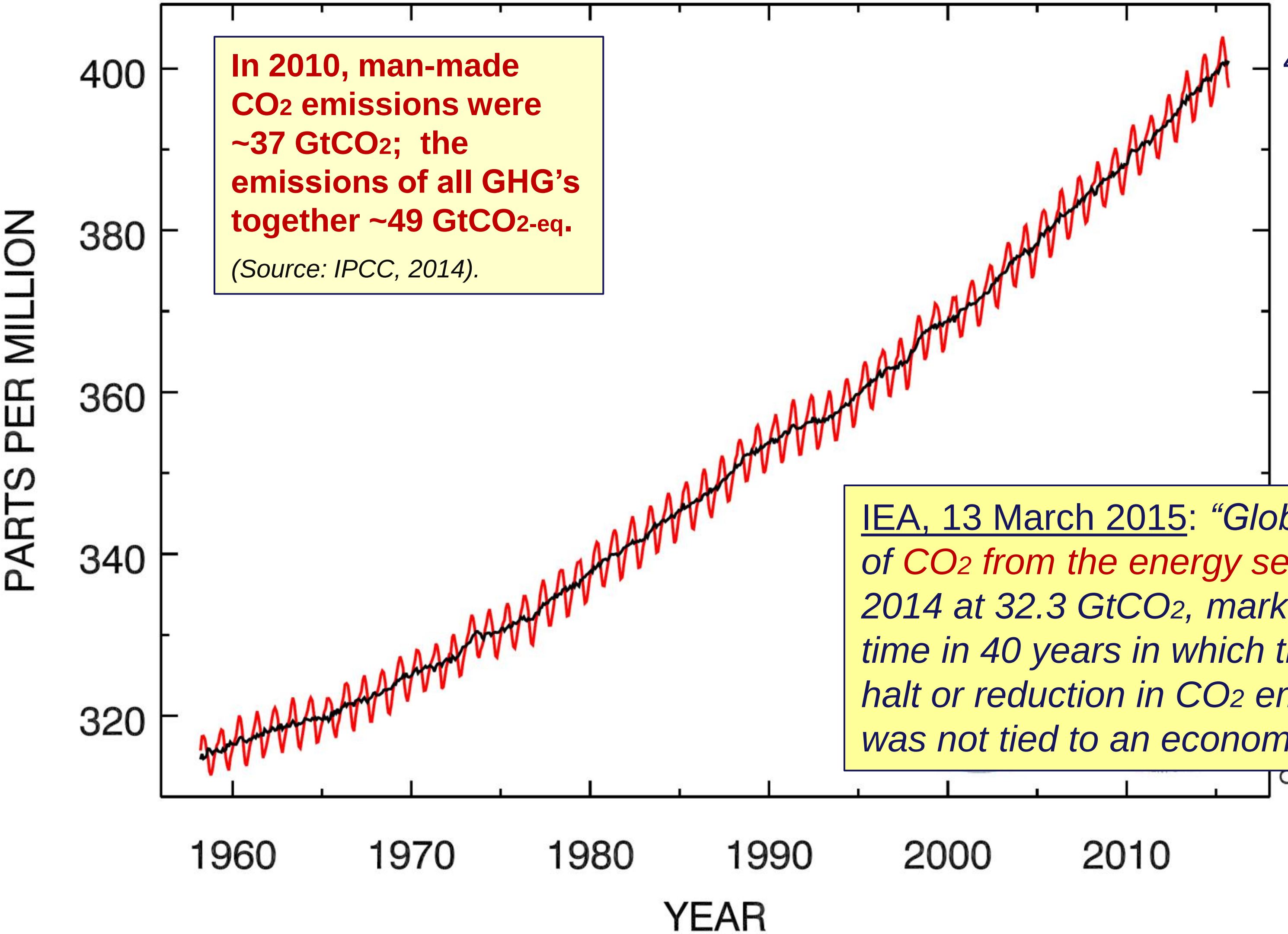
G7 Summit, 7-8 June 2015:
"All countries should (be enabled to) follow a low-carbon and resilient development pathway in line with the global goal to hold the increase in global average temperature below 2°C".

"Science tells us that 1.5 °C might be considerably better."

Nature, 2 April 2015

Source: J. Tollefson, 'Global-warming limit of 2ºC hangs in the balance', Nature, 2 April 2015

Monthly average CO_2 concentration in the atmosphere at Mauna Loa Observatory (1958 – September 2015)



In 2010, man-made CO_2 emissions were ~37 $GtCO_2$; the emissions of all GHG's together ~49 $GtCO_{2\text{-eq}}$.

(Source: IPCC, 2014).

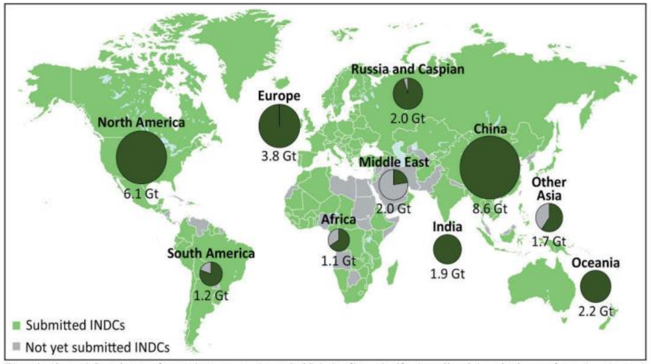
IEA, 13 March 2015: *"Global emissions of CO_2 from the energy sector stalled in 2014 at 32.3 $GtCO_2$, marking the first time in 40 years in which there was a halt or reduction in CO_2 emissions that was not tied to an economic downturn."*

Source curve: http://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.pdf (visited: 28 Oct. 2015)

IEA (October 2015)

Impact pledges (INDCs) on global emissions of CO_2

Figure 1 ▷ National climate pledges submitted for COP21 and coverage in terms of energy-related CO_2 emissions in 2013



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: The bubbles represent total energy-related carbon dioxide (CO_2) emissions. The share of these emissions covered by an INDC (as of mid-October) is shown in green and those that are not in grey.

"Global temp. may increase with 2.7 °C in 2100."

"Pledges accelerate the transition, but it is not yet fast enough."

Figure 2 ▷ Growth in world electricity demand and related CO_2 emissions since 1990 (left) and related CO_2 emissions by region (right)

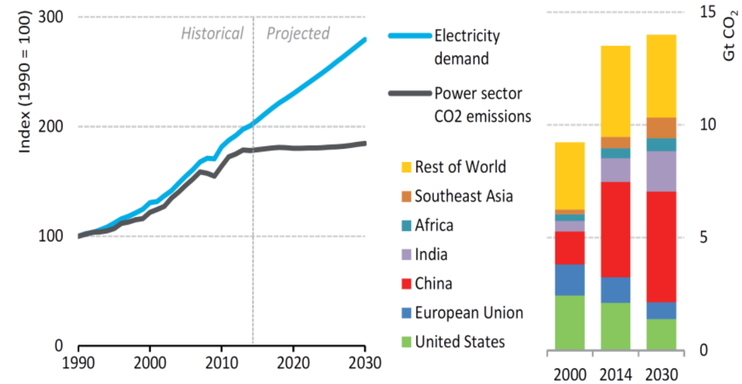


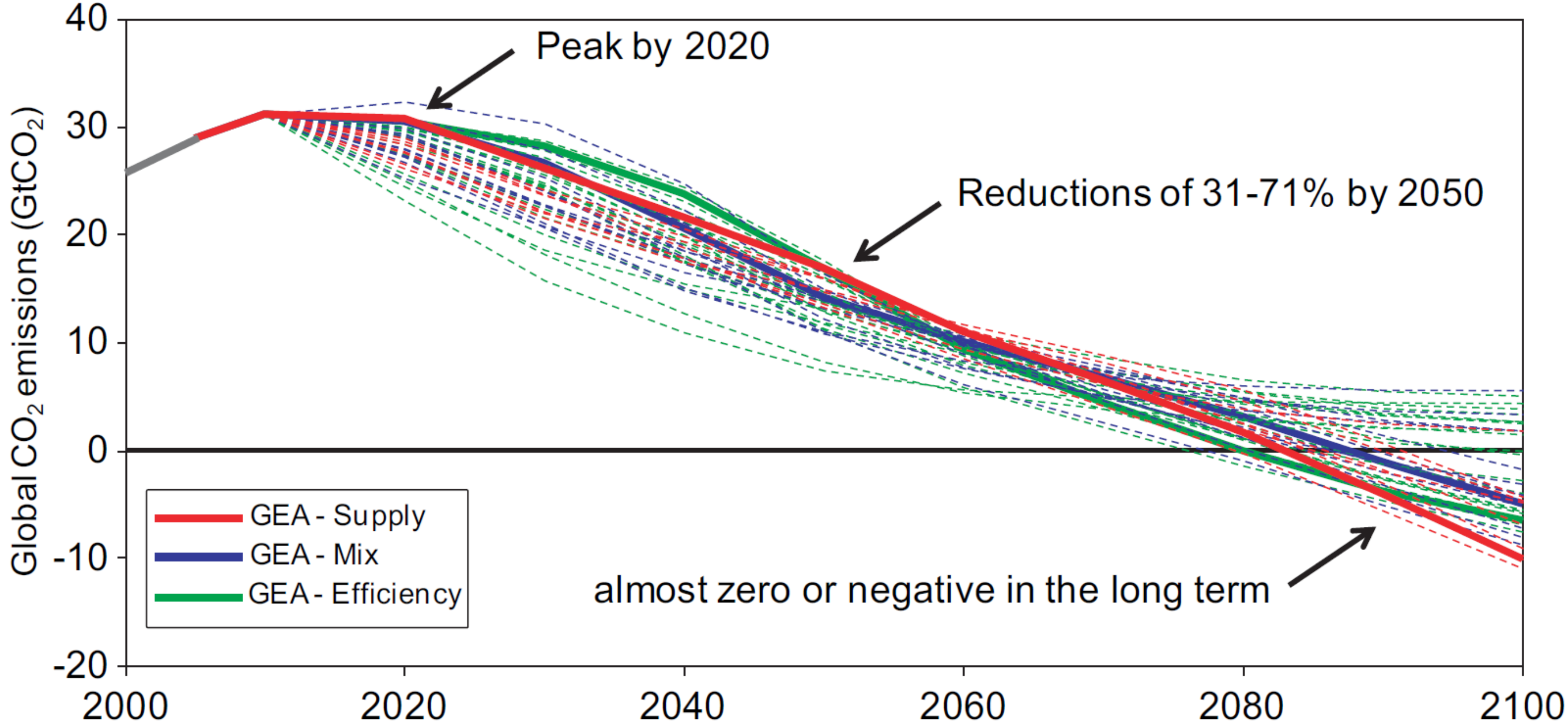
Table 1 ▷ Global energy- and process-related greenhouse-gas emissions in the INDC Scenario (Gt CO_2-eq)

	2014	2020	2025	2030
Energy-related GHG emissions	35.5	36.9	37.5	38.4
Process-related CO_2 emissions	2.8	3.2	3.4	3.5
Total	**38.2**	**40.1**	**40.9**	**41.9**

Source: IEA, 'Energy and Climate Change – WEO Special Briefing for COP21', 21 October 2015

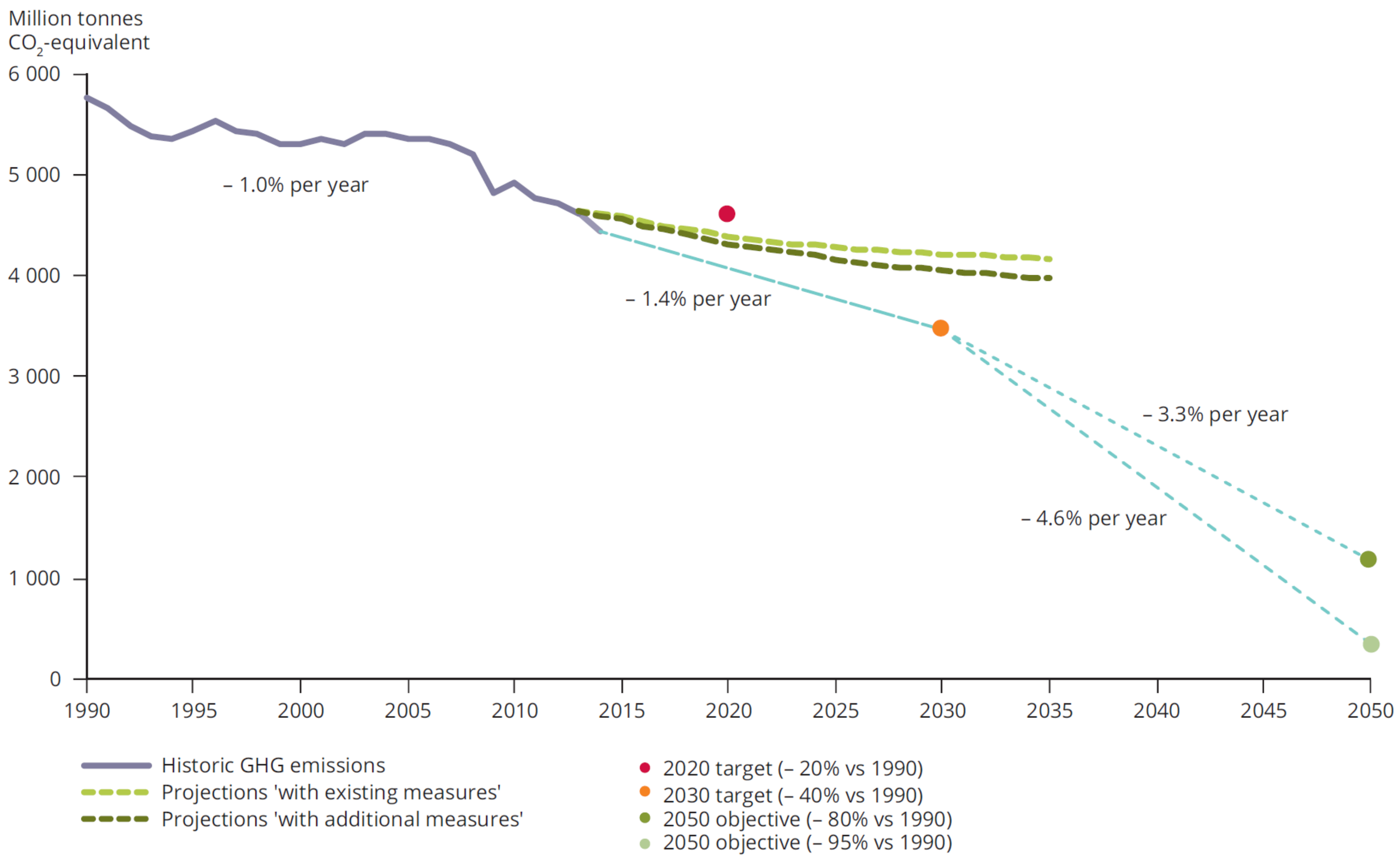
Development of global CO_2 emissions from energy and industrial sources to limit temp. change to below 2°C (prob. > 50%)

- GEA energy pathways toward a sustainable future -



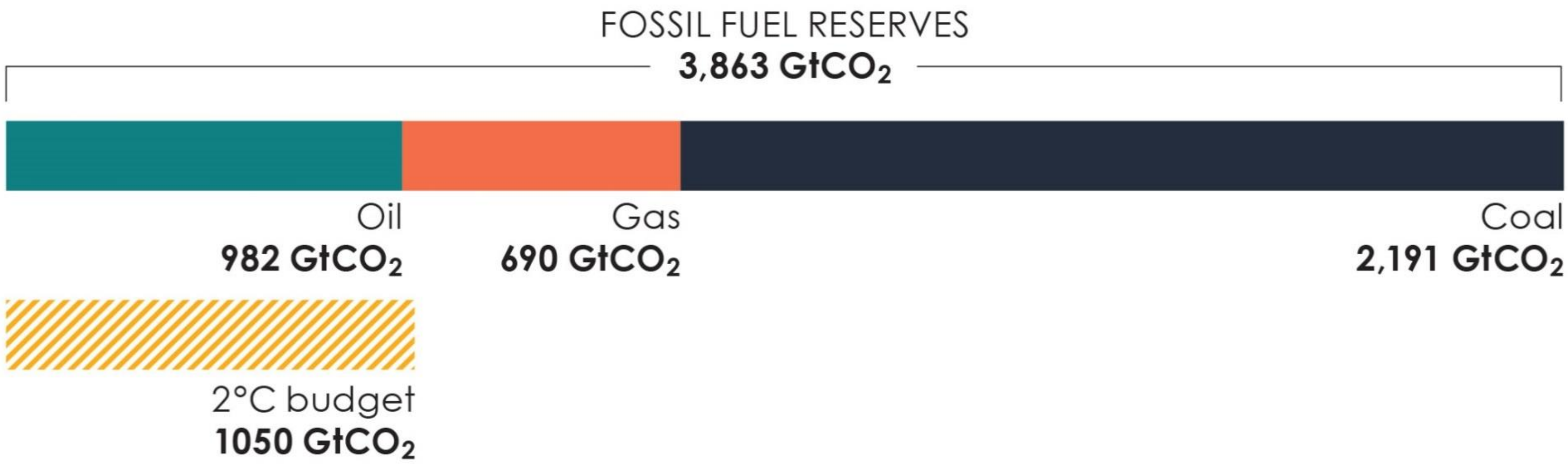
Source: Global Energy Assessment, 2012

EU greenhouse gas emission: trends, projections and reduction targets



Source: EEA, October 2015

Global Carbon budget compatible with limiting global warming to +2°C *versus* fossil fuel reserves



Conventional and unconventional fossil fuel reserves of coal, oil, and gas and the global carbon budget compatible with scenarios limiting global mean warming to 2°C above pre-industrial temperatures (with a 66% probability).

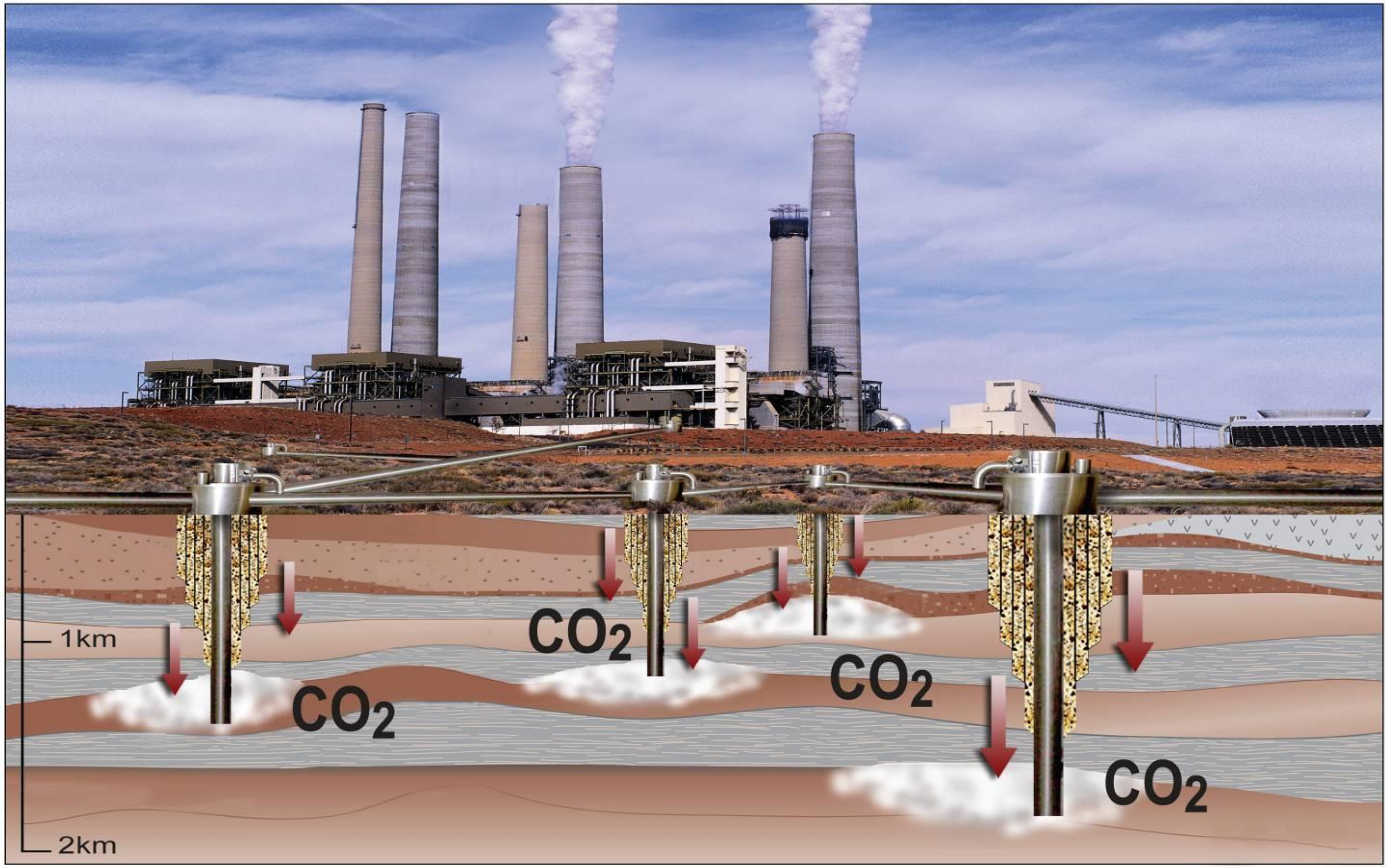
Source Fossil Fuel reserves: IPCC, 2011 (figure 1.7).
Source Carbon budget: IPCC, 2013 and IPCC erratum, November 2013.

Source figure: ECF, "Statement by leading climate and energy scientists", 2013

Unburnable Carbon and Stranded Assets

- Not the use of fossil fuels but **the emission of CO_2** (at present ~37 Gton/yr globally) is the problem!
- *Carbon Tracker* and groups like *Urgenda* in NL don't give enough attention to **the potential of CCS**.
- CCS can have a large impact (~***2,000 GtCO$_2$*** *till 2100*) on 'unburnable carbon'.
- But: within about 20 years we can't allow **any** new investments in **unabated use** of any fossil fuel (given 'max +2°C), having **huge consequences** for Shell, Exxon, BP, Gasunie, Gasterra, EBN, RWE, E.ON, Vattenfall, ENECO, KVGN, etc. Therefore a Roadmap CCS for the Netherlands is urgently needed!
- Note also the statement of the EC (Dec. 2011): *"No new investments in fossil fuel power plants after 2030 without CCS".*

Emissions of CO_2, the most important long-lived anthropogenic greenhouse gas, can be reduced by CCS



Capture → Compression → Pipeline Transport → Geological Sequestration

Removal of CO_2 from power plants

- **CCS: a proven technology that today securely stores 25 Mt CO_2 per year.**
- **There are 21 large-scale projects in operation or construction, all expected to be online by 2016. These will have the capacity to capture up to 40 Mt CO_2 per annum.**

- In Saskatchewan (Canada) the first commercial scale operation of CCS at a power plant started October 2014: the *Boundary Dam project* (Shell involved).
- It's a coal-burning plant that generates 110 MW and would emit more than 1 Mt of CO_2 per year. Its operators say, the project is "exceeding expectations."

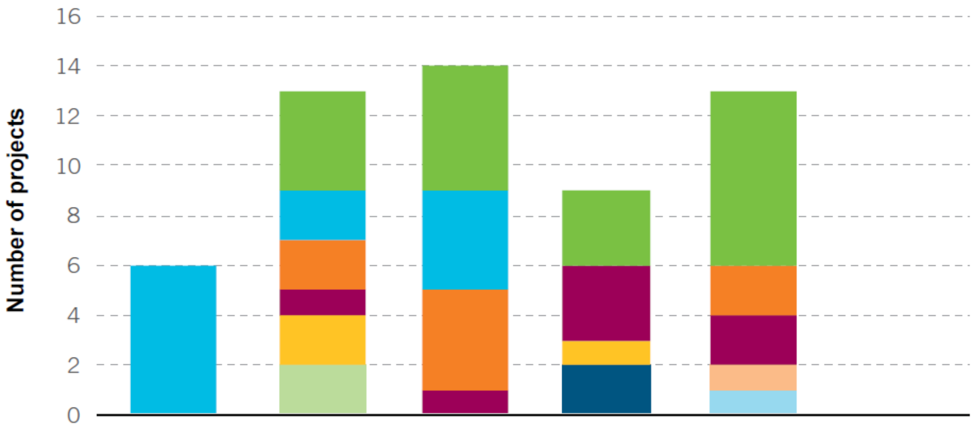
Aerial Photo of SaskPower's Boundary Dam Project near Estevan, Saskatchewan

- Shell/Cansolv and SSE are looking to develop the world's first full-scale gas CCS project – the *Peterhead Project* (Scotland), with support of the UK Gov't

Sources: GCCSI, 2014; SaskPower, 2015; Shell UK, 2015

Large scale CCS projects by country/region

- Status Nov. 2014 -



	Identify	Evaluate	Define	Execute	Operate	**Total**
United States	0	4	5	3	7	**19**
China	6	2	4	0	0	**12**
Europe	0	2	4	0	2	**8**
Canada	0	1	1	3	2	**7**
Australia	0	2	0	1	0	**3**
Middle East	0	0	0	2	0	**2**
Other Asia	0	2	0	0	0	**2**
South America	0	0	0	0	1	**1**
Africa	0	0	0	0	1	**1**
Total	**6**	**13**	**14**	**9**	**13**	**55**

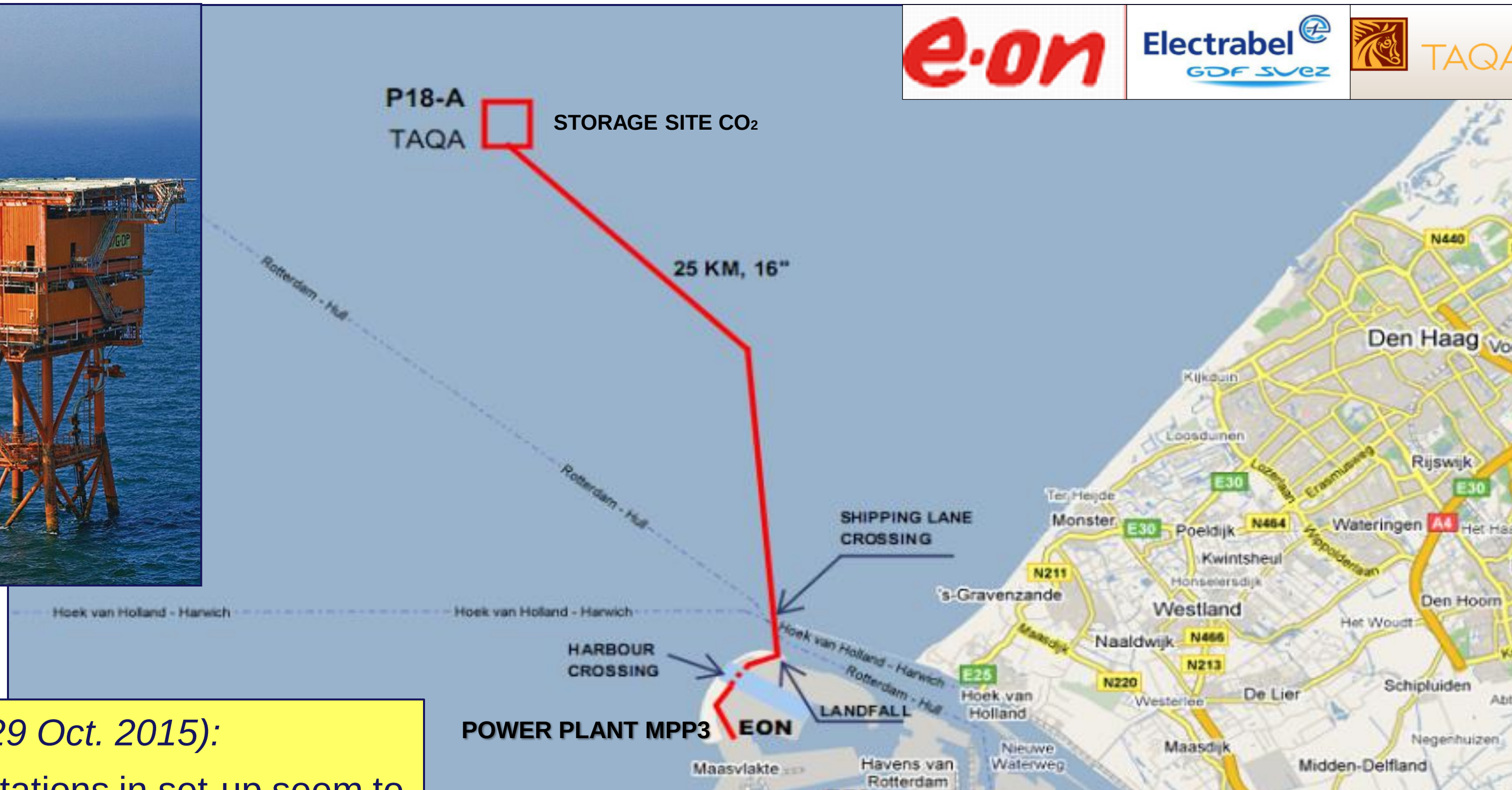
Source: GCCSI, 'The Global Status of CCS 2014', Melbourne, 2014

Conclusions Int. Conf. GHGT-12 (Oct. 2014): *'At present optimism on CCS in North America and China, pessimism in Europe, apart from UK and Norway.'*

'Nowadays the ROAD-project is about the only EU demo-plant project left'.

ROAD: EERP Demo project MPP3 - Rotterdam (NL)

CCS: 1.1 Mt/yr



Note WCT (29 Oct. 2015):

Recent adaptations in set-up seem to solve the financial problems, making realization of the project quite likely.

ROAD = Rotterdam Opslag and Afvang Demonstratieproject
EERP = European Economic Recovery Plan
MPP3 = Maasvlakte Power Plant 3

Consequences of Excluding CCS from the Mitigation Portfolio

1 Cost of mitigation will increase

- *Including CCS reduces the cost of the overall mitigation portfolio*

2 Sufficiently large emission reductions will not be possible without CCS

- *Base and peak load generation will be challenging without fossil fuels*

3 Political support for mitigation will be weak

- *Fossil fuel-rich regions will resist mitigation*

4 Some geographic areas will not be able to reduce emissions rapidly enough

- *Renewable energy and nuclear power may be poor options in some areas*

Source: S. Benson et al., 'Carbon Capture and Storage', Global Energy Assessment, 2012, chapter 13

Energy scenarios
&
Renewables

World Primary Energy Supply in 2009

(using GEA substitution method to calculate contribution from renewables)

Fossil fuels:		**412 EJ**	**(78 %)**
- oil	167 EJ		
- gas	106 EJ		
- coal	139 EJ		
Renewables:		**89 EJ**	**(17 %)**
- large hydro	30 EJ *)		
- traditional biomass	39 EJ		
- 'new' renewables	**20 EJ *)**		**(~ 4%)**
Nuclear:		**27 EJ**	**(5 %)**
Total:		**528 EJ**	**(100 %)**

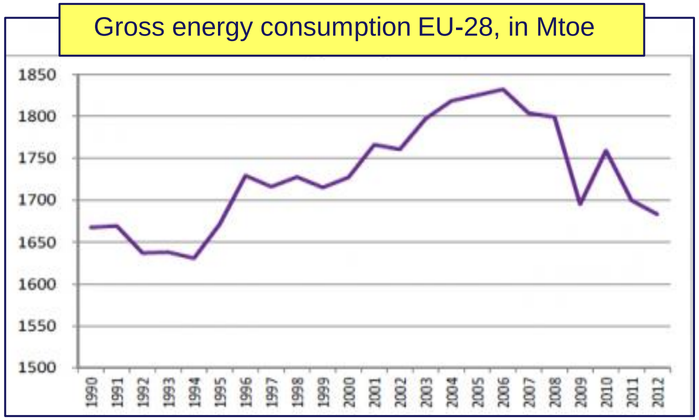
Figure NL: also ~ 4%

**) Assuming for hydro, wind, solar and geothermal electricity: 1 EJ(el) = 2.85 EJ savings on fossil fuels, and for solar and geothermal heat: 1 EJ(th) = 1.17 EJ savings on fossil fuels.*

Source: W.C. Turkenburg et al., 'Renewable Energy'. In: Global Energy Assessment, 2012, chapter 11

Development gross inland energy consumption EU-28

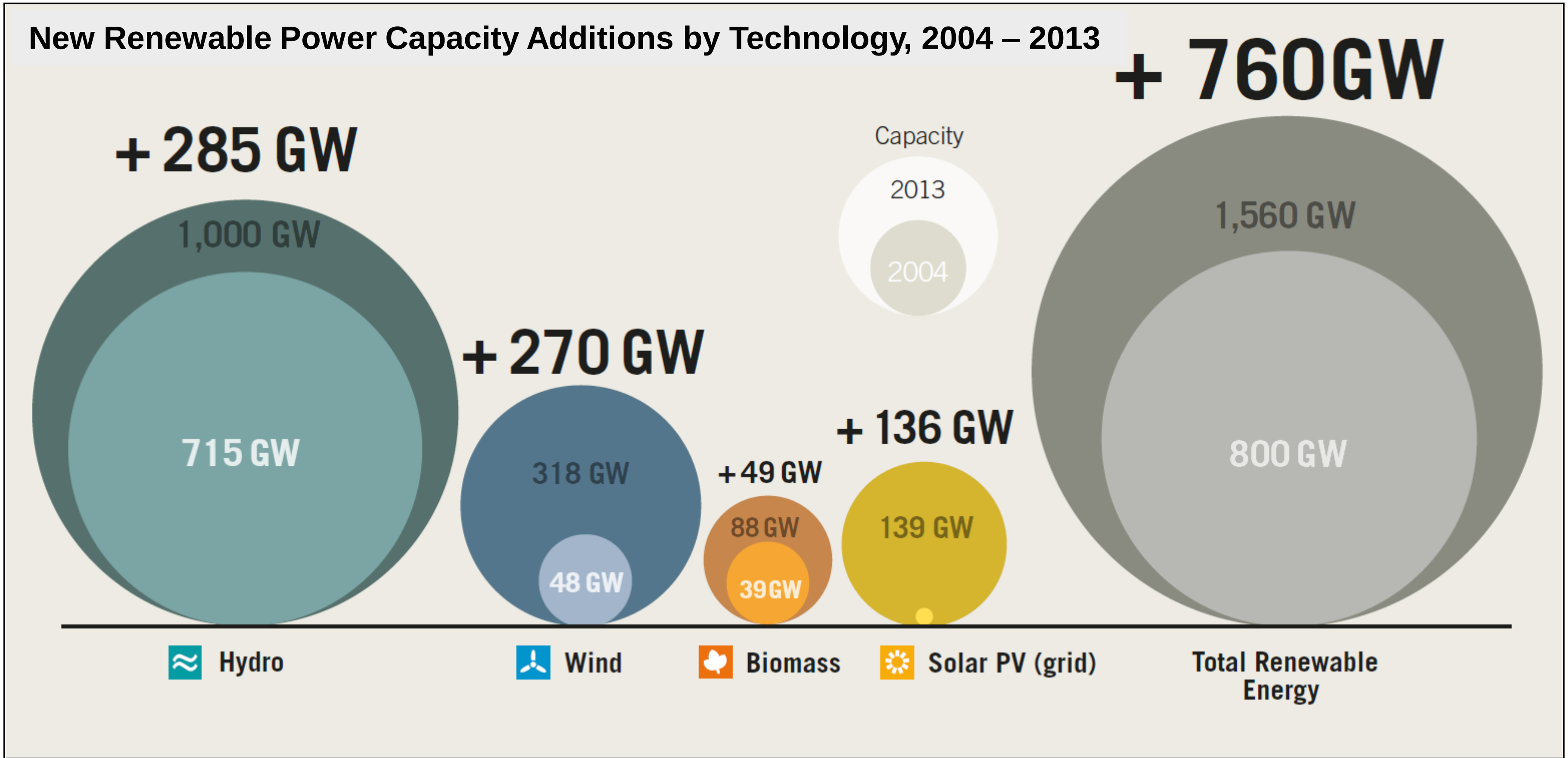
- Between 2006 and 2012, gross inland energy consumption in the EU-28 has fallen by 8%.
- Between 2006 and 2012 energy consumption *fell* in 24 Member states, but *increased* in Estonia (+12%), Netherlands (+3%), Poland (+1%), and Sweden (+0.4%).
- In 2012, Denmark the only *net exporter* of energy.



	1990 *(EJ)*	**2000** *(EJ)*	**2006** *(EJ)*	**2010** *(EJ)*	**2012** *(EJ)*	**% change 2006/2012**		***Energy dependence rate, 2012***
EU-28	**69.82**	**72.31**	**76.71**	**73.65**	**70.46**	**-8%**		***53%***
Belgium	2.04	2.48	2.41	2.54	2.36	-2%		*74%*
Denmark	0.75	0.83	0.88	0.84	0.76	-14%		*-3%*
Germany	14.92	14.33	14.73	13.97	13.38	-9%		*61%*
Netherlands	**2.80**	**3.17**	**3.33**	**3.63**	**3.43**	**+3%**		***31%***
UK	8.83	9.66	9.65	8.84	8.47	-12%		*42%*

Source: Eurostat, 17 February 2014

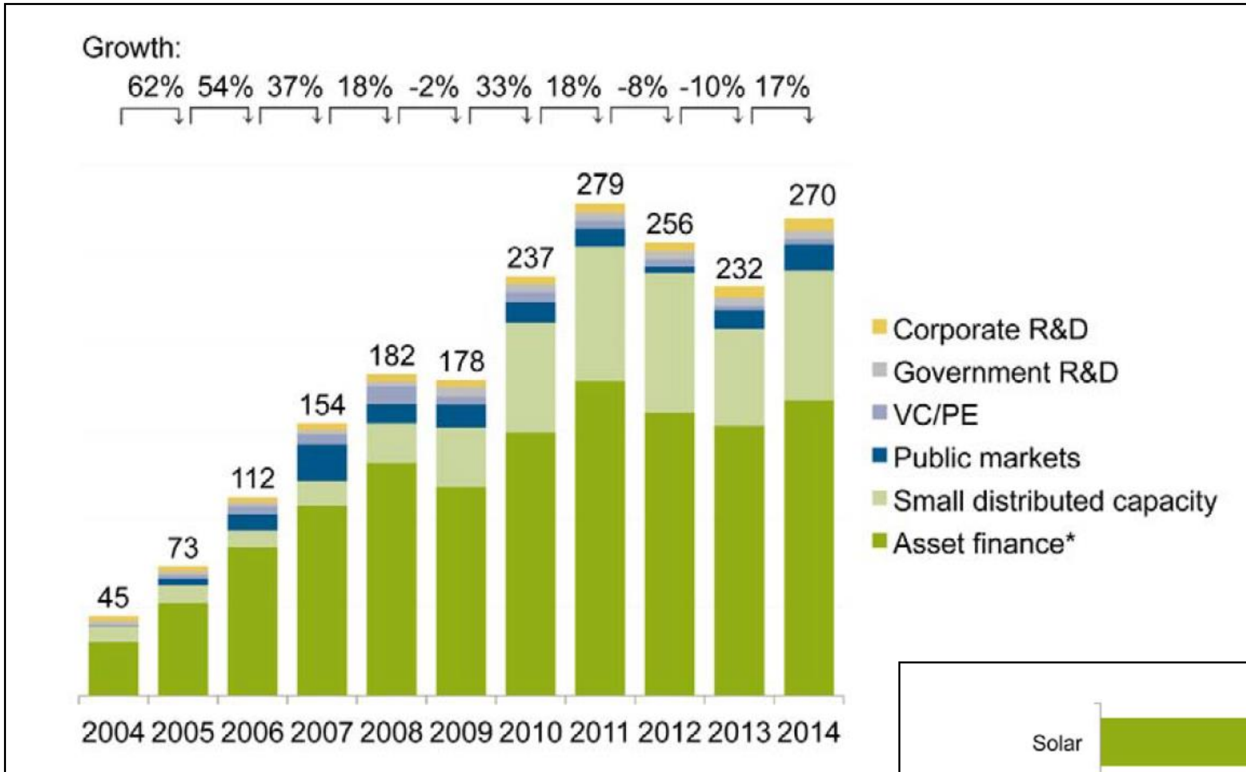
Ten years of renewable energy progress (2004-2013)



Geothermal figures for 2004 and 2013 were 9 and 12 GW respectively. For CSP, capacity was 0.4 GW in 2004 and 3.4 GW in 2013. These amounts have been included in the Total Renewable Energy calculation.

Source: REN21, November 2014

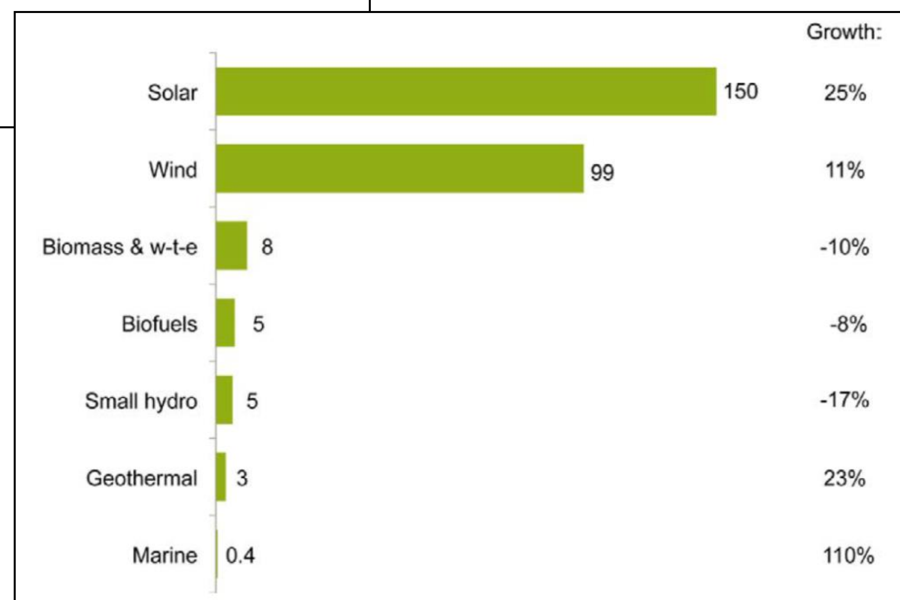
Global new investment in renewables, 2004-2014 ($bn)



Source: BNEF, 2015

Increase investments in *new* renewables by a factor 100 between 1991 and 2011!

Global new investment in renewables by sector in 2014 ($bn) and growth on 2013



Global Market Overview – Power Markets

- **Renewable energy comprises more than 26% of global power generation capacity in 2012.**

- **Almost 22% of global electricity was produced from renewable energy (with 16.5% from hydro).**

- **Renewables accounted globally for *just over half (51%)* of the estimated 280 GW of new installed electric capacity in 2012 (and in Europe even *70%).***

- **We are witnessing a revolution in the energy field!**

Source: REN21, 'Renewables 2013 Global Status Report', June 2013

Some recent energy scenario studies

- Can we achieve a sustainable future? -

- **Shell, 2013: 'New LENS scenarios'** (*Mountains* and *Oceans*)
  - Global warming will continue up to at least +4°C.
  - Increase energy efficiency: 1.4% per year.
  - Contribution from renewables in 2050: 22%-31%.

  NO !

- **GEA, 2012: 'Toward a Sustainable Future'**

  YES !

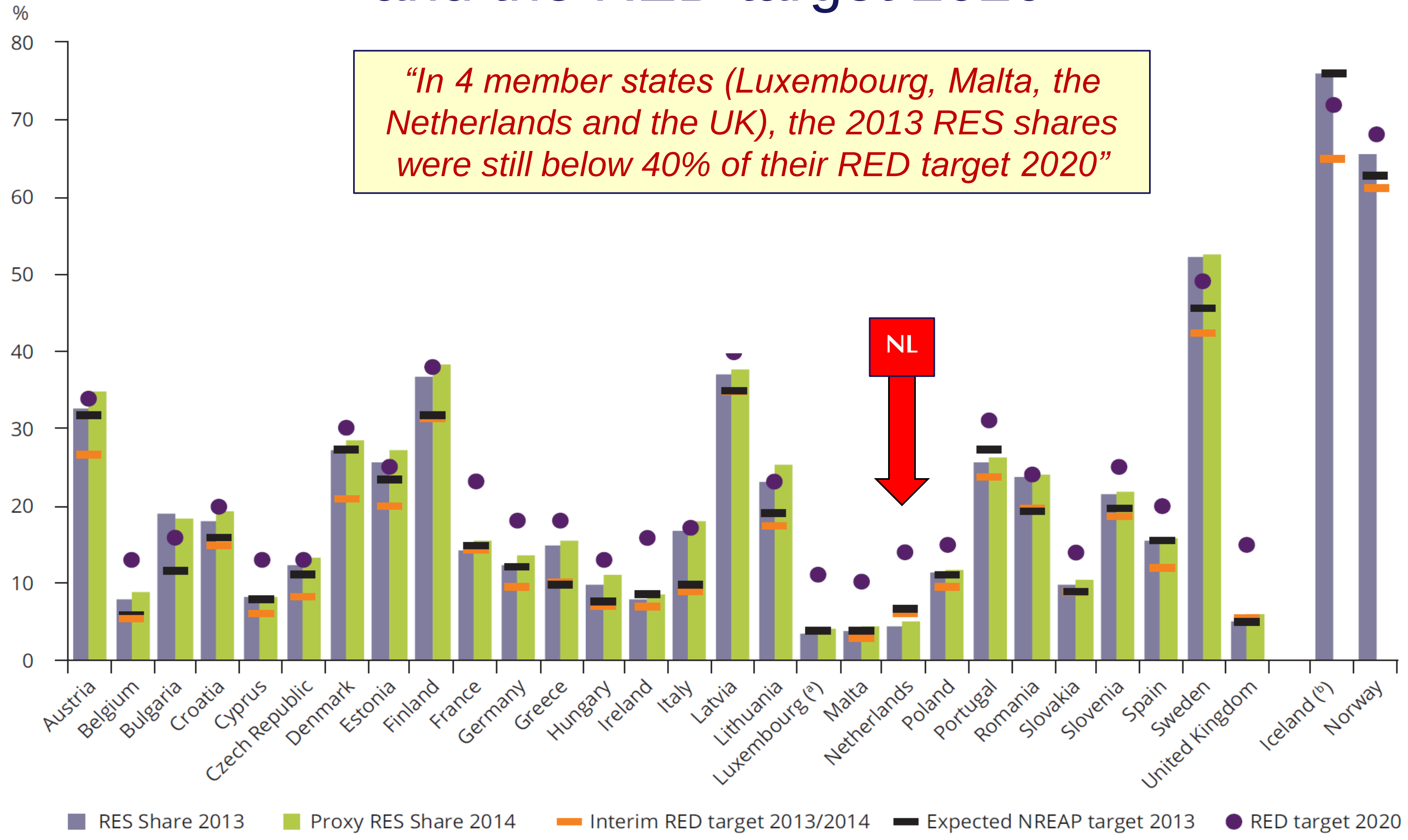
  - Many combinations of energy resources, end-use, and supply technologies that can simultaneously address the multiple sustainability challenges.
  - Increase energy efficiency: 1.5% up to 2.2% per year.
  - Contribution from renewables in 2050: 30%-75%.
  - Cumulative storage of CO_2 in 2050: up to 250 $GtCO_2$.

- **Ecofys and WWF, 2011: 'The Energy Report'**

  YES !

  - A fully sustainable system is possible by 2050.
  - Increase energy efficiency: 3%-4% per year.
  - Almost 100% of all energy carriers, all regions and all sectors of the global energy system can be renewable, by 2050.

EU member states' RES shares (2013-2014) in relation to the indicative RED target 2013-2014 and the RED target 2020



Source: EEA, October 2015

Contribution renewables to gross *energy* and *electricity* consumption in NL and EU-28 in 2012

NL: Contribution RE to energy consumption in 2012: a ~ 4.5%

- mostly from biomass (86.9%) and wind (11.3%)
- from solar 1.3%, geoth. 0.3% and hydro 0.2%

EU-28: Contribution RE to energy cons. in 2012: ~ 14.1%

- 65.4% from biomass energy
- 16.2% from hydro power
- 10.0% from wind energy
- 5.2% from solar energy
- 3.2% from geothermal energy
- 0.02% from tide, wave, and ocean power

NL: Contribution RE to electricity consumption in 2012: ~ 10.5%

- nearly all from biomass and wind

EU-28: Contribution RE to electricity cons. in 2012: ~ 23.5%

- mostly from biomass and hydropower

Ranking NL on renew. energy: nr. 25 and on renewable electricity: nr. 24

Note:

- NL has limited ren. energy resources:
  - small country (in km^2);
  - hardly any hydro power resources;
  - limited availability of land for biomass energy cultures.
- Also: high ranking NL on population density: nr. 2 (less ‘free space’)

Source: Eurostat, 2014

Potential of renewable energy sources in EU countries

and contributions RES in 2011

Country	Renew. In 2011 (PJ/yr)	Share RE in 2011	RE/cap (GJ/cap)	RE/GDP (kJ/USD)	RE/km² (GJ/km²)	Wind	Solar	Hydro	Biom.	Geoth.	Ocean
Austria	367.3	26.5%	43.7	879	4,379						
Belgium	119.7	4.9%	10.9	233	3,944						
Bulgaria	56.6	7.1%	7.8	1,058	510						
Cyprus	5.1	5.1%	4.6	206	551						
Czech Rep.	125.2	6.9%	11.9	577	1,616						
Denmark	170.7	22.4%	30.5	512	3,961						
Estonia	34.8	15.0%	26.8	1,568	770						
Finland	379.9	25.8%	70.4	1,444	1,128						
France	765.0	7.2%	11.7	276	1,188						
Germany	1,307.7	10.1%	16.0	363	3,660						
Greece	89.3	7.8%	7.9	308	677						
Hungary	79.0	7.5%	7.9	564	849						
Ireland	34.3	6.2%	7.5	158	491						
Italy	834,9	11.7%	13.7	381	2,771						
Latvia	60.1	34.7%	28.6	2,124	931						
Lithuania	44.2	15.1%	14.7	1,035	677						
Luxembourg	5.1	2.9%	9.8	86	1,977						
Malta	0.1	0.1%	0.24	11	323						
Netherlands	138.1 (13)	4.2% (24/25)	8.3 (20)	165 (23)	3,697 (4)						
Poland	332.9	7.8%	8.6	647	1,067						
Portugal	215.3	22.4%	20.3	907	2,335						
Romania	212.2	14.0%	9.9	1,180	890						
Slovakia	57.2	7.8%	10.6	596	1,167						
Slovenia	39.7	13.1%	18.9	802	1,949						
Spain	612.9	11.7%	13.3	415	1,211						
Sweden	659.4	32.1%	70.1	1,222	1,464						
Un. Kingdom	326.6	4.2%	5.2	134	1,347						

high	*High/medium*	*medium*	*medium/low*	*low*	*unknown*	*Not-applicable*

- The colour table shows that, within the EU, NL is not a favourable country for developing renewable en. sources, apart from wind energy.

- Therefore alternatives like Gas+CCS also important for especially NL to reduce CO_2 emissions.

Source: Wim Turkenburg, 2013 - based on data from IRENA, 2013

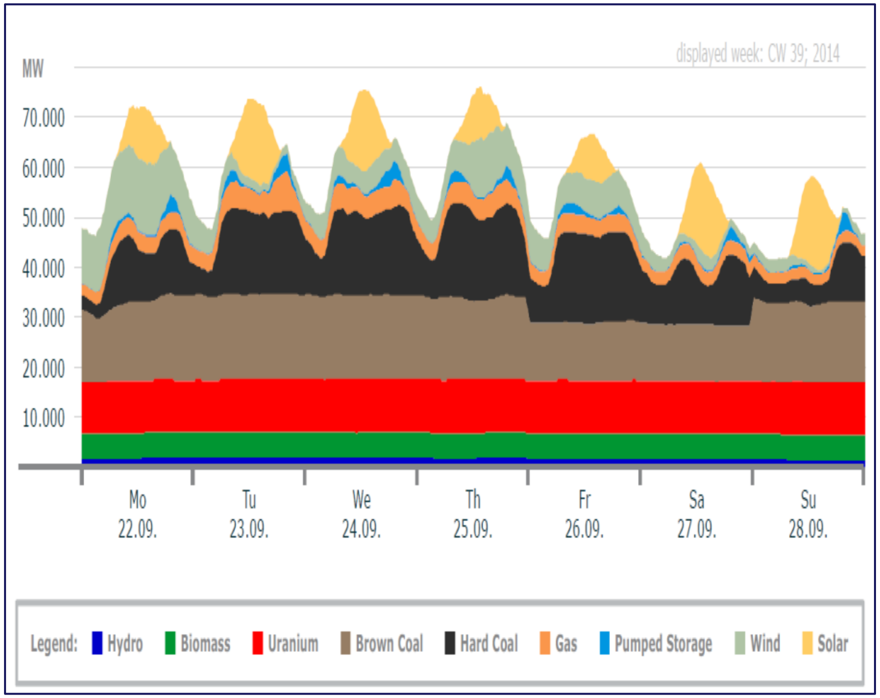
How to deal with intermittent renewables (wind / solar-PV)?

Integrating intermittent renewables

Electricity production in Germany

2014, Week 39 (22-28 Sept.)

- by solar PV, wind, pumped storage, conventional capacity, biomass and hydropower -

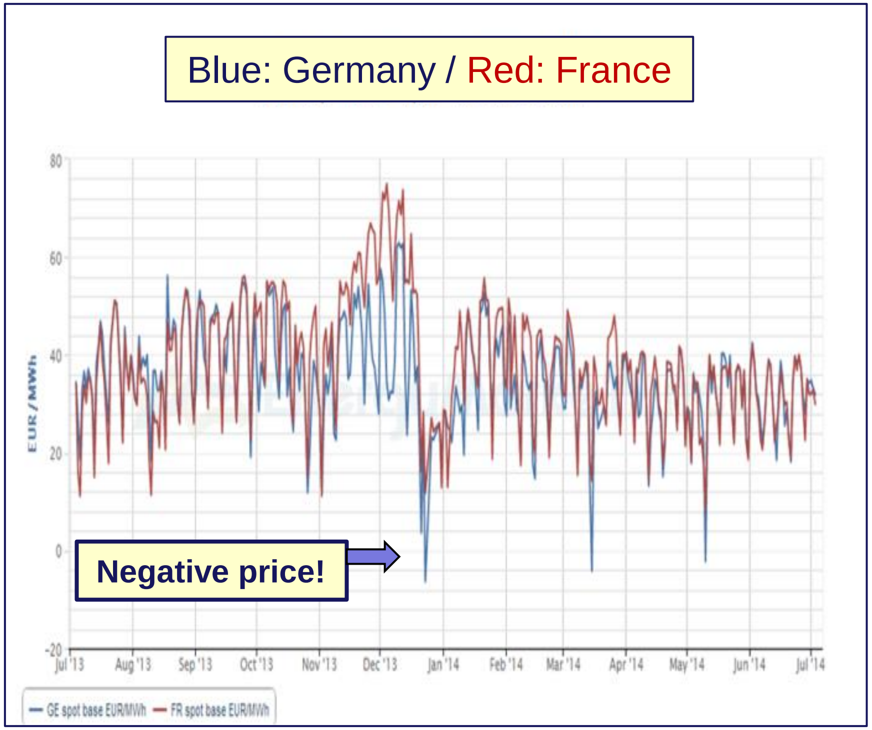


Source: Bruno Burger, Fraunhofer ISE, 2014

Spot price of base load electricity

July 2013 – July 2014

(EUR/MWh)



Source: Energy Market Price, 3 July 2014

Options to balance the fluctuating supply from wind and solar-based electricity

In random order:

1. Temporary curtailment of variable electricity generation sources;
2. Exchanging electricity surpluses with other countries;
3. More flexible utilization of part of the *electricity* demand (demand side response);
4. Flexible electrification of *energy* demand (e.g. Power-to-Heat);
5. Use of dispatchable gas-based electricity generation units (using natural gas or biogas, also combined with CCS);
6. Implementation of some type of electricity storage, such as Pumped Hydro, Compressed Air Energy Storage (CAES) and batteries (in homes / electric vehicles);
7. Converting electricity into a gaseous energy carrier (P2G).

Sources: GEA, 2012; REP, 2012; RWE, 2013; ECN, July 2014; UU, 2016

Interaction between renewable energy supply, conventional energy supply, and the demand side

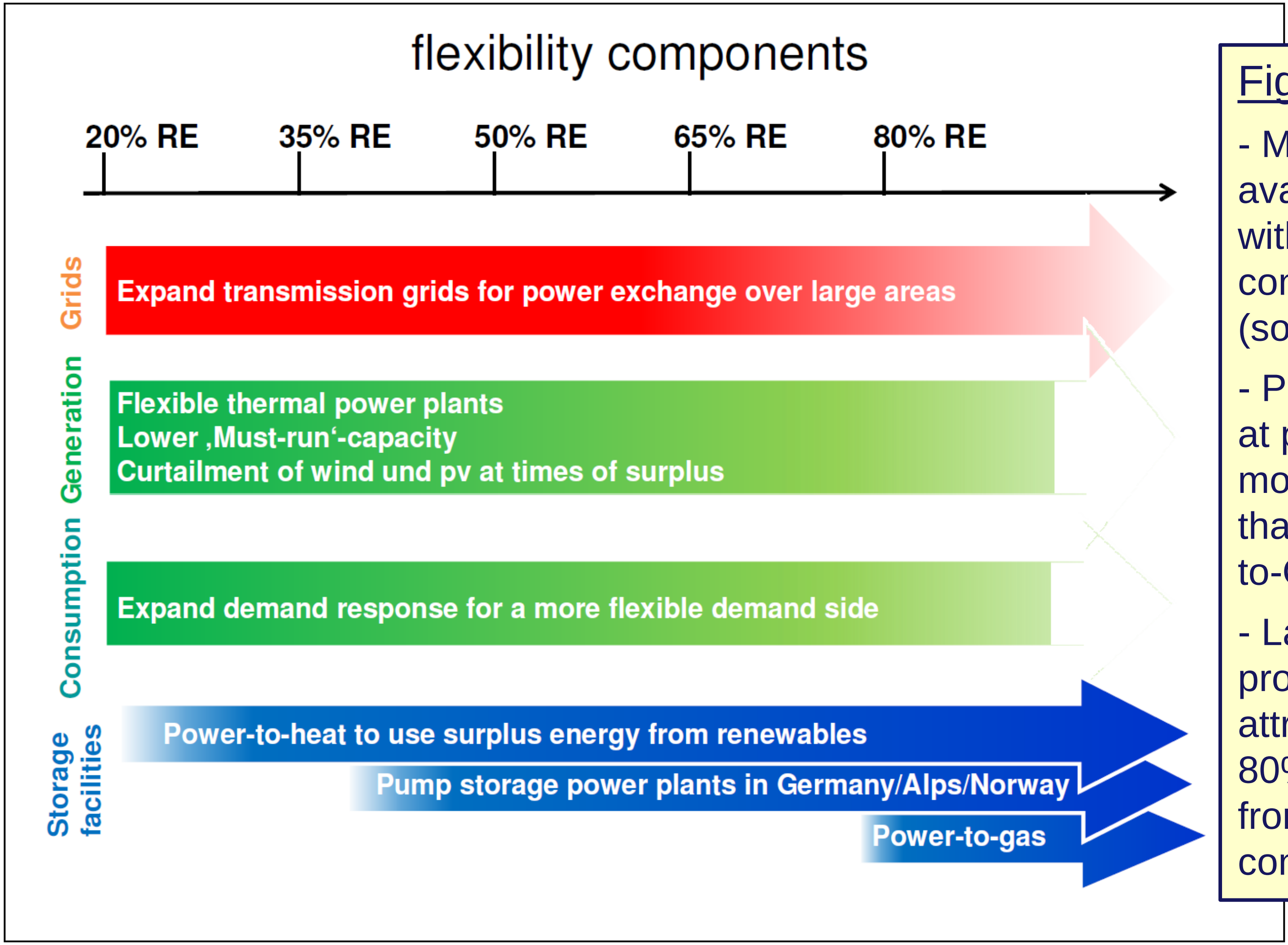


Figure shows:

- Many options available to deal with flexibility components (solar-PV & wind).
- Power-to-Heat at present far more attractive than e.g. Power-to-Gas (P2G).
- Large scale P2G probably not attractive below 80% contribution from flexibility components!

Source: Steering Committee of the Renewable Energy Platforms, Germany, 15 Oct. 2012

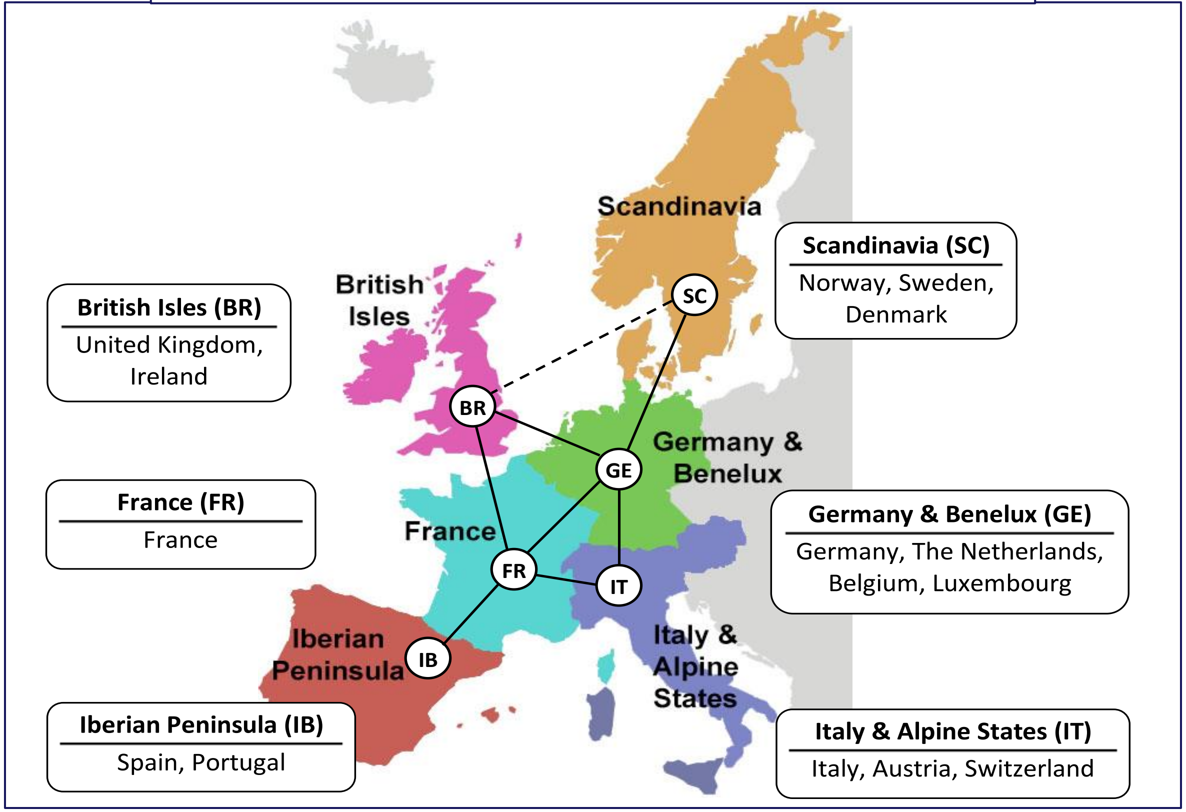
UU-study:

‘Least-cost options for integrating intermittent renewables in low-carbon power systems’

(Applied Energy, 2016)

Hourly simulation of electricity supply in 2050 in Western Europe using the PLEXOS model

The six regions considered in the UU study



Boundary conditions:

1) **96% reduction of power sector CO_2 emissions in 2050 compared to 1990**
2) **Maintaining reliability of supply (LoL<0.1 day/year)**
3) **Increase RE in 2050 up to 40%, 60%, 80%**
4) **Looking for lowest costs electricity**

Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

Some input data used in the study

Category	Fuel / Technology	Cost per unit
Fuel cost	- Coal	1.7 €/GJ
(2035)	- Natural Gas	6.5 €/GJ
	- Uranium	1.0 €/GJ
	- Biomass	7.2 €/GJ
	- CO_2 transport en storage	13.5 €/tCO_2
TCR Investment cost	- Gasturbine (GT)	438 €/kW
(2035)	- NGCC / NGCC+CCS	902 €/kW / 1,349 €/kW
	- PC / PC+CCS	2,088 €/kW / 2,847 €/kW
	- Nuclear power	4,841 €/kW
	- Wind onshore / offshore	1,402 €/kW / 2,655 €/kW
	- Solar PV	700 €/kW
	- Biomass power	1,644 €/kW
	- Geothermal power	2,151 €/kW
	- Hydropower	2,059 €/kW

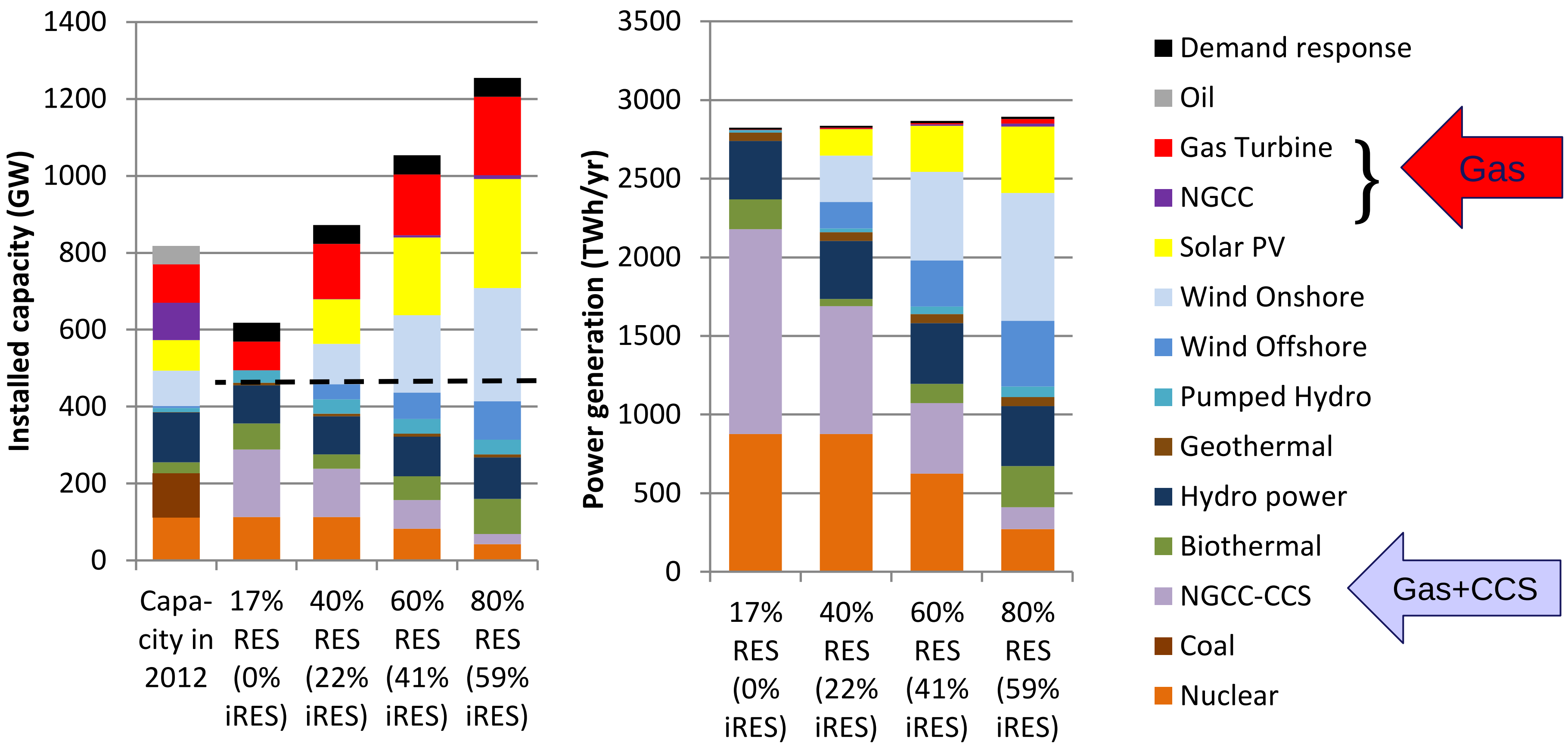
€ = $€_{2012}$

TCR = Total Capital Requirement

Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

Installed capacity *(GW)* ***and power generation*** *(TWh/y)* ***in the core scenarios in the year 2050***

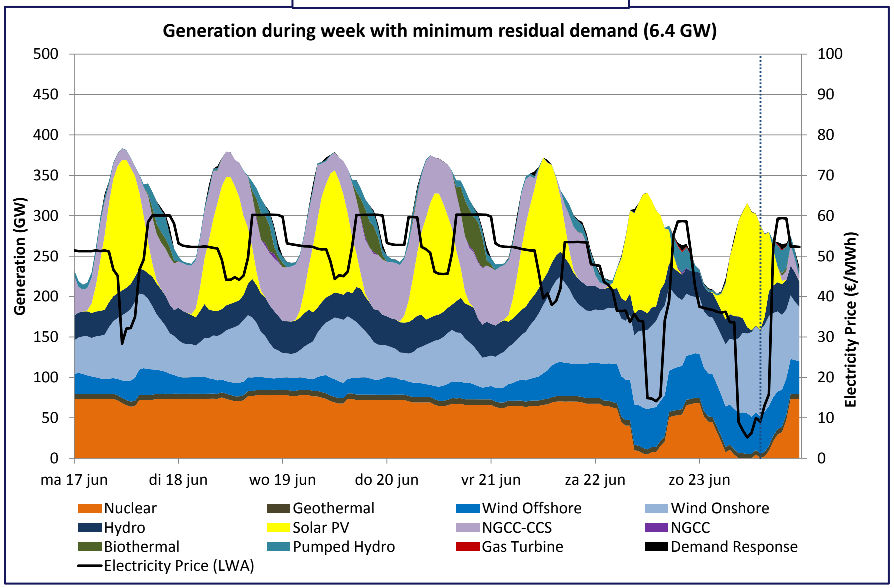
(The dashed line depicts the assumed peak load in 2050)



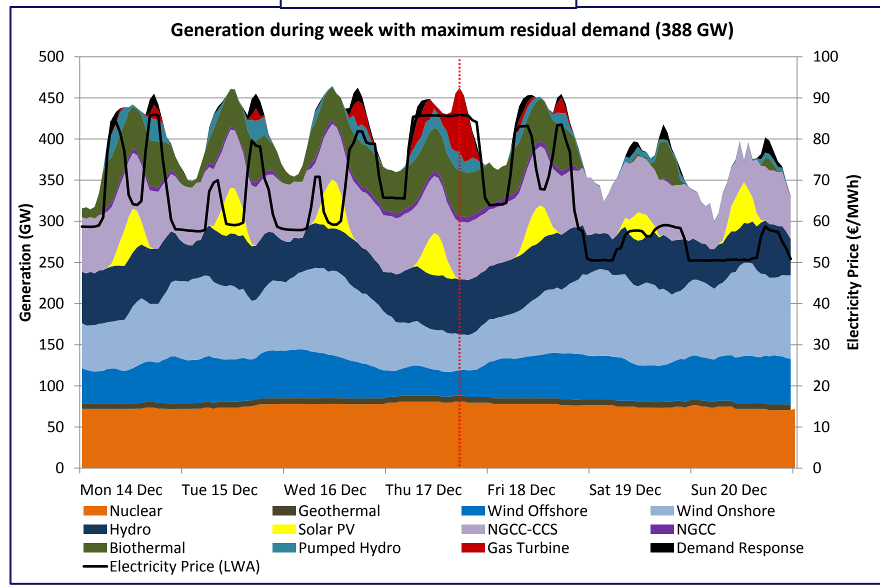
Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

Power generation in summer and winter (60% RES)

summer time



winter time



- NGCC+CCS generates power during the nights in the summer.
- Electricity storage could replace NGCCs in the summer but ...
- Baseload generation by NGCC+CCS during winter time is very costly to replace by (seasonal) storage.
- Gas turbines supply peak demand.

Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

Total annual system costs in the core scenarios in Western Europe in 2050

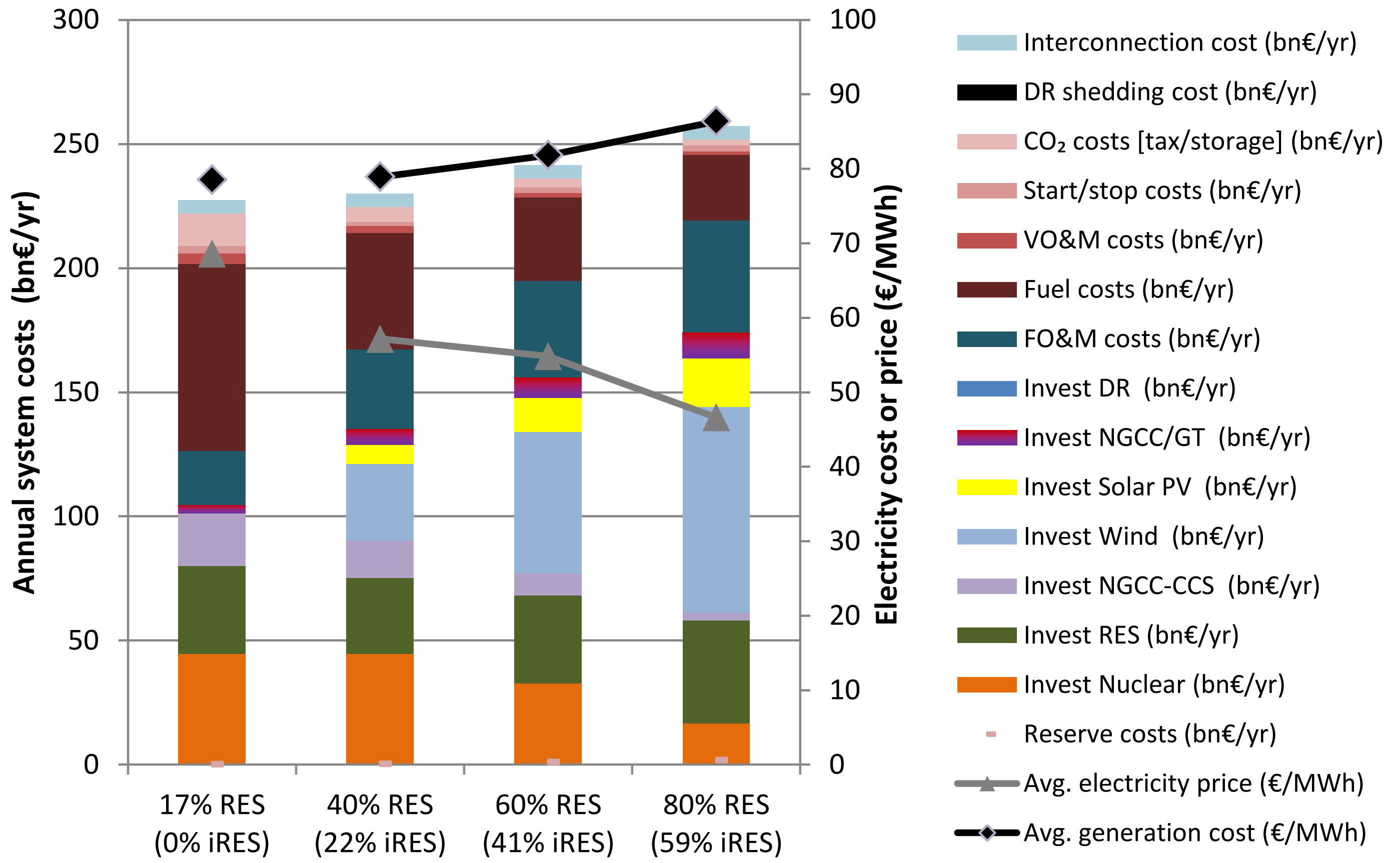
Also shown: electricity costs vs. electricity price (€/MWh)

Conclusions:

1) Increase contribution renewables causes <u>increase</u> total system costs.

2) NGCC+CCS cost-effective balancing option.

3) Income per kWh <u>less</u> than costs per kWh, for renewables and for convent. power plants.



Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

Enige conclusies

- *Aanpassing vraag aan aanbod* en toepassing *curtailment* van belang voor goede inpassing zon- en windvermogen.
- Nog heel lang geen noodzaak *grootschalige opslag elektriciteit*; financieel voordeel ervan in de onderzochte scenario's nul tot negatief.
- Noodzaak nieuwe *zware koppelnetten* tussen de regio's in Europa niet heel groot. Uitbreiding bestaande koppelnetten levert financieel voordeel.
- Weinig of geen toekomst voor nieuwbouw van *kolencentrales+CCS.* (NB: er is niet gekeken naar de optie kolen+biomassa+CCS).
- Wel veel toekomst voor *aardgas+CCS*; toepassing van NGCC's met CCS levert grote kostenbesparingen t.o.v. toepassing heel veel hernieuwbaar.
- *Kerncentrales* komen vanwege kosten en bedrijfstijd niet gunstig uit de studie.
- Zonder aanpassing van het huidige *'energy only' marktmodel* gaan de systemen (met name de windparken en het balansvermogen) er niet komen.

Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

Thanks!

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