Gebruiken we in 2050 nog fossiele brandstoffen?

"Ruim beneden 2 °C en streven naar maximaal 1,5 °C" - wat betekent dit?

'Klimaatbeleid moet om na Parijs'

Bron: Trouw, 14 december 2015

Barack Obama: ***"We've got to accelerate the transition away from dirty energy"***

State-of-the-Union, 12 January 2016

Wim Turkenburg

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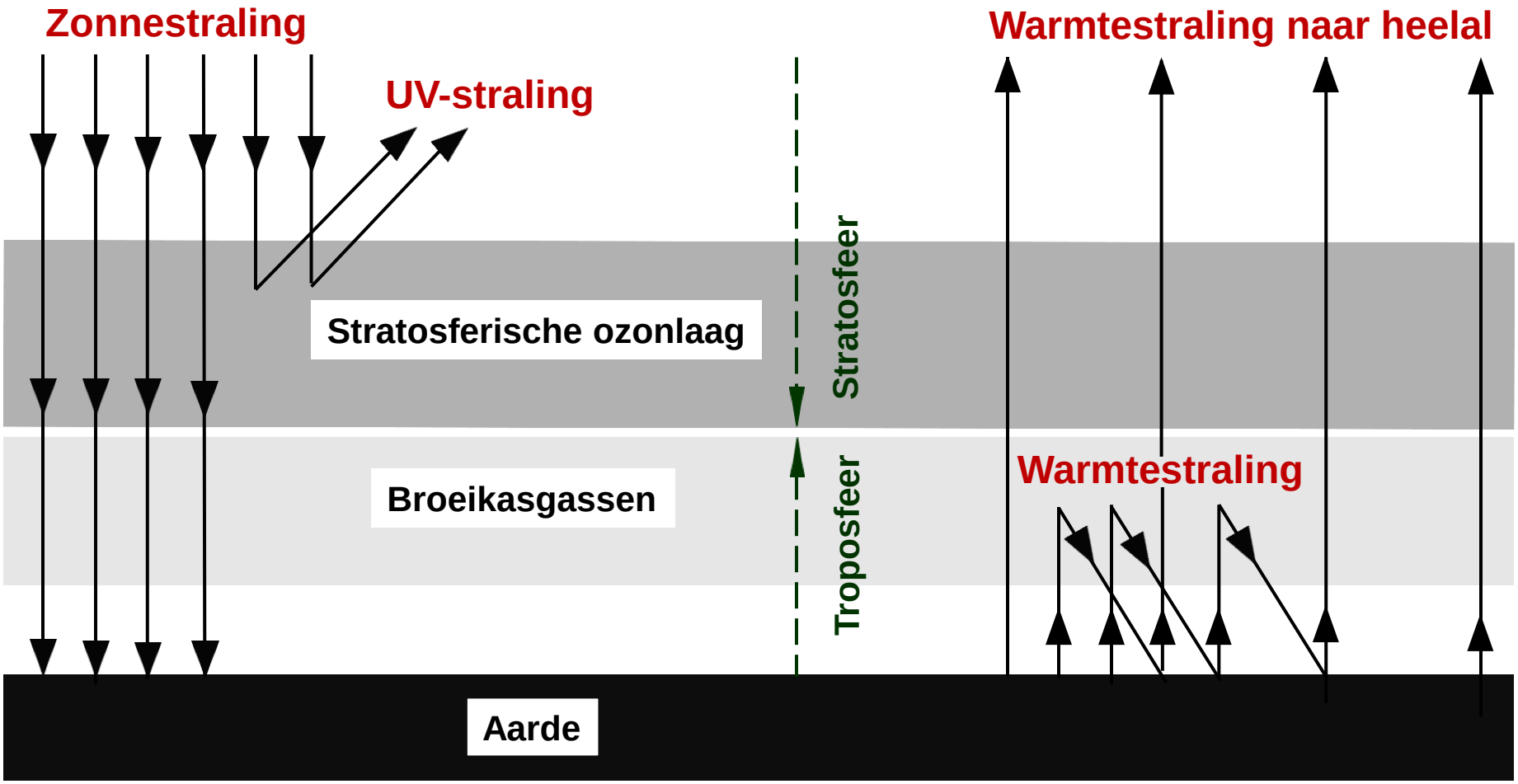
Copernicus Institute,
Utrecht University
&
Wim Turkenburg Energy and Environmental Consultancy, Amsterdam

KIVI, regio Gelderland – Arnhem, 4 april 2016

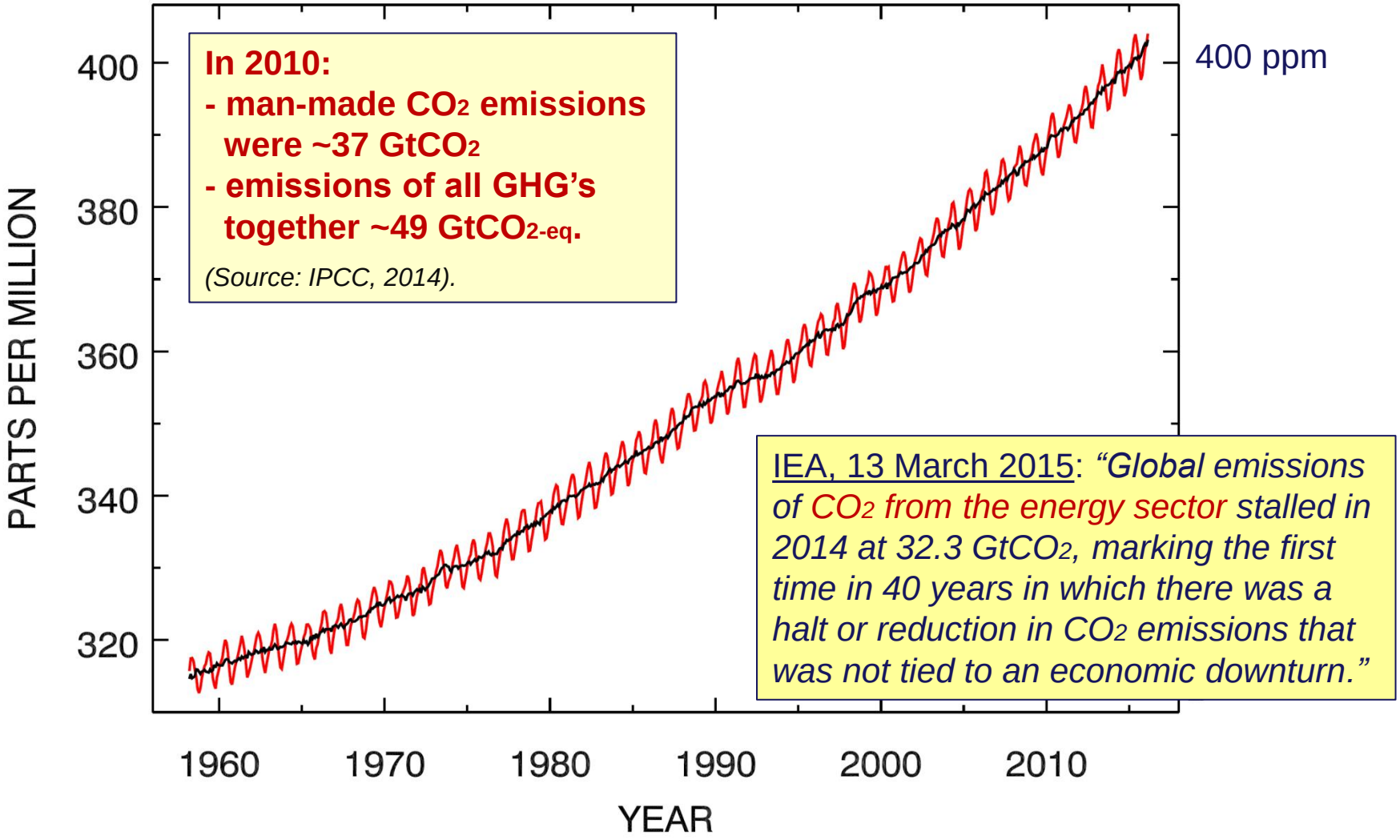
Klimaatverandering
&
Klimaatakkoord Parijs

Schematische werking broeikaseffect



De zon verwarmt de aarde. Door onder meer warmtestraling wordt deze warmte afgevoerd naar het heelal. Broeikasgassen kunnen warmtestraling absorberen en de energie terugsturen naar het aardopppervlak. Dit is het broeikaseffect. Door meer broeikasgassen in de atmosfeer te brengen neemt de warmtestraling op het aardoppervlak toe en verandert daar het klimaat.

Monthly average CO_2 concentration in the atmosphere at Mauna Loa Observatory (1958 – March 2016)



Source curve: http://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.pdf (visited: 4 April 2016)

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."

"The 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, pp. 14-15.

Important articles from the Paris Agreement

(COP21, Paris, December 12, 2015)

Article 2:

"This agreement aims to strengthen the global response to the threat of climate change (…) by:
(…) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change." (…)

Article 4.1:

"Parties aim to reach global peaking of greenhouse gas emissions as soon as possible (...) and to undertake rapid reductions thereafter (…) as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century (…)".

Source: UN-FCCC, 'Paris Agreement', 12 December 2015

Zes vragen

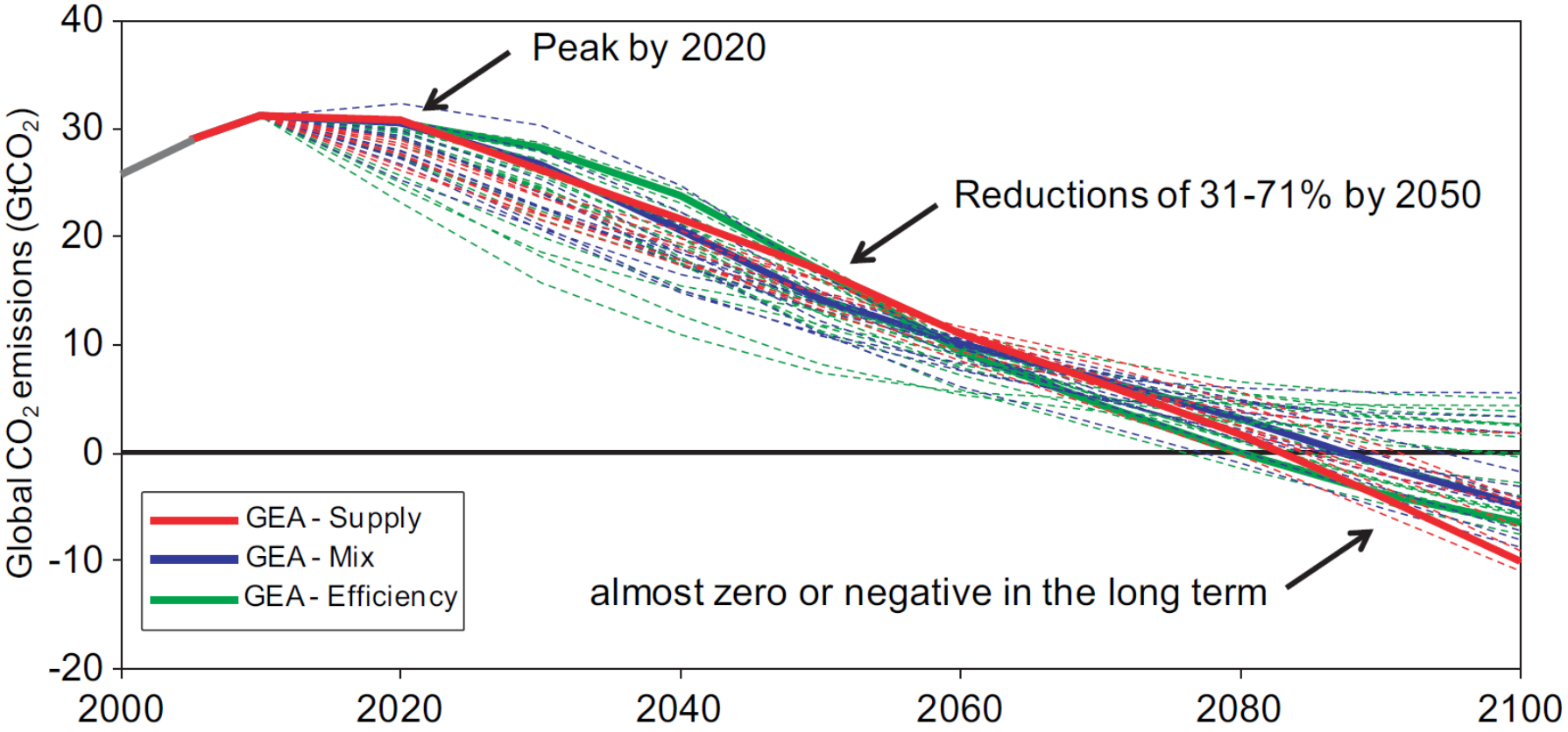
1. *Wat is nodig om de mondiale temperatuurstijging tot maximaal anderhalve of twee graden te beperken ?*
2. *Welk energiebesparingstempo is gedurende een reeks van jaren mogelijk ?*
3. *Wat is de noodzaak en haalbaarheid van een groeiende inzet van biomassa in de energievoorziening (naast vooral zon en wind) ?*
4. *Wat is de noodzaak en haalbaarheid van het afvangen en opslaan van CO_2 (CCS) ?*
5. *Wat is de noodzaak en haalbaarheid van het verwijderen van CO_2 uit de atmosfeer (‘negatieve emissies’) en welke opties zijn daarvoor beschikbaar ?*
6. *Gebruiken we in Nederland in 2050 nog fossiele brandstof?*

1.

Wat is nodig voor “ruim beneden twee en streven naar niet meer dan anderhalve graad”?

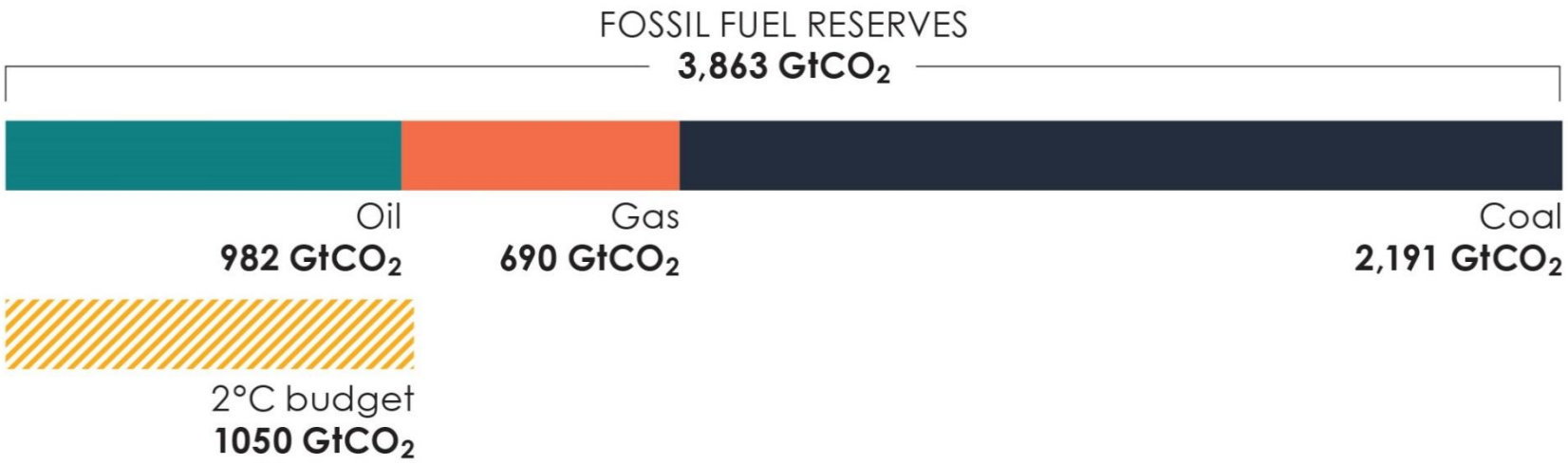
Development of global CO_2 emissions from energy and industrial sources to limit temp. change to below 2°C (prob. > 50%)

- GEA energy pathways toward a sustainable future -



Source: Global Energy Assessment, 2012

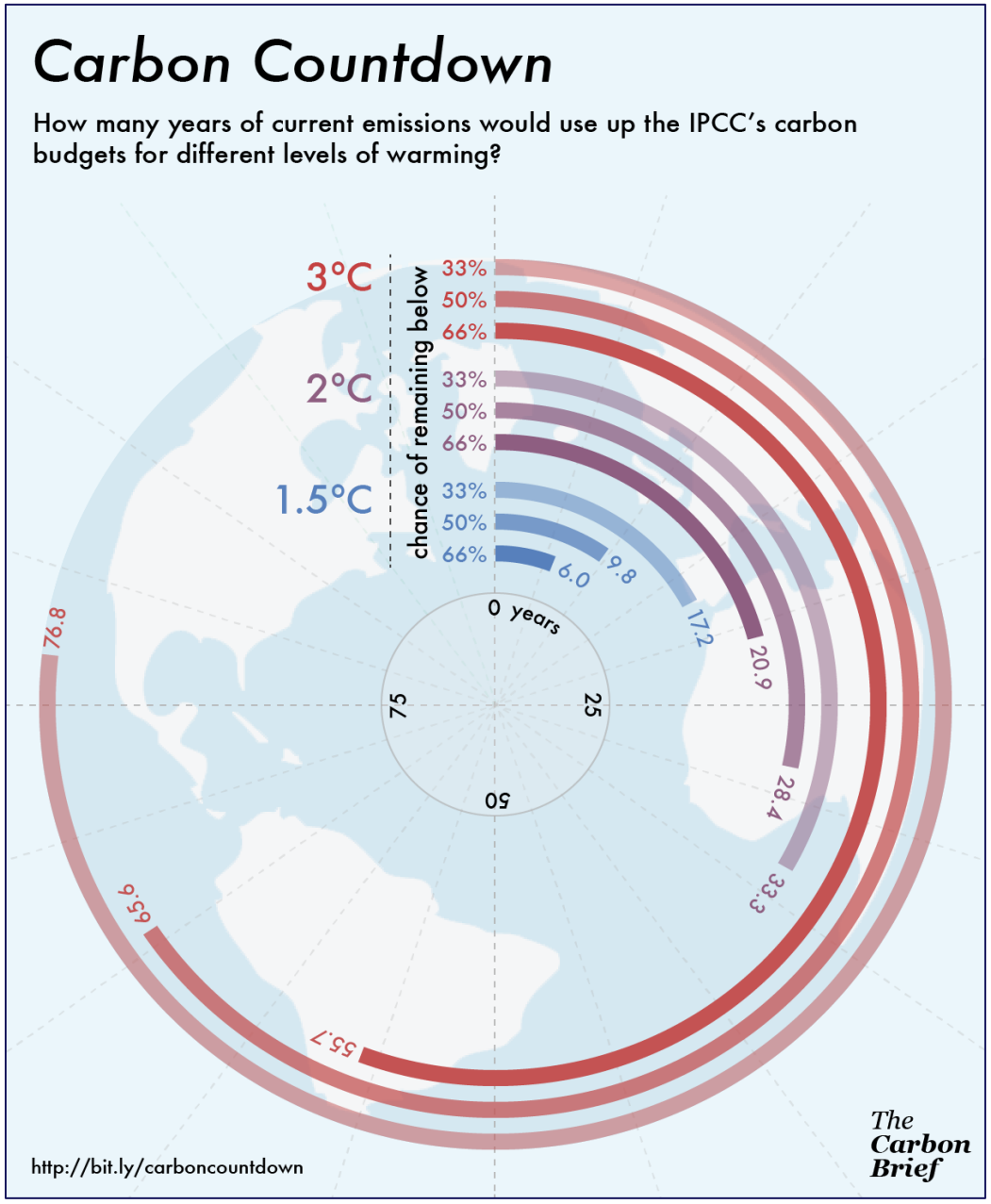
Global Carbon budget compatible with limiting global warming to +2°C *versus* fossil fuel reserves



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

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



Maximaal 1,5 tot 2 graad:

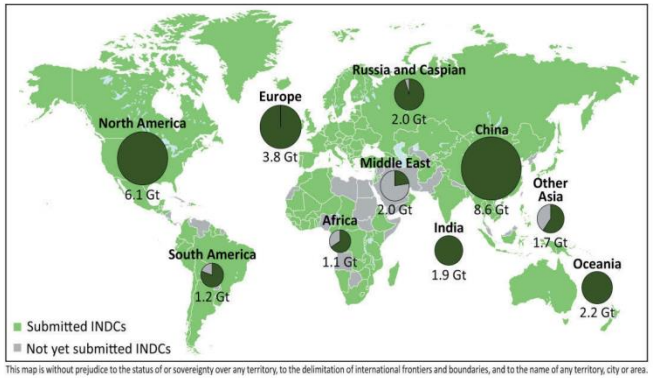
Hoeveel jaar kunnen we de huidige mondiale uitstoot van CO_2 nog handhaven voordat deze nul moet zijn ?

Opm.: genoemde aantal jaren kan zowel een onderschatting als een overschatting zijn.

Source: Carbon Brief, 10 Dec. 2015

Impact (I)NDCs 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 3-3.5 °C in 2100.

IEA: "Pledges accelerate the transition, but 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)

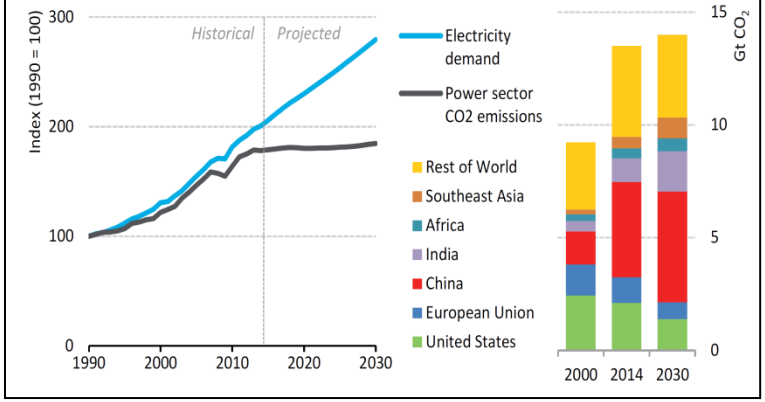


Table 1 ▷ **Global energy- and process-related greenhouse-gas emissions in the INDC Scenario** (Gt CO_2-eq)

	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**

Sources: IEA, 23 Oct. 2015 & UNEP, 3 Nov. 2015

Evaluatie mondiale energie-en-klimaat scenario's

IPCC (2014) vond 10 scenario's met een emissiepiek die na 2020 optreedt en leidt tot een kans van 66% op temp. stijging van maximaal 2 ºC

- Al deze scenario's maken gebruik van biomassa, CCS en 'negatieve emissies'

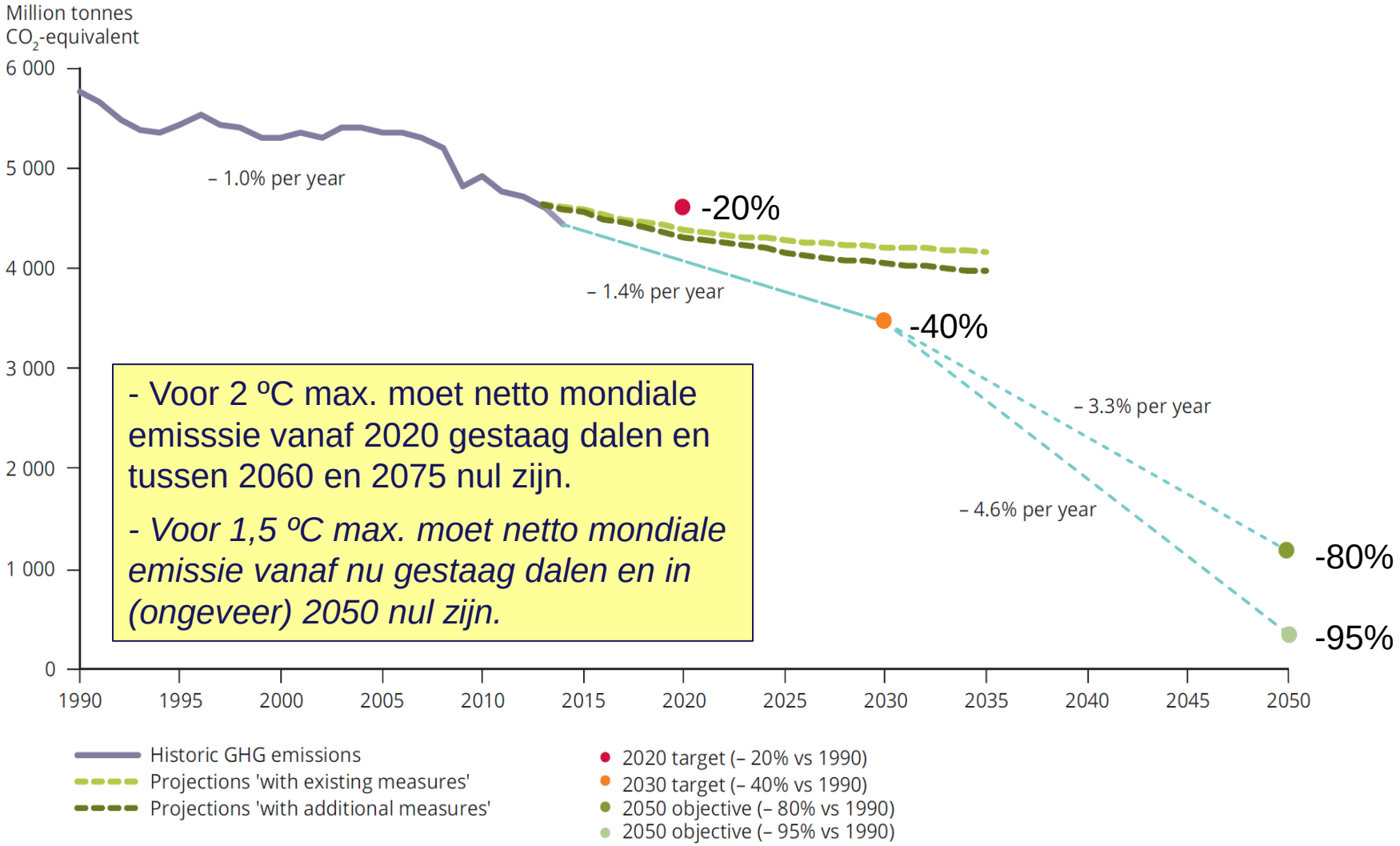
- Geen van deze scenario's bevat aannames zoals in WWF, 2011 & Greenpeace, 2015

Soortgelijke scenario's voor maximaal 1,5 ºC zijn nog maar heel beperkt ontwikkeld. Voorlopige conclusies (J. Rogelj et al., 2015):

- *Er zijn nog maar heel weinig vrijheidsgraden in het te voeren energiebeleid.*
- *Nog harder op energiebesparing en het toepassen van 'low carbon technologies' inzetten, met name ook op CCS.*
- ***Zonder negatieve emissies lukt het niet. Tussen 2010 en 2100 kan het gaan om in totaal 450 tot 1000 Gt CO_2.***
- *Na 2050 zal de netto uitstoot van CO_2 mondiaal negatief moeten zijn.*
- *Totale mitigatiekosten waarschijnlijk tenminste twee keer zo hoog als in een 2 ºC scenario. Hier staan baten van minder klimaatverandering tegenover.*

Bron: IPCC, 2014a & IPCC 2014b & Nature Climate Change, 2015

EU greenhouse gas emission: trends, projections and reduction targets



Source: European Environmental Agency, October 2015

2.

Het tempo van energiebesparing

Energiebesparing: vergelijking van scenario's

- *Gangbare business-as-usual scenario's: efficiencyverbetering economie circa 1,2% per jaar (autonoom).*
- *Shell scenario's (2013): eff. verbetering 1,4% per jaar.*
- *Global Energy Assessment (2012): eff. verbetering 1,5% – 2,2% per jaar. Bij 2,2% per jaar is mondiale energievraag in 2050 met ca. 50% toegenomen.*
- *Greenpeace (2015) en WFF (2011): 3% - 4% eff. verbetering per jaar. Dan mondiale energievraag in 2050 ca. 20% lager dan in het jaar 2000.*

- *Beleid EU: alle landen moeten 1,5% per jaar realiseren tot 2020. Nederland heeft grote moeite dit percentage te halen, zie ook Energieakkoord.*
- *Nederland: heeft eerder al gestreefd naar 2% per jaar. Het werd toen niet veel meer dan een verbetering met ca. 1% per jaar.*
- *Nederland: Bij realisatie 2% per jaar en tevens 2% groei BNP per jaar, blijft onze secundaire energievraag min of meer constant (~2200 PJ per jaar).*

3.

Biomassa als energiebron

(naast meer zon en wind)

Inzet biomassa in diverse scenario's

- Mondiale inzet in 2010: circa 55 EJ/jaar, waarvan 35 EJ 'traditioneel'.
- Energiepaden GEA (2012): In 2050 tussen 80-140 EJ/jaar. In veel paden wordt helft of meer van biomassa-inzet gekoppeld aan CCS.
- In WWF scenario (2011): ca. 100 EJ/jaar (totaal ~180 EJ/jaar) in 2050.
- In Greenpeace scenario (2015): ca. 80 EJ/jaar in 2050.
- *NB1: In WWF en Greenpeace scenario dekt biomassa ca. 40% van finale energievraag in 2050.*
- *NB2: in Urgenda-scenario voor Nederland ('100% hernieuwbaar in 20 jaar') is bijdrage biomassa ca. 60%.*
- *NB3: In alle scenario's geldt: biomassa-inzet mag niet ten koste gaan van voedselvoorziening, bebossing en behoud biodiversiteit. Ook moet inzet netto substantieel bijdragen aan reductie broeikasgasemissies.*

Conclusie onderzoek:

Duurzame biomassa kan medio deze eeuw mondiaal ca. 100 EJ per jaar leveren. In 2100 wellicht >200 EJ/jaar haalbaar; dit te zijner tijd bezien.

Energievoorziening Nederland in 2050 alleen met zon en wind?

Dekking secundaire energievraag (2200 PJ/j) uit alleen zon en wind

- Stel: In het jaar 2050 dragen wind en zon ieder voor 50% bij.
  Dan tenminste vereist: **1 miljard zonnepanelen met een totaal vermogen van 400.000 MW en 110.000 MW wind** (vrijwel geheel op Noordzee).
- Merk op: grote energieverliezen in zo'n energiesysteem - vanwege noodzaak energieopslag (met aanzienlijke conversieverliezen). Ter compensatie nog meer opwekking (>30% ?) door zon en wind nodig.
- Windvermogen in NL: *we streven thans naar 10.000 MW in 2023.*
  Zon-PV in NL: *eind 2014 stond er 1000 MW; in 2023 wellicht 10.000 MW.*
- Potentie Zon-PV in NL: *PBL en DNV-GL zeggen, op onze daken misschien 66.000 MW te plaatsen. Daarmee is 180 PJ (50 TWh) per jaar op te wekken.*

  => Een overgroot deel van de zonne-energie zou geïmporteerd moeten worden; dit in die omvang binnen 35 jaar reëel gezien niet haalbaar.

  => 100% uit alleen zon en wind in 2050 niet realistisch.

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/km^2 (GJ/km^2)	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 energy 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

4.

CO_2 Capture and Storage

Statement Environmental NGO Network on CCS

'Closing the Gap on Climate – Why CCS is a vital part of the solution'

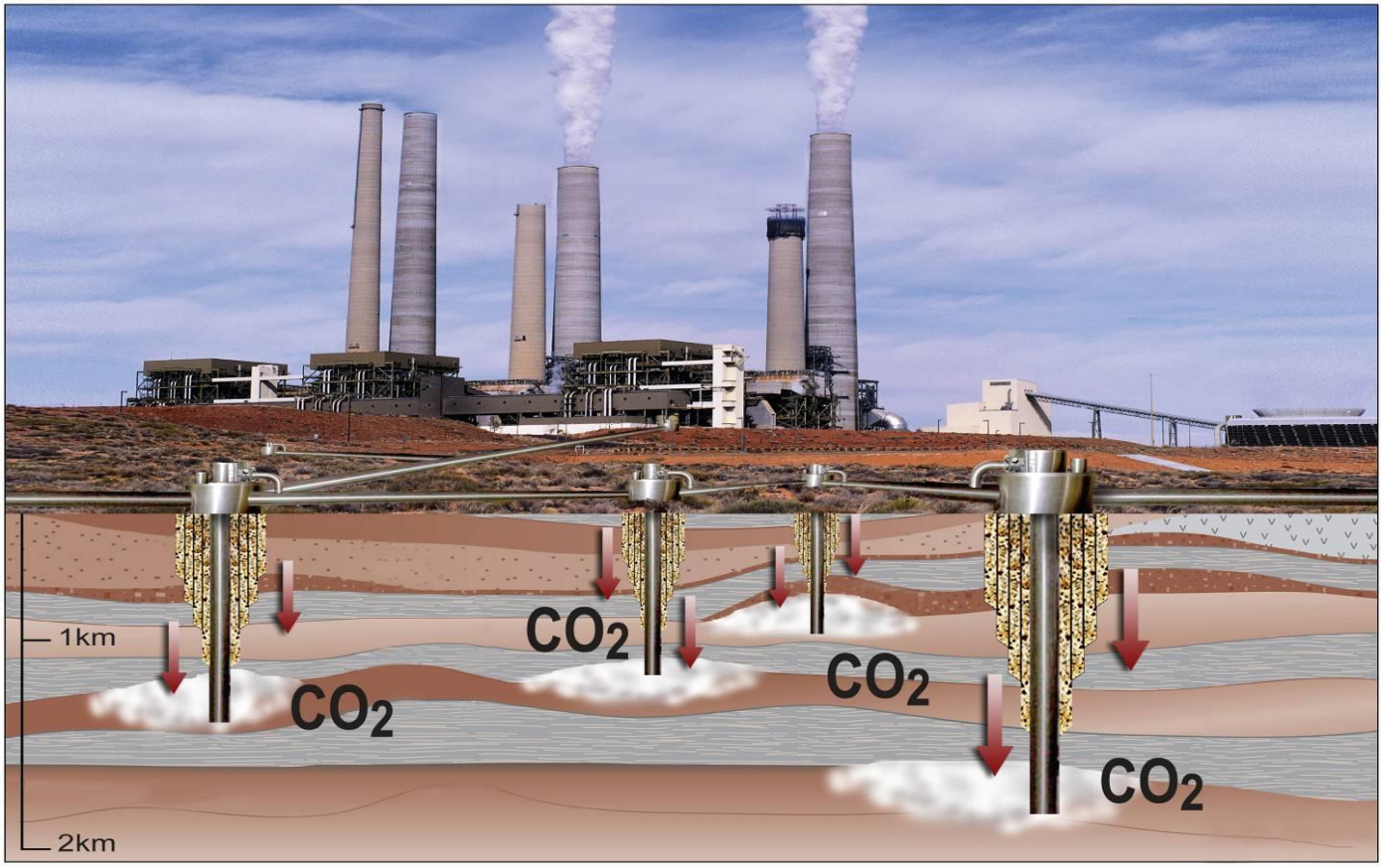
- The ENGO Network on CCS comprises organizations coming together around the safe and effective deployment of CCS as a timely mitigation tool for combating climate change.
- Because urgent reductions in GHG emissions are needed to prevent dangerous climate change, a variety of innovative solutions is necessary.
- **Given the world's current and projected reliance on fossil fuels, CCS should be considered a critical mitigation technology that will provide faster and deeper emission reductions.**
- The mission of the International ENGO Network on CCS is to pursue domestic and international policies, regulations and initiatives that enable CCS to deliver on its emissions reduction potential safely and effectively.

- *The Bellona Foundation*
- *Clean Air Task Force*
- *The Climate Institute*
- *E3G*
- *Environmental Defense Fund*
- *Green Alliance*

- *Natural Resources Defense Council*
- *The Pembina Institute*
- *Sandbag*
- *World Resources Institute*
- *Zero Emission Resource Organisation*

Source: ENGO Network on CCS, 'December 2015.

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



Capture → Compression → Pipeline Transport → Geological Sequestration

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.*

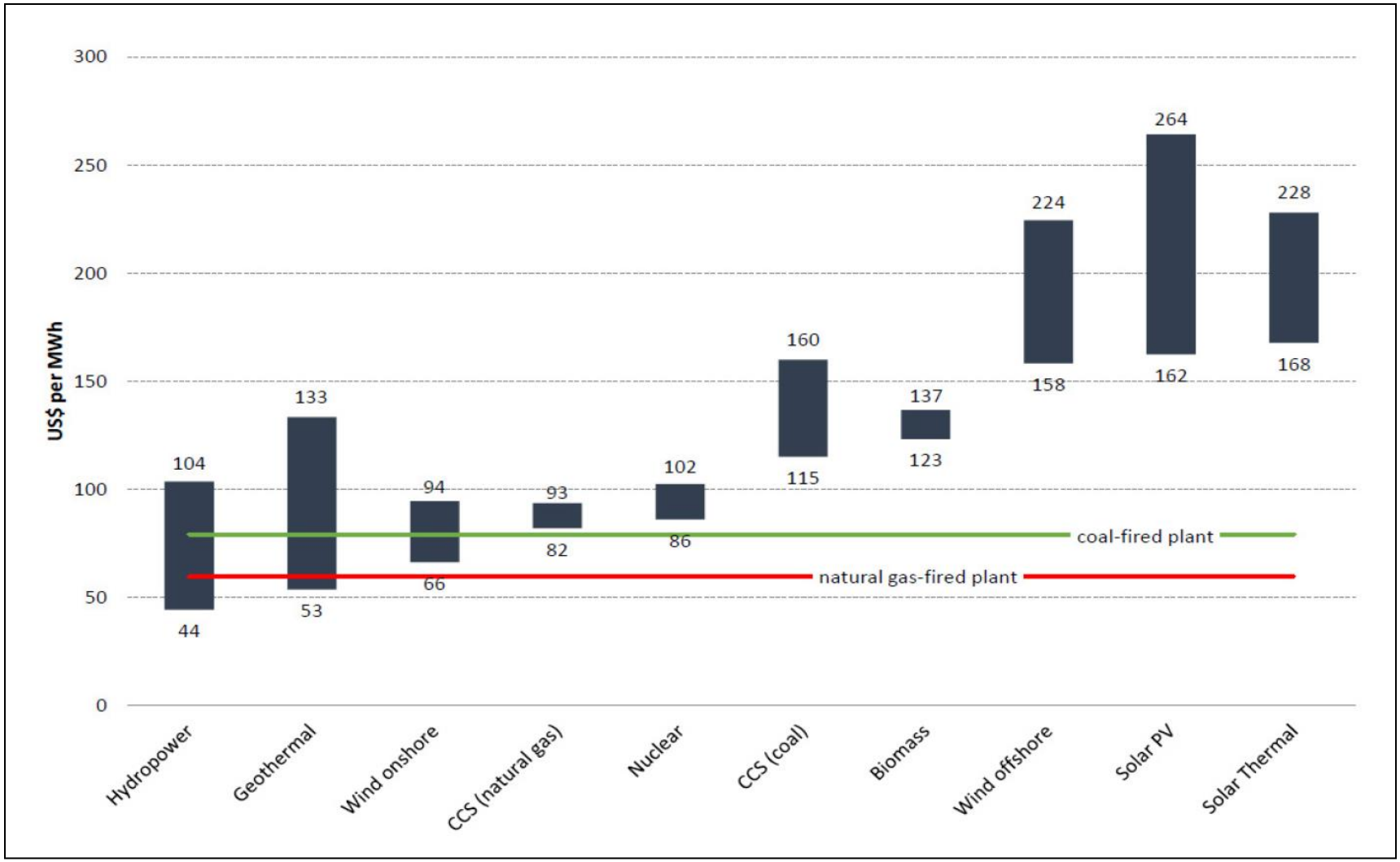
4 Some geographic areas will not be able to reduce emissions rapidly enough

- *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

Levelised cost of electricity (LCOE) - USA

(2014 US$)



Source: GCCSI, 'The cost of CCS and other low-carbon technologies – 2015 update'

Removal of CO_2 from power plants

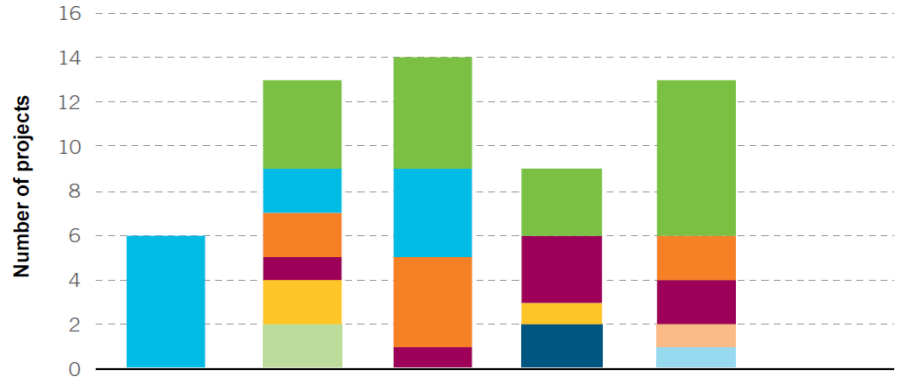
- **CCS: a proven technology that today securely stores 25 Mt CO_2 per year.**
- ***There are ~21 large-scale projects in operation or construction, all expected to be online by 2016-2017. These projects will have the capacity to capture up to ~40 Mt CO_2 per year.***
- **Global potential for safe storage: ~2000 $GtCO_2$.**

- 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

Sources: GCCSI, 2014 ; SaskPower, 2015

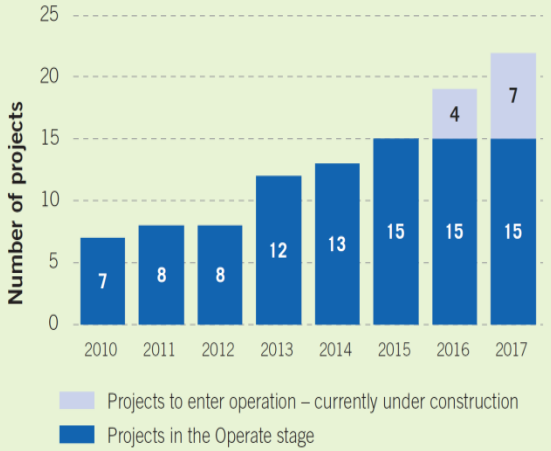
Large scale CCS projects by country/region



	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: Global CCS Institute, 'The Global Status of CCS 2014' , Nov. 2014

Large-scale CCS projects in operation, by year



Source: Global CCS Institute, 2015

Conclusions Int. Conf. GHGT-12 (Oct. 2014):

- *'At present optimism on CCS in North America and China, pessimism in Europe (apart from Norway and UK).'*
- *'Nowadays the ROAD-project is about the only EU demo-plant project left'.*

Large-scale CCS projects operational in 2016-2017

Illinois Industrial CCS Project

World's first large-scale Bio-CCS project, capturing ~1 Mt/y from a corn-to-ethanol production facility in Decatur. Injection of the CO_2 into a deep saline formation.

Kemper County Energy Facility

CCS power project, capturing ~3 Mt/y from a coal gasification process. The CO_2 will be used for EOR.

Petra Nova Carbon Capture Project

Post-combustion capture project, capturing ~1.4 Mt/y by retrofitting unit 8 of the W.A. Parish power plant near Houston. The captured CO_2 will be used for EOR.

Abu Dhabi CCS Project

World's first iron and steel project to apply CCS at large-scale. Around 0.8 Mt/y will be captured for the purpose of EOR.

Gorgon Carbon Dioxide Injection Project

Between 3.4 to 4.0 Mt/y CO_2 from a gas processing plant will be injected in a deep saline formation at a depth of more than 2 km.

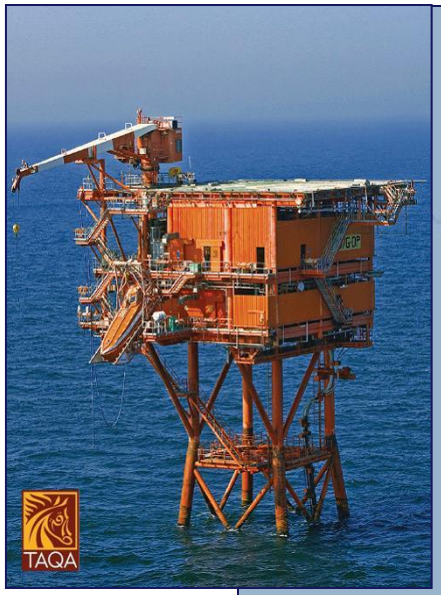
Alberta Carbon Trunk Line (ACTL) project

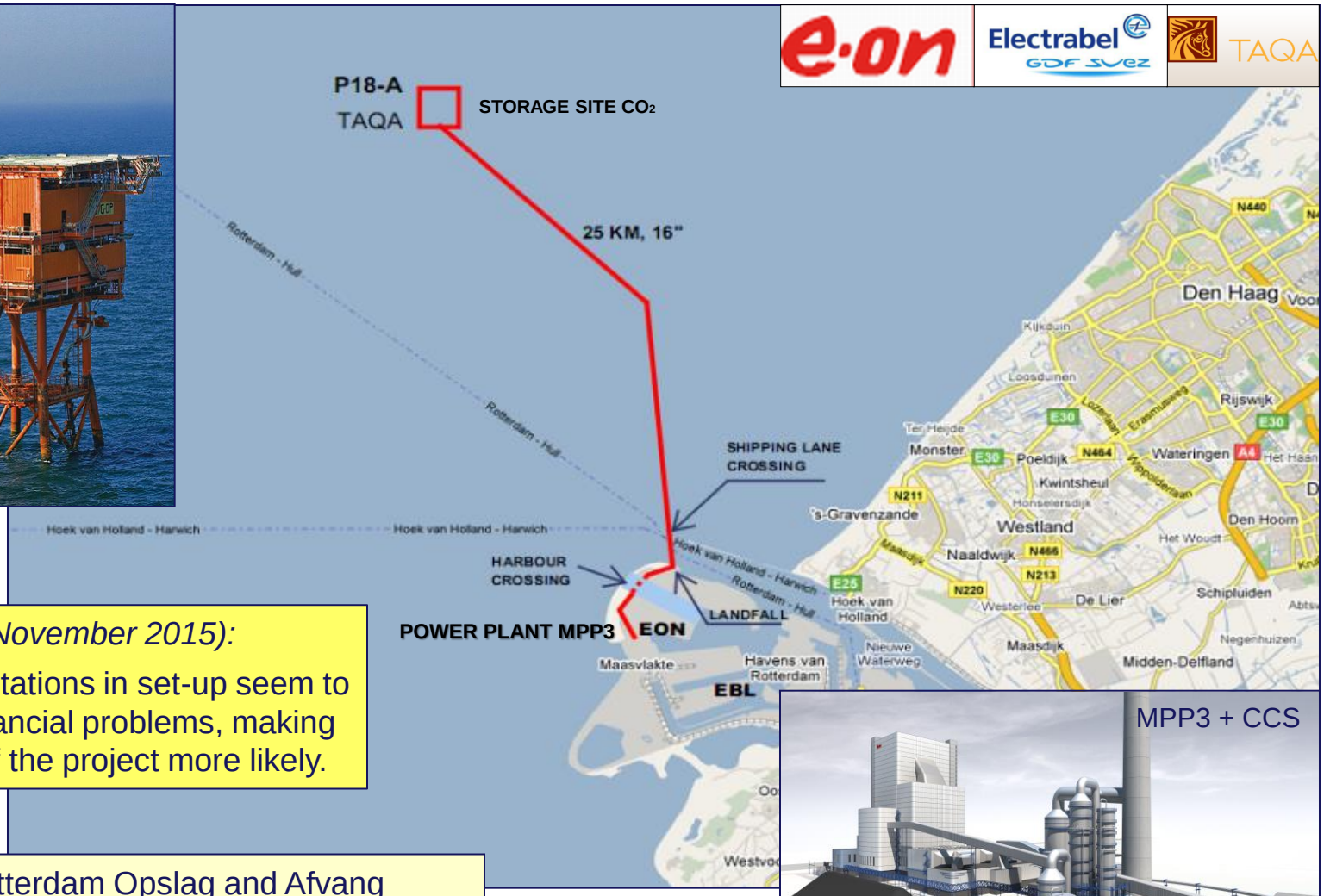
A 240 km trunk line to transport CO_2 from a number of sources (incl. a fertilzer plant and a bitumen refinery) to declining oil fields in Central Alberta for EOR.

Source: Global CCS Institute, 'The Global Status of CCS 2015', November 2015

ROAD: EERP Demo project MPP3 - Rotterdam (NL)

CCS: 1.1 Mt/yr





Note WCT (November 2015):

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

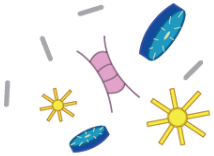
ROAD = Rotterdam Opslag and Afvang Demonstratieproject
EERP = European Economic Recovery Plan
MPP3 = Maasvlakte Power Plant 3

5.

Negatieve emissies

TAKE YOUR PICK

A plethora of schemes have been proposed to extract carbon dioxide from the atmosphere. Here are nine, some more speculative than others.

TECHNIQUE	HOW IT WORKS
Bioenergy with carbon capture and storage (BECCS) 	Crops grown for the purpose are burnt in power stations (providing energy), and the resulting CO_2 is captured for secure long-term storage.
Afforestation and reforestation 	Large-scale tree plantations increase natural storage of carbon in biomass and forest soil.
'Blue carbon' habitat restoration 	The recovery of degraded or over-exploited coastal ecosystems that have a high potential for carbon storage, such as saltmarshes and mangroves.
Biochar 	Carbon from partly burnt biomass is added to soil, with potential for agricultural benefits.
Enhanced ocean productivity 	Marine photosynthesis and CO_2 drawdown from the atmosphere is increased, either by adding nutrients to promote phytoplankton growth in the open ocean or through seaweed cultivation in shallow seas.
Enhanced weathering (using silicate rock) 	Crushed olivine or other silicate rocks are added to soil surfaces or the ocean for chemical absorption of CO_2. (Could help to reduce ocean acidification.)
Direct air capture (DAC) 	Chemicals (or possibly low temperatures) are used to extract CO_2 from ambient air. Safe CO_2 transport and storage are subsequently required.
Cloud treatment to increase alkalinity 	Alkaline rain resulting from cloud treatments reacts with, and removes, atmospheric CO_2.
Building with biomass 	A massive increase in the use of biomass (straw and timber) as a building material removes carbon for decades or centuries.

Bron: Nature, 11 feb. 2016

Nodig: 450-1000 Gt CO_2 tussen 2010 en 2100

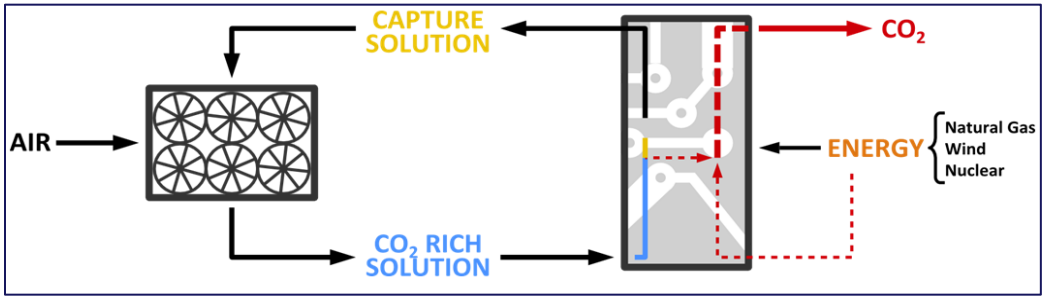
Negen routes die tot verwijdering van CO_2 uit de atmosfeer kunnen leiden

(de ene meer speculatief dan de andere)

'BECCS biedt thans meeste zekerheid'

Direct Air Capture (DAC) of CO_2 from air
in a closed industrial process

David Keith: "Capturing CO_2 directly from the air allows its management with standardized scalable industrial facilities."



David Keith: "This full-scale design could absorb the emissions created by 300,000 typical cars."

Enabling Low Carbon Fuels

Air Capture provides *atmospheric* CO_2 for industrial use. When used in fuel production, air capture can produce fuels with a much lower carbon-intensity than CCS. This makes air capture an important *complement*, rather than a competitor, to CCS.

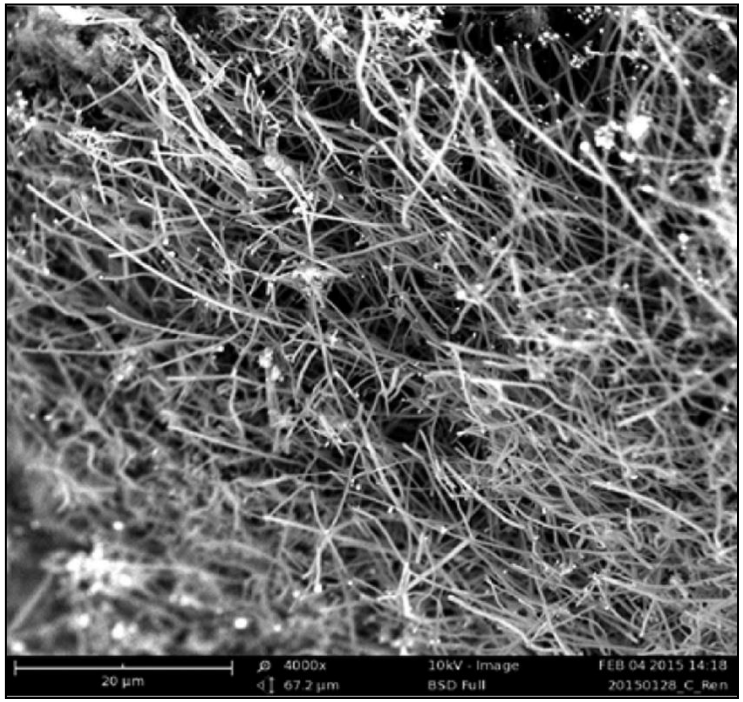
Source: http://carbonengineering.com/air-capture/

(5 augustus 2015)

Wetenschappers zetten CO_2 om in koolstofvezels

- Wetenschappers van de Amerikaanse George Washington Universiteit hebben een manier gevonden om CO_2 uit de lucht te halen en er zuurstof en koolstofvezels van te maken.
- Met die koolstofvezels zijn weer licht-gewicht, maar sterke vliegtuigonderdelen, auto's of bijvoorbeeld windturbines te maken.
- *Om koolstof uit de lucht te halen, is gesmolten lithiumcarbonaat nodig met opgeloste lithiumoxide. Lithiumoxide bindt met CO_2 in de lucht en vormt lithiumcarbonaat.*
- *Wanneer de onderzoekers het goedje een stroomschok geeft, ontstaat er zuurstof, koolstof (dat als vezel wordt afgezet op de elektrodes) en lithiumoxide.*

Bron: Fluxenergie, 23 augustus 2015



Ren et al.: "We present the first high yield, inexpensive synthesis of carbon nanofibers from the direct electrolytic conversion of CO_2, dissolved in molten carbonates to Carbon Nano Fibers at high rates using scalable, inexpensive nickel and steel electrodes."

Source: Nanoletters, 5 August 2015

(Her)bebossing en koolstofvastlegging

- Groeiend tropisch bos bindt jaarlijks ca. 6 ton koolstof (tC) per hectare. Dit getal is onzeker. Volwassen bos legt netto nauwelijks nog koolstof vast.
- Nieuw bos verdringt de bestaande begroeiing, dus de netto winst is geringer.
- Schatting mondiaal beschikbare grondoppervlak voor bebossing: 600-1300 mln ha; bebossing mondiaal toch al wenselijk, en ook haalbaar, voor een paar honderd mln ha.
- **Conclusie: via herbebossing lijkt vastlegging van 50-100 GtC haalbaar (gelijk aan zo'n 180-360 Gigaton CO_2).**
- *NB1: Volgens het IPCC (1990) is door herbebossing 100 GtC vast te leggen in 100 jaar. Als nieuw bos gedurende 100 jaar jaarlijks gemiddeld 2,7 tC per ha vastlegt, dan hiervoor 370 mln ha nodig. Dit geldt voor akkerland; voor grasland ongunstiger*.
- *NB2: "Afforestation of 200 mln ha is needed because of: soil erosion, maintenance of watersheds, improvement of local climates, biodiversity, agriculture, et cetera".*

  Bron: Wim Turkenburg, 'Energie voor een Duurzame Samenleving, deel 1', VUB, Brussel, 1992.

Myles Allen (Oxford University): *"Any company that sells fossil fuels (should be) obliged to take back an equivalent amount of CO_2 and dispose of it safely. Right now, that means re-injection underground: forests can't be relied on over geological timescales (they might burn down, or even die out, and re-release their carbon due to climate change itself)."*

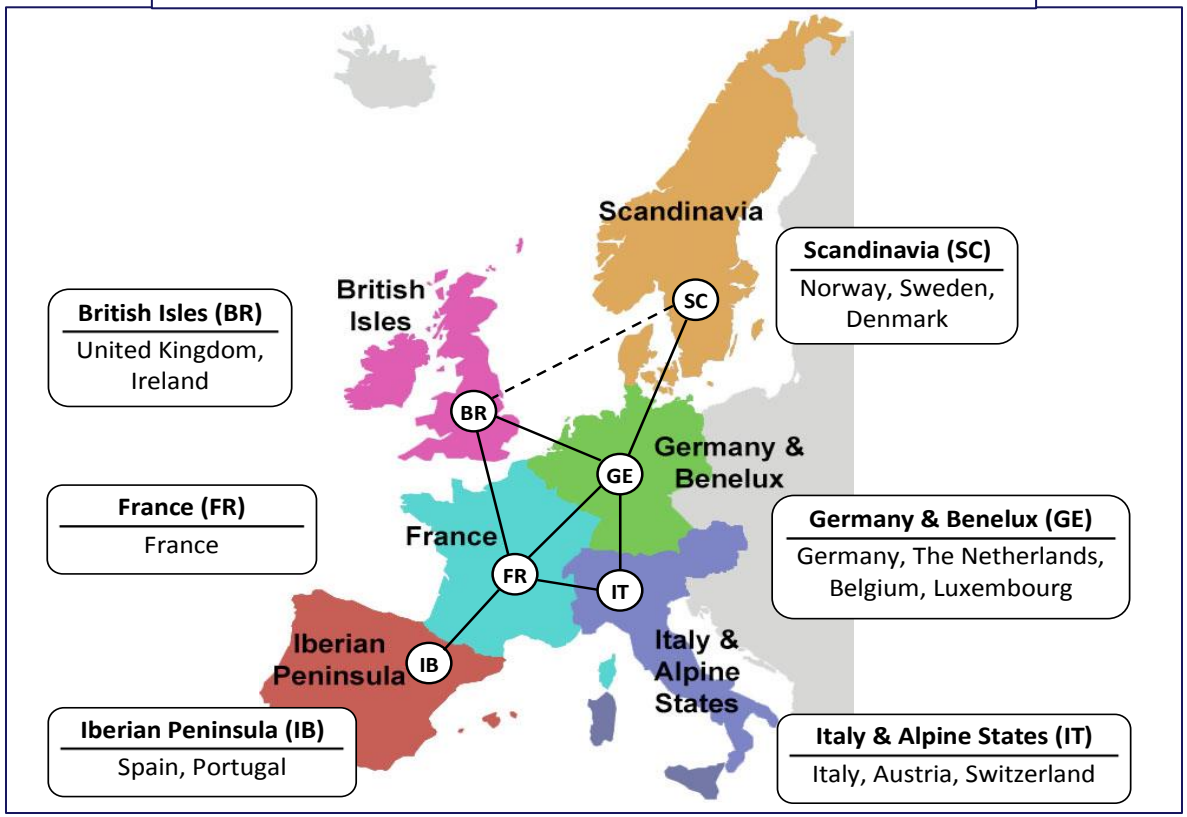
Source: The Conversation, 12 December 2015.

6.

Gebruiken we in Nederland in 2050 nog fossiele brandstof?

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 cost of 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**

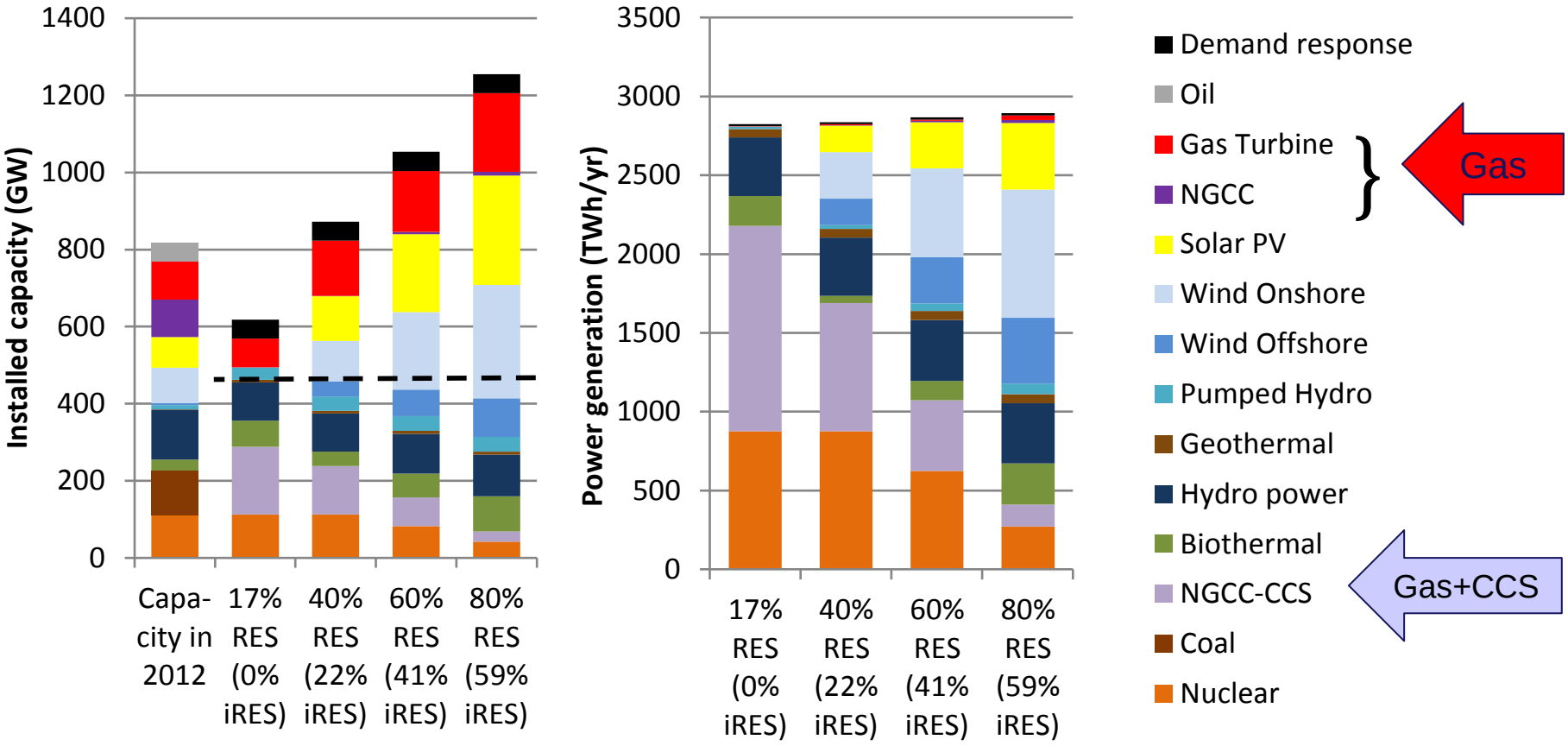
€ = €$_{2012}$

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

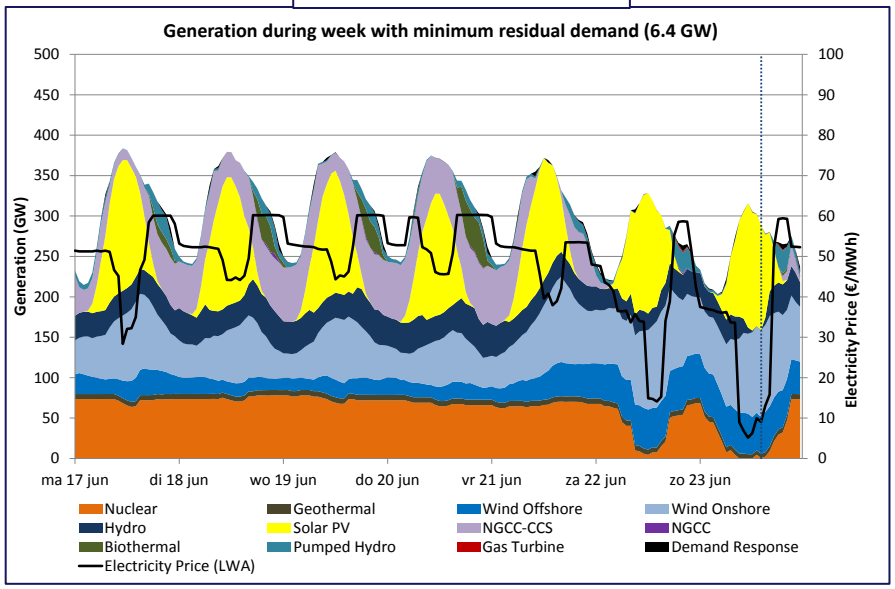
(The dashed line depicts the assumed peak load in 2050)



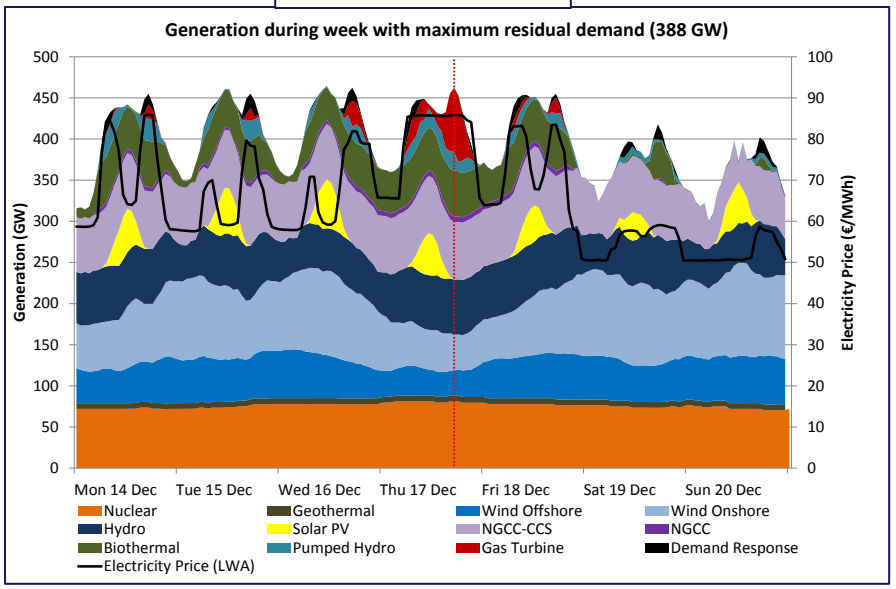
Source: A.S. Brouwer, M. van den Broek, W. Zappa, W. Turkenburg and A. Faaij, Applied Energy, 2016

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

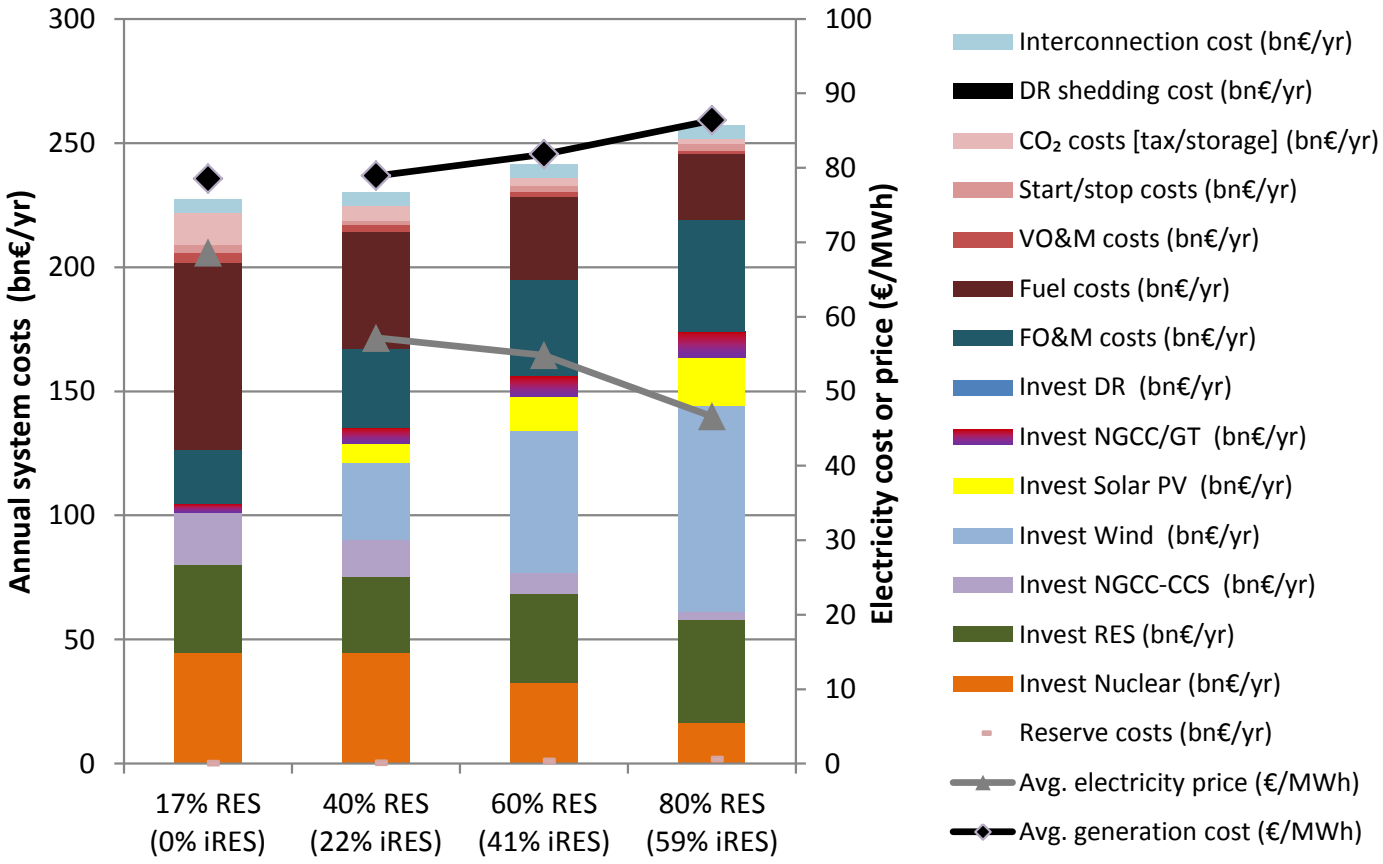
Also shown: electricity costs vs. electricity price (€/MWh)

Conclusions:

1) Increase contribution renewables causes increase total system costs.

2) NGCC+CCS cost-effective balancing option.

3) Income per kWh less 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

Belangrijke 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 in de UU-studie 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 én het balansvermogen) er niet komen.

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

Bedankt!

Wim Turkenburg

Meer informatie in de discussienotitie "De klimaat-doelstelling van Parijs' (15 maart 2016), te vinden op: https://hier.nu/klimaatbureau/pagina/publicaties