The Abdus Salam International Centre for Theoretical Physics

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Joint ICTP-IAEA Advancing Modelling of Climate, Land-use, Energy and Water (CLEW) Interactions

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Energy Resources

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Sustainable development means overcoming several energy challenges

Energy Poverty

Energy Security

Land Use & Forests

Climate Change

Resources

Water

Air Pollution

Image sources: NASA, http://www.powernewsnetwork.com/white-house-releases-plan-to-cut-oil-imports-by-13-by-2025/1798/, http://wheresmyamerica.wordpress.com/2007/08/26/i-cant-see-my-america/, http://www.americanprogress.org/issues/green/report/2009/05/14/6142/energy-poverty-101/, http://today.uconn.edu/blog/2010/12/reclaiming-water-a-green-leap-forward/, http://te.wikipedia.org/wiki/%E0%B0%A6%E0%B0%B8%E0%B1%8D%E0%B0%A4%E0%B1%8D%E0%B0%B0%E0%B0%82:Forest_Osaka_Japan.jpg

Sustainable development means overcoming several energy challenges

Resources in a nutshell

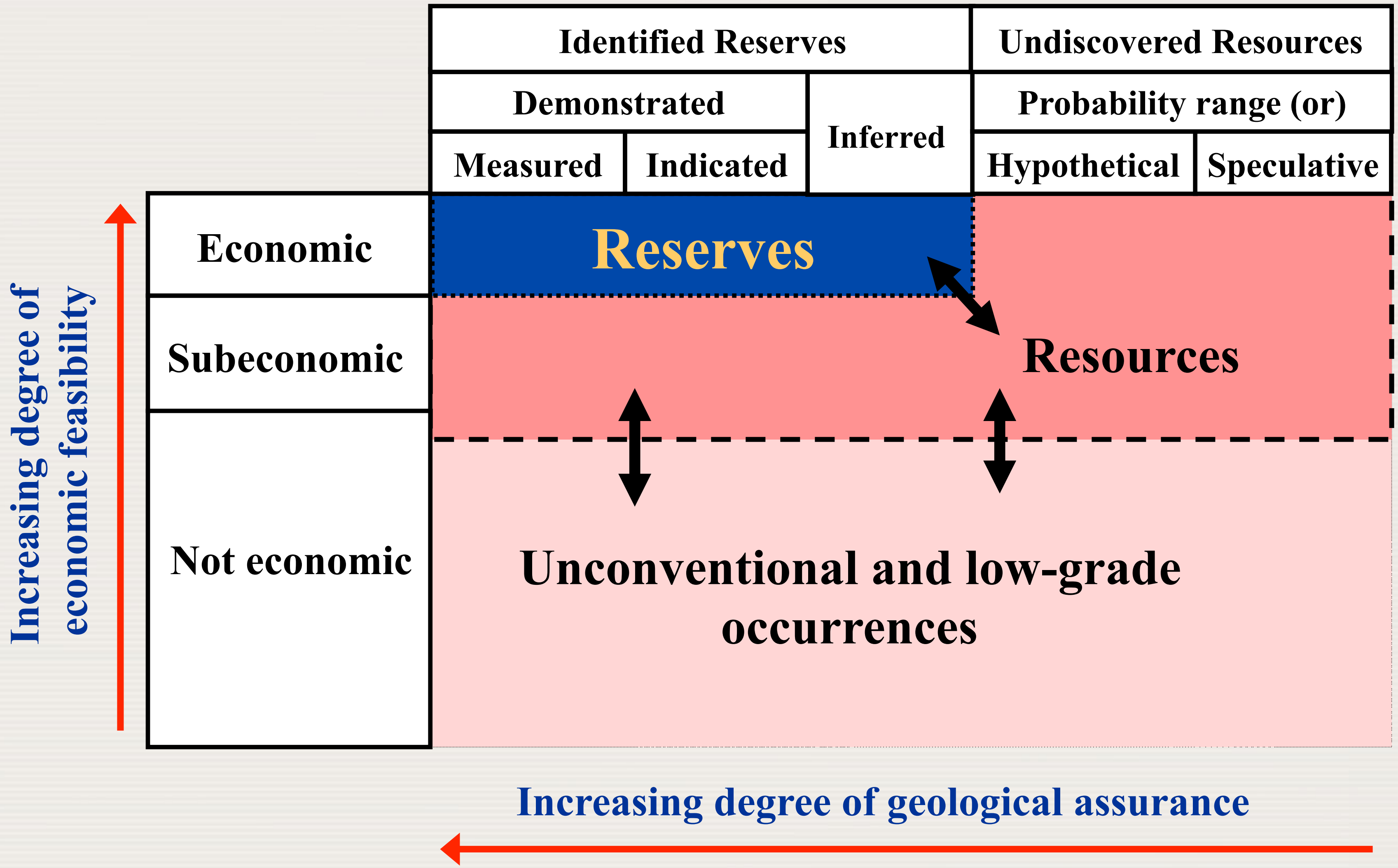
- **Occurrence of hydrocarbons and fissile materials in the earth's crust are plentiful**
  - **There is enough carbon in the ground to fuel global warming**
  - **Above ground investments unlock below ground resources**
    - **Exploration**
    - **Production capacity (incl. upgrading)**
    - **RD&D in innovative technology**
- **Renewable energy flows are gigantic**
  - **RD&D and investment required for the commercialization of technologies tapping renewable energy flows**
- **Resources per se pose no inherent limitation to meeting even rapidly growing future global energy need as long as timely upstream and/or technology investment is forthcoming**

Resources are not – they become[1)]

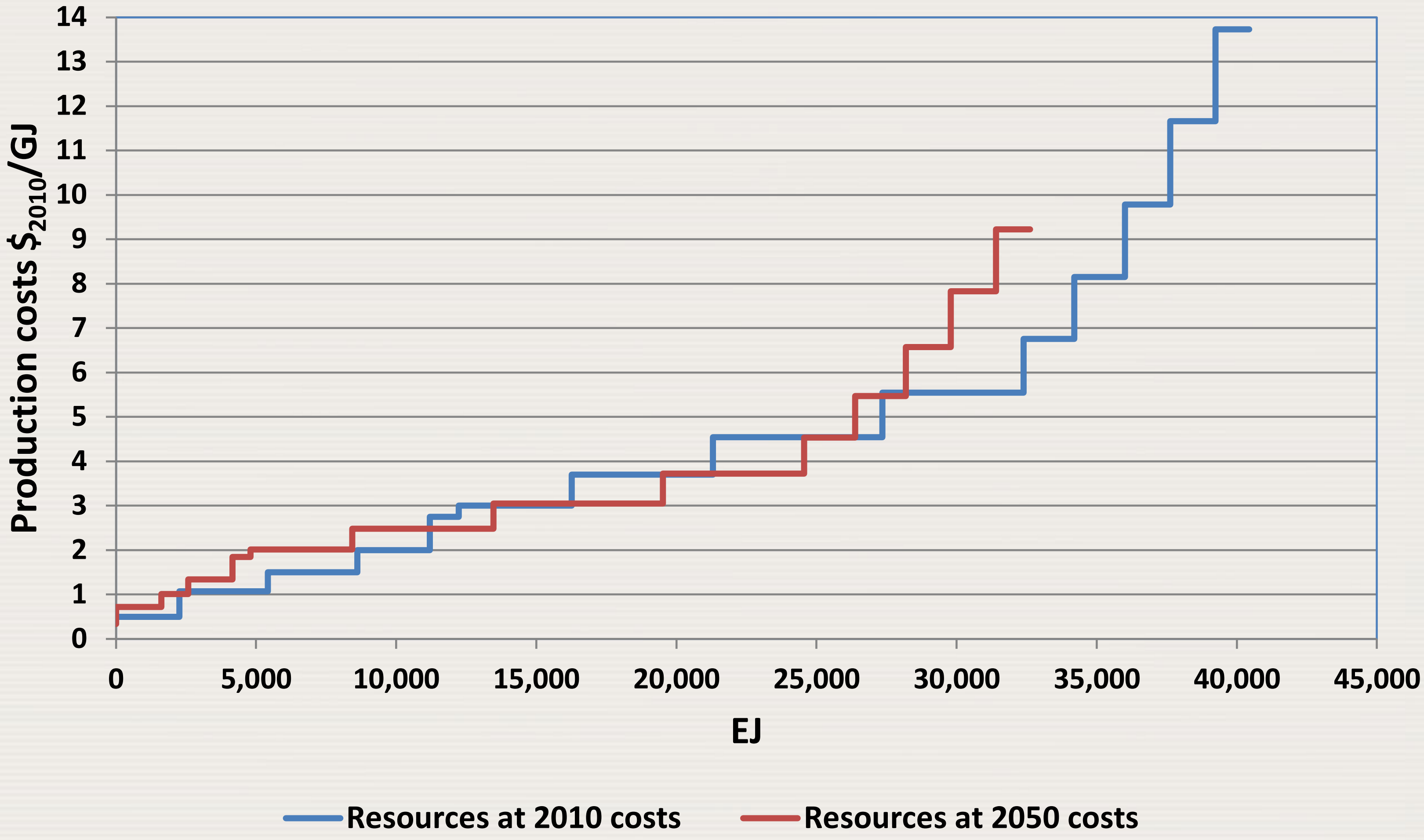
- The quantity of carbon occurrences in the Earth's crust is but one consideration = neutral stuff
- Reserve assessments are the futile effort of estimating the economic portion of an unknown total (M. Adelman)
- Reserves are "created" by a mutual interdependence of
  - Demand and markets
  - Investment and technology (determine production capacity)
  - RD&D and innovation (pushing frontier)
  - Environmental and social constraints (policy)
- These factors are shape the reserves "created"
- Moreover, in many cases the "low-hanging" fruit has already been harvested

[1)] E. Zimmermann

Resource Classification: The McKelvey Box

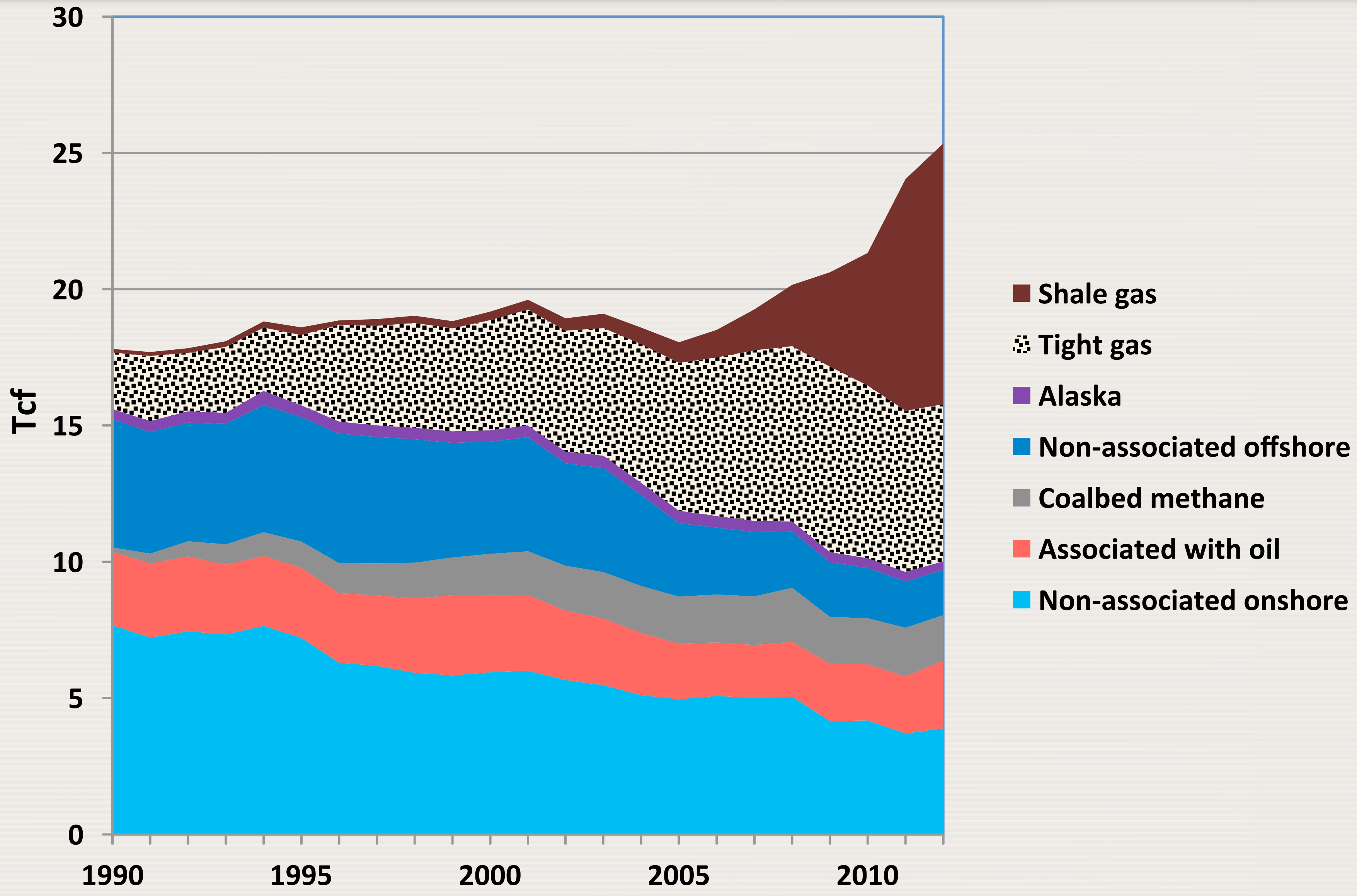


Global natural gas supply cost curves
(conventional and unconventional gas)

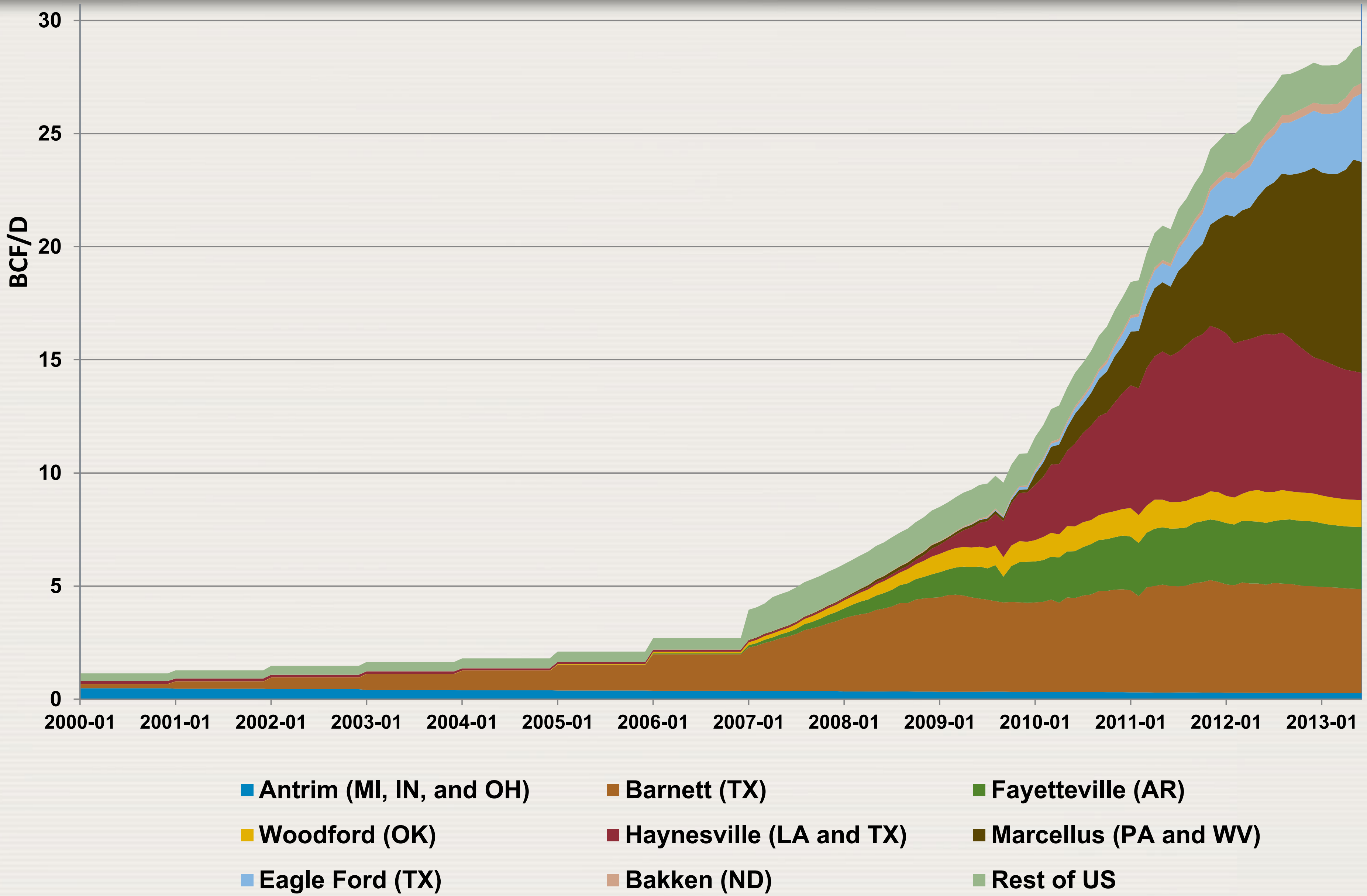


Global gas use in 2010: 120 EJ of which 16 EJ unconventional

US natural gas production



US shale gas production



Map of 95 major shale gas basins in 41 countries

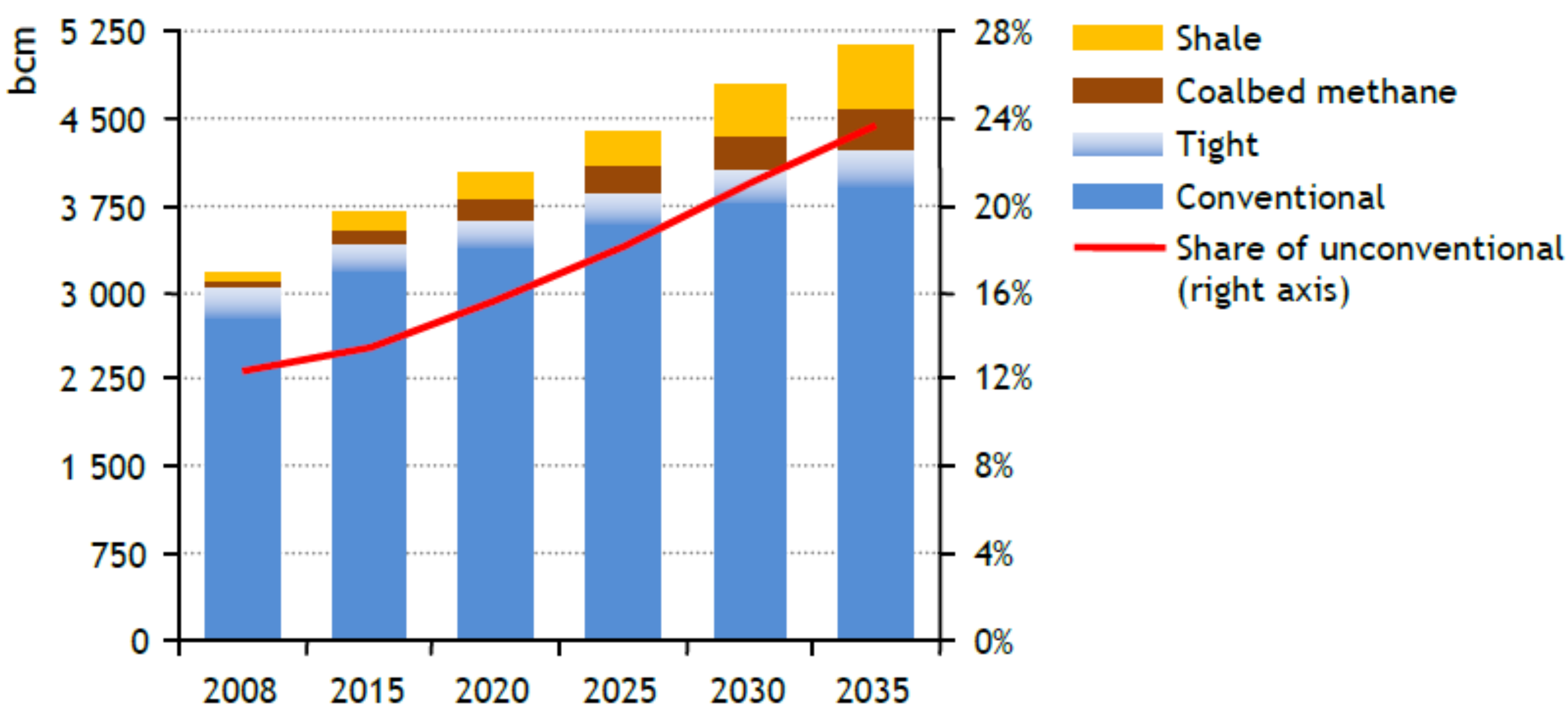
Source: USDOE EIA, 2013

Risked gas in-place and technically recoverable shale gas resources

Continent	Risked gas in-place (Tcf)		Risked technically recoverable (Tcf)	
	2011	2013	2011	2013
North America w/o USA	3,856	4,647	1,069	1,118
USA	3,760	4,644	940	1,161
Australia	1,381	2,046	396	437
South America	4,569	6,390	1,225	1,431
Europe	2,587	4,895	624	883
Africa	3,962	6,664	1,042	1,361
Asia	5,661	6,495	1,404	1,403
TOTAL	25,776	35,782	6,700	7,795

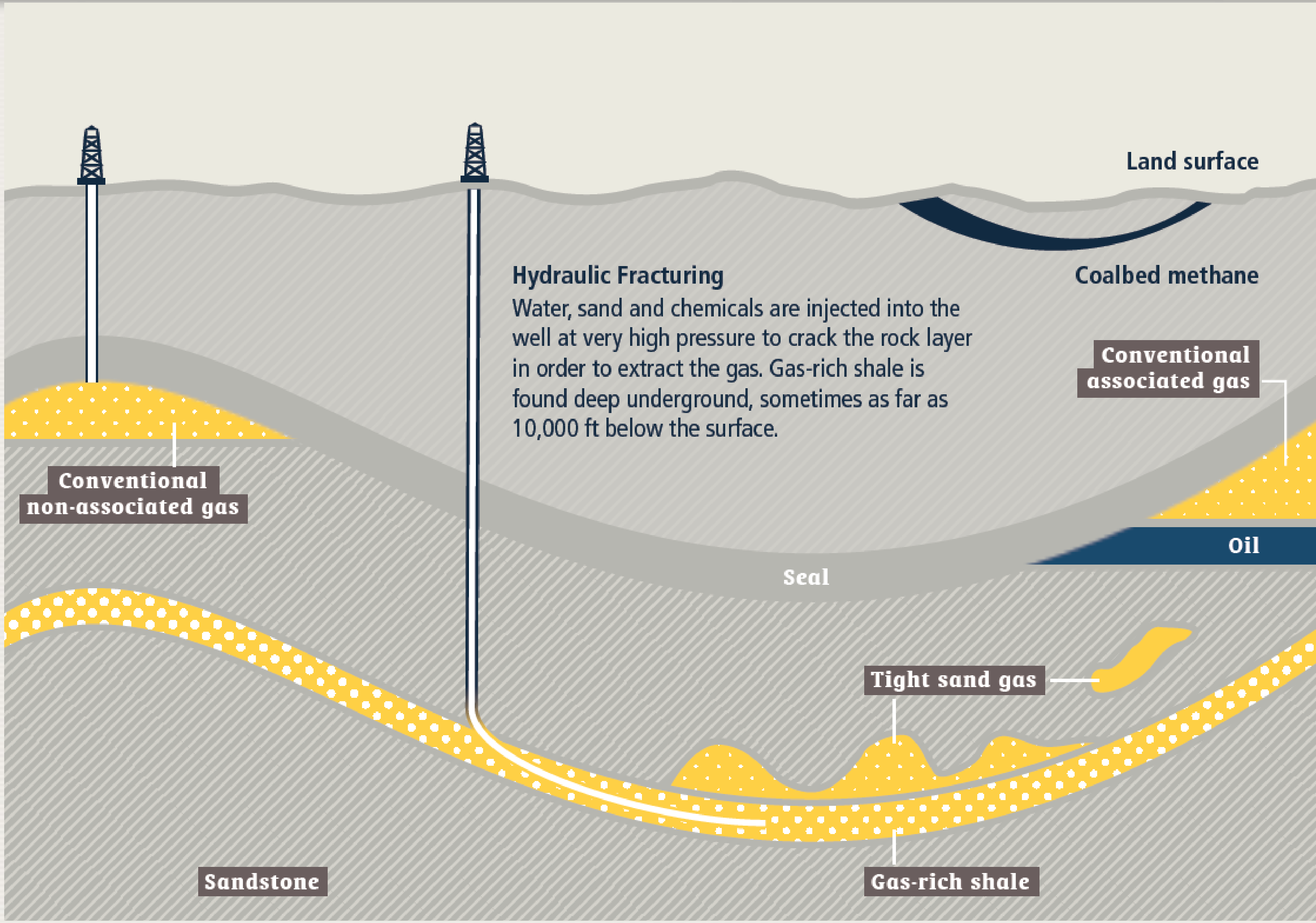
Advanced Resources International, Inc.

Natural gas production by type in the GAS Scenario

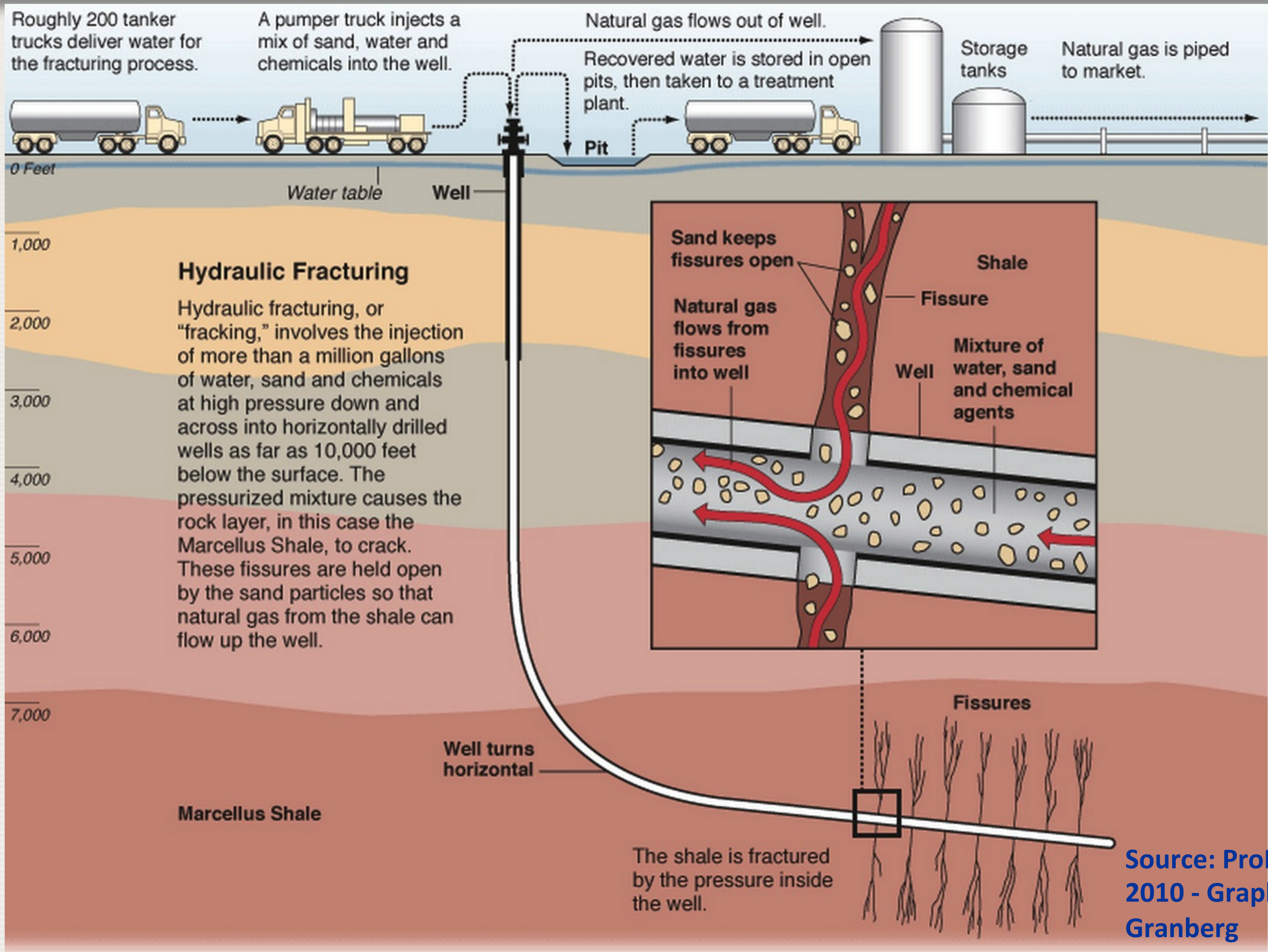


Source: Are we entering a golden age of gas? IEA, 2011

Gas extraction from different plays

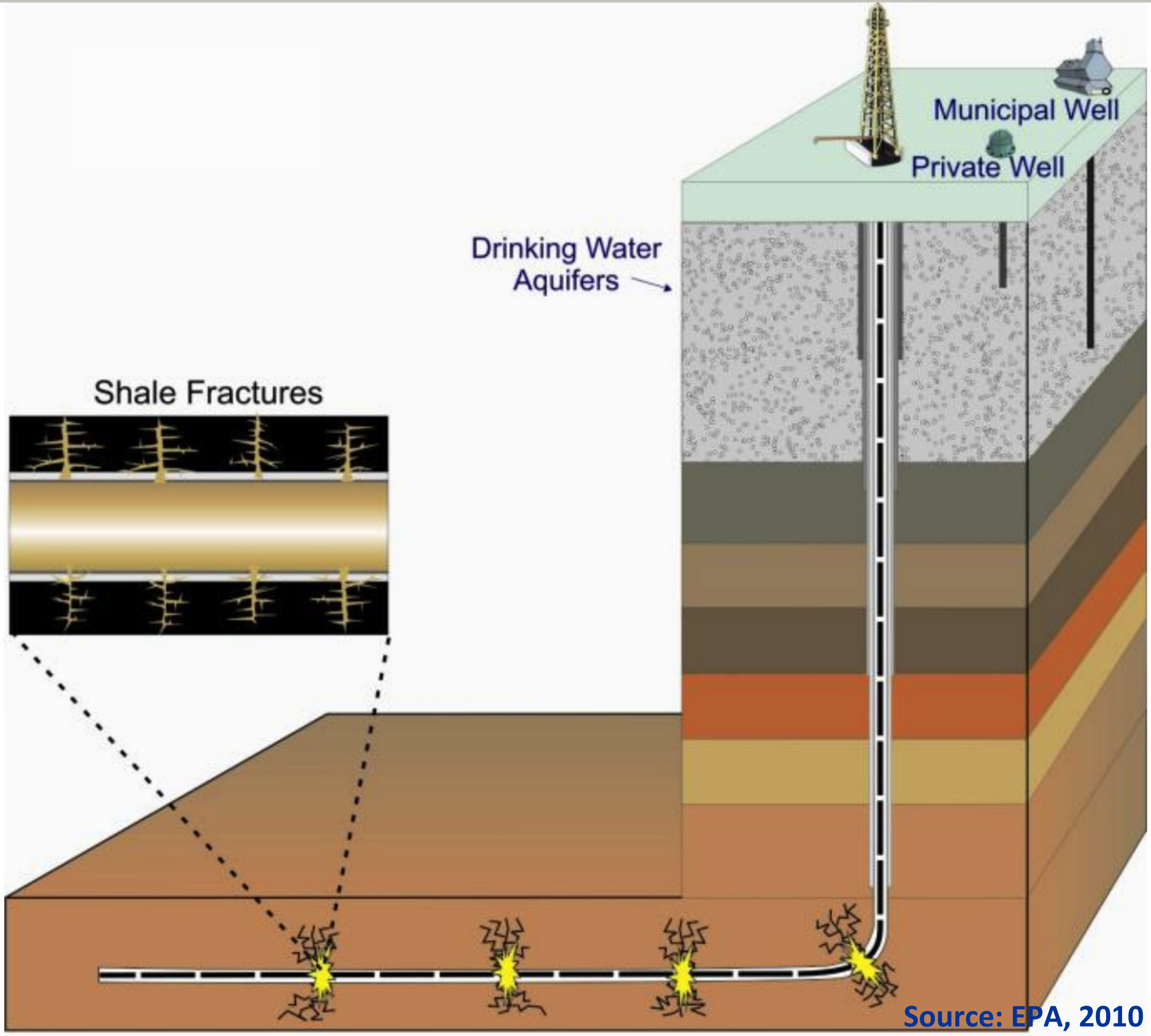


Shale gas extraction

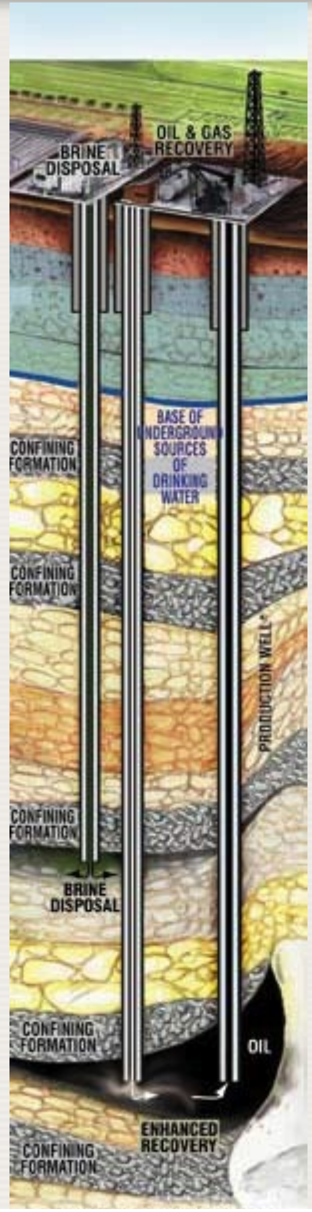


Source: ProPublica, 2010 - Graphic by Al Granberg

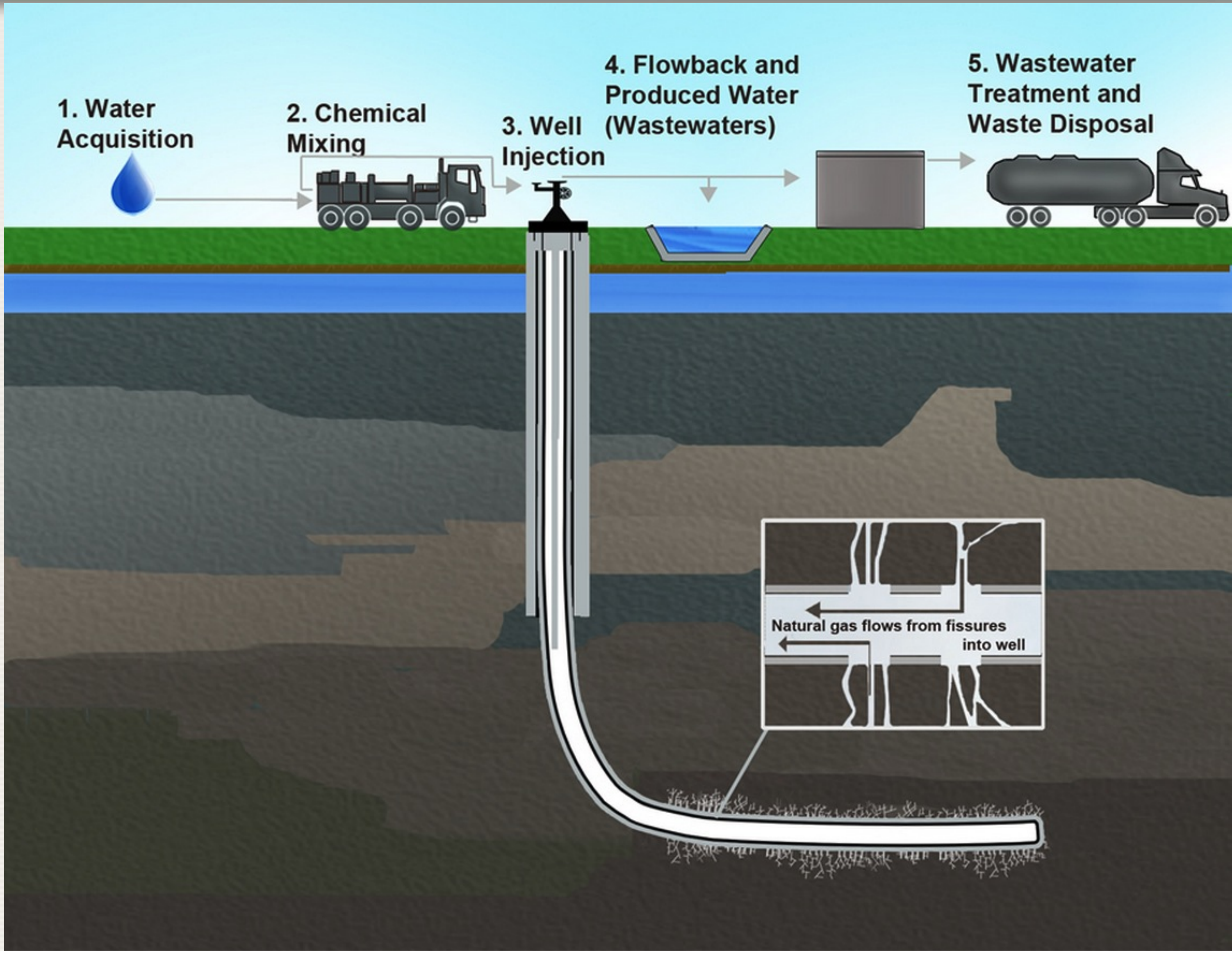
Hydraulic fracturing well



Source: EPA, 2010

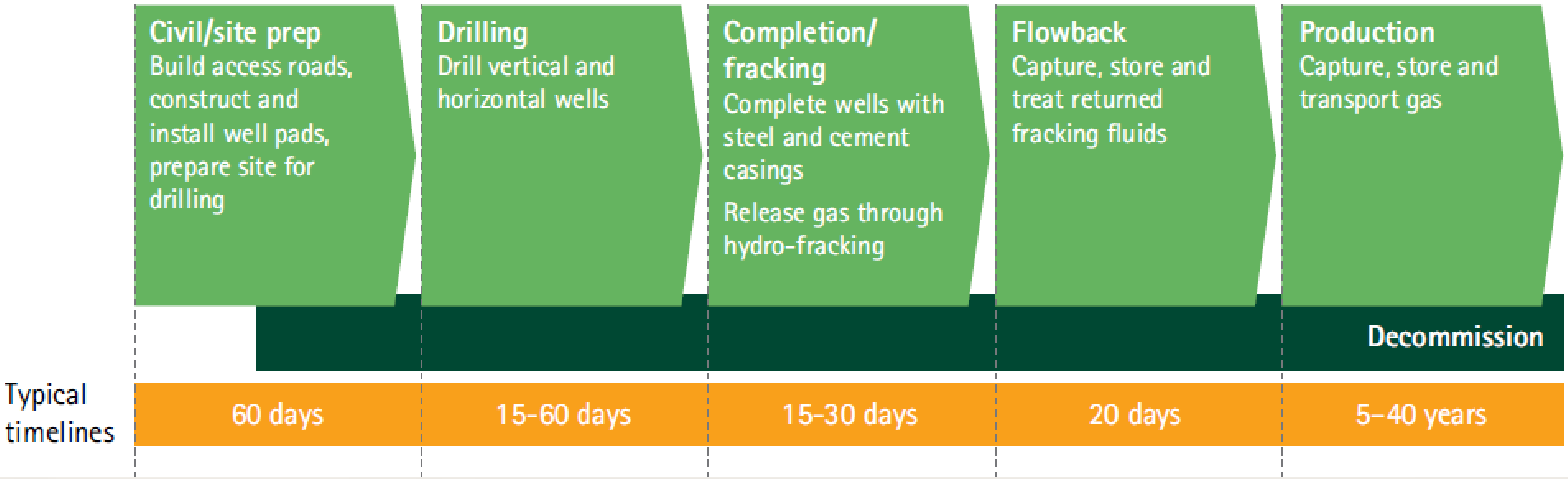


The hydraulic fracturing water cycle



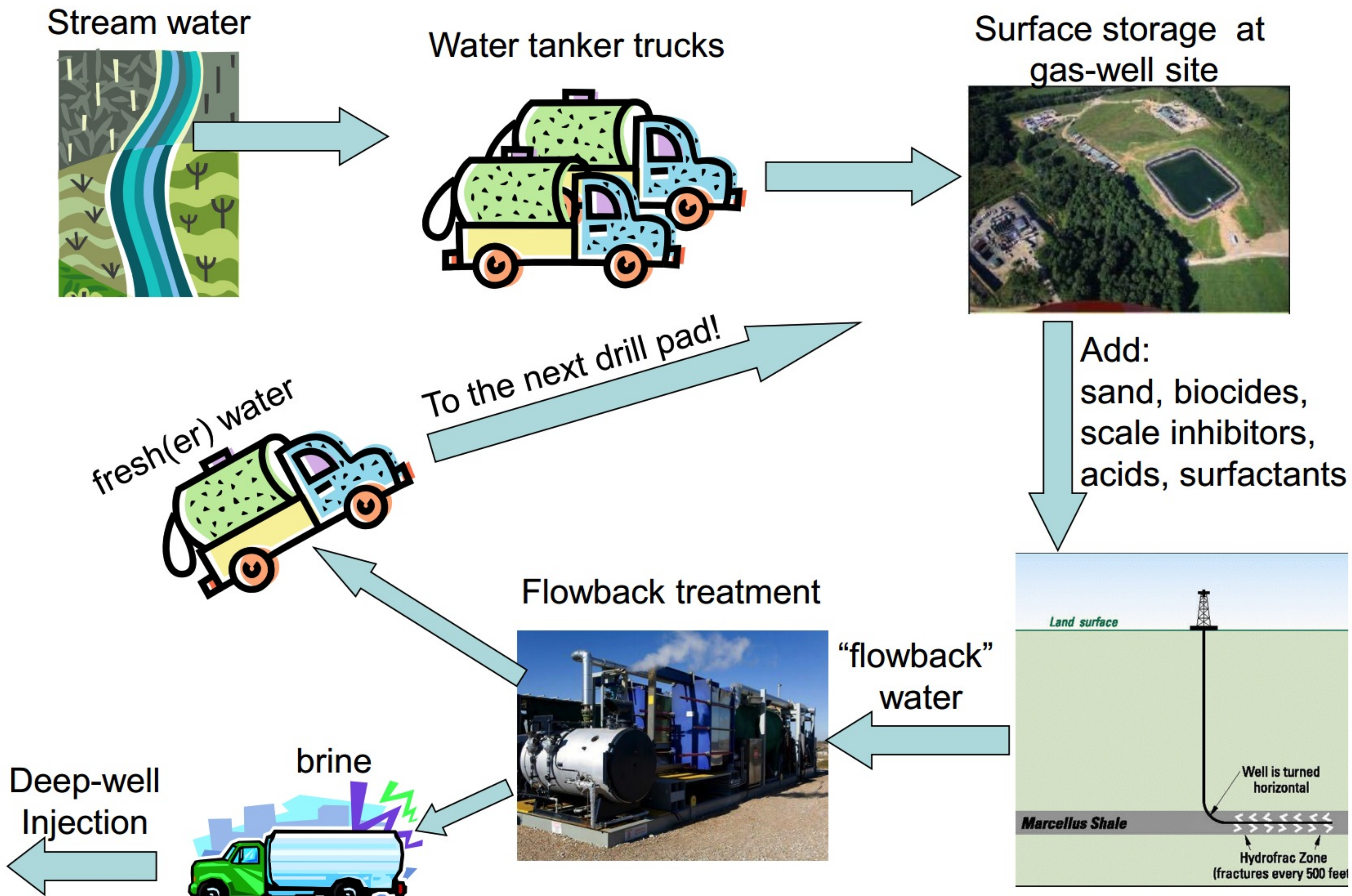
Source: EPA, 2010

Shale gas life cycle



Source: Accenture, 2012

Frac-Water: From cradle to grave



Source: Saiers, 2011

Water for fracking

- An average multi-stage frac job with current technology today uses somewhere between 5000 and 14,000 m^3 of water (average 11,000 m^3)
- 11,000 m^3 is about 1.3% of the amount of water used in car washes in the USA every day.
- Just one of the 16,000 golf courses across the US uses of water in less than one summer month
- Amount needed to operate a 1,000 MW coal-fired power plant for 12 hours
- New York City uses 11,000 m^3 of water every 6 minutes

Water use in hydraulic fracturing

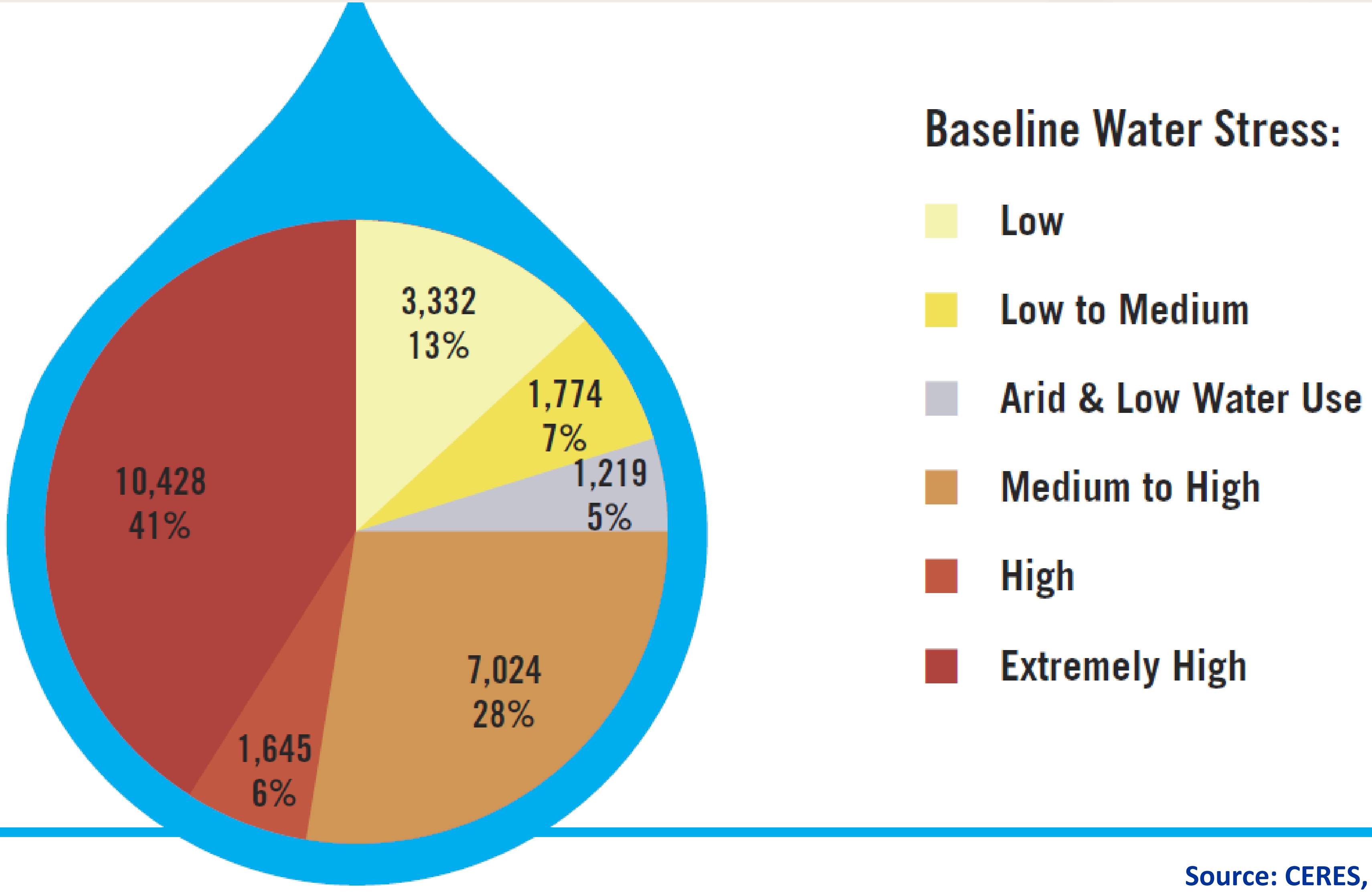
Water acquisition	Impact of water withdrawal from ground and surface water on local fresh water supply
Chemical mixing	Impact of leakages of hydraulic fracturing fluids on fresh water resources
Well injection	Impact of injection and fracturing process on local fresh water resources
Flowback and produced water	Impact of flowback and produced water on fresh water resources
Waste water treatment & disposal	Impact of inadequate treatment of hydraulic facrturig waste water on fresh water resources

Water movement challenges across the shale gas lifecycle

	Civil/site prep	Drilling	Completion/ fracking	Flowback	Production
	Build access roads, construct and install well pads, prepare site for drilling	Drill vertical and horizontal wells	Complete wells with steel and cement casings Release gas through hydro-fracking	Capture, store and treat returned fracking fluids	Capture, store and transport gas
					Decommission
Typical timelines	60 days	15-60 days	15-30 days	20 days	5–40 years
Water movement challenges	Diverse transportation needs to support the well pad preparation and infrastructure construction effort. Water movement requirement is minimal at this stage	Intensive and time-sensitive nature of water usage in drilling operation requires flexible and efficient logistics support	Intensive and time-sensitive nature of water usage in completion/fracking operation requires flexible and efficient logistics support	High volume of flowback water requires effective logistics management to minimize congestions, pollution and other social impacts	Transportation planning and effective cost management become increasingly important as demand for water movement stabilizes

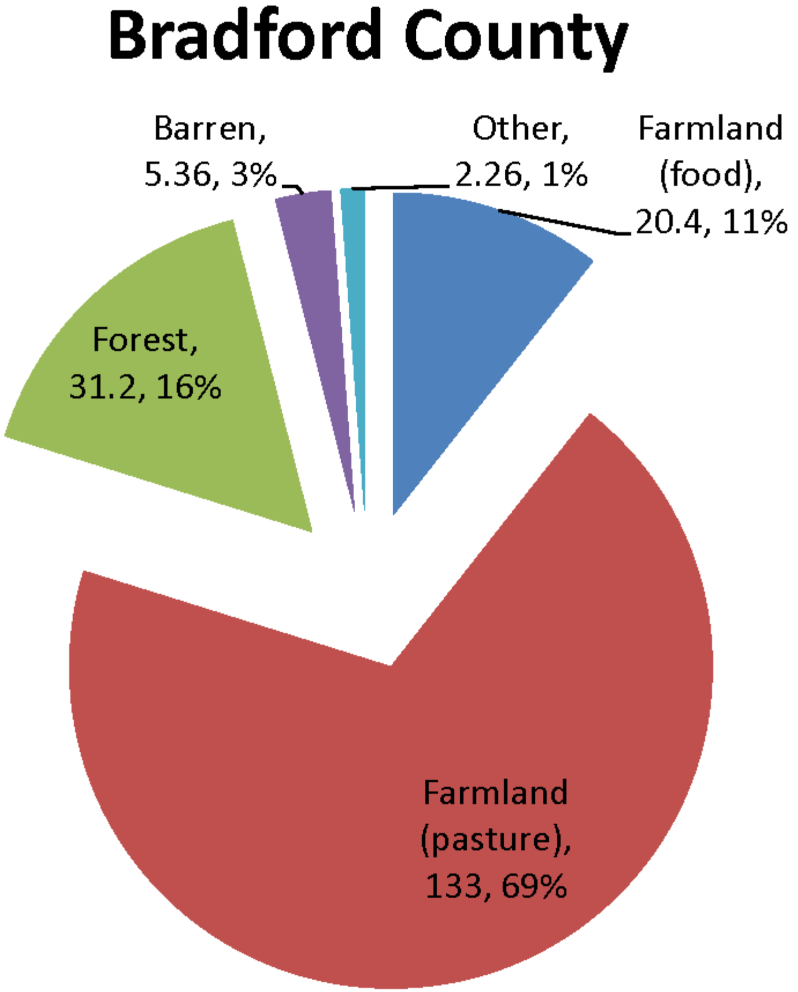
Source: Accenture, 2012

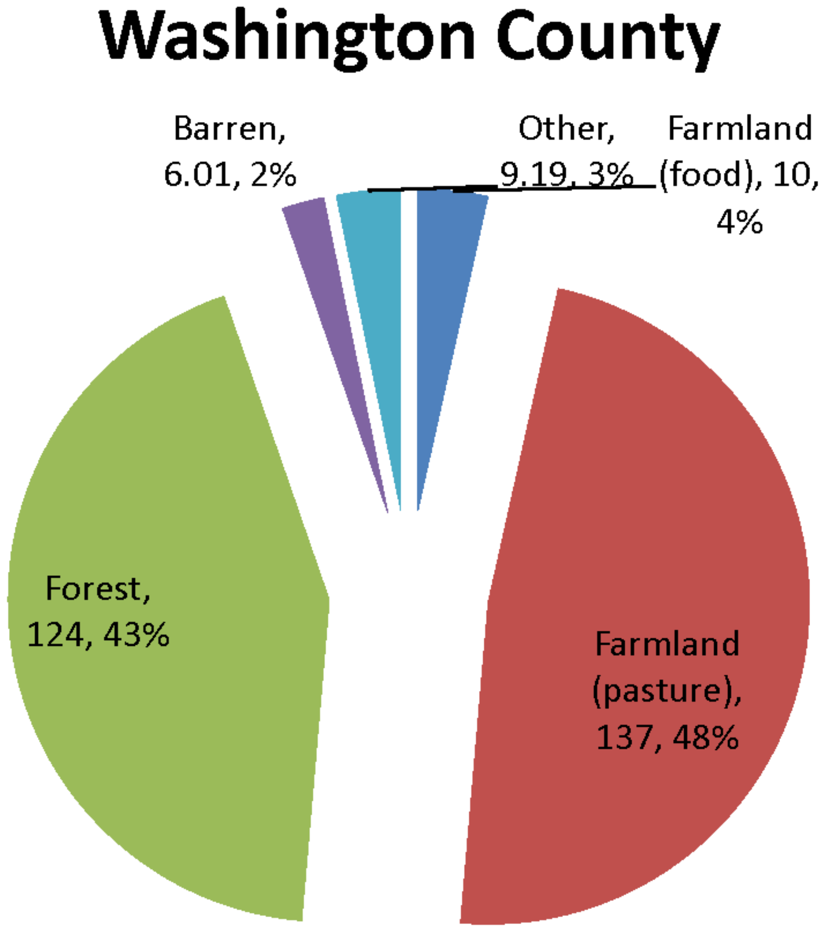
Number & percentage of hydraulically fractured wells by water stress



Source: CERES, 2013

Land-cover classes disturbed through shale-gas site preparation





Cucura et al., 2011

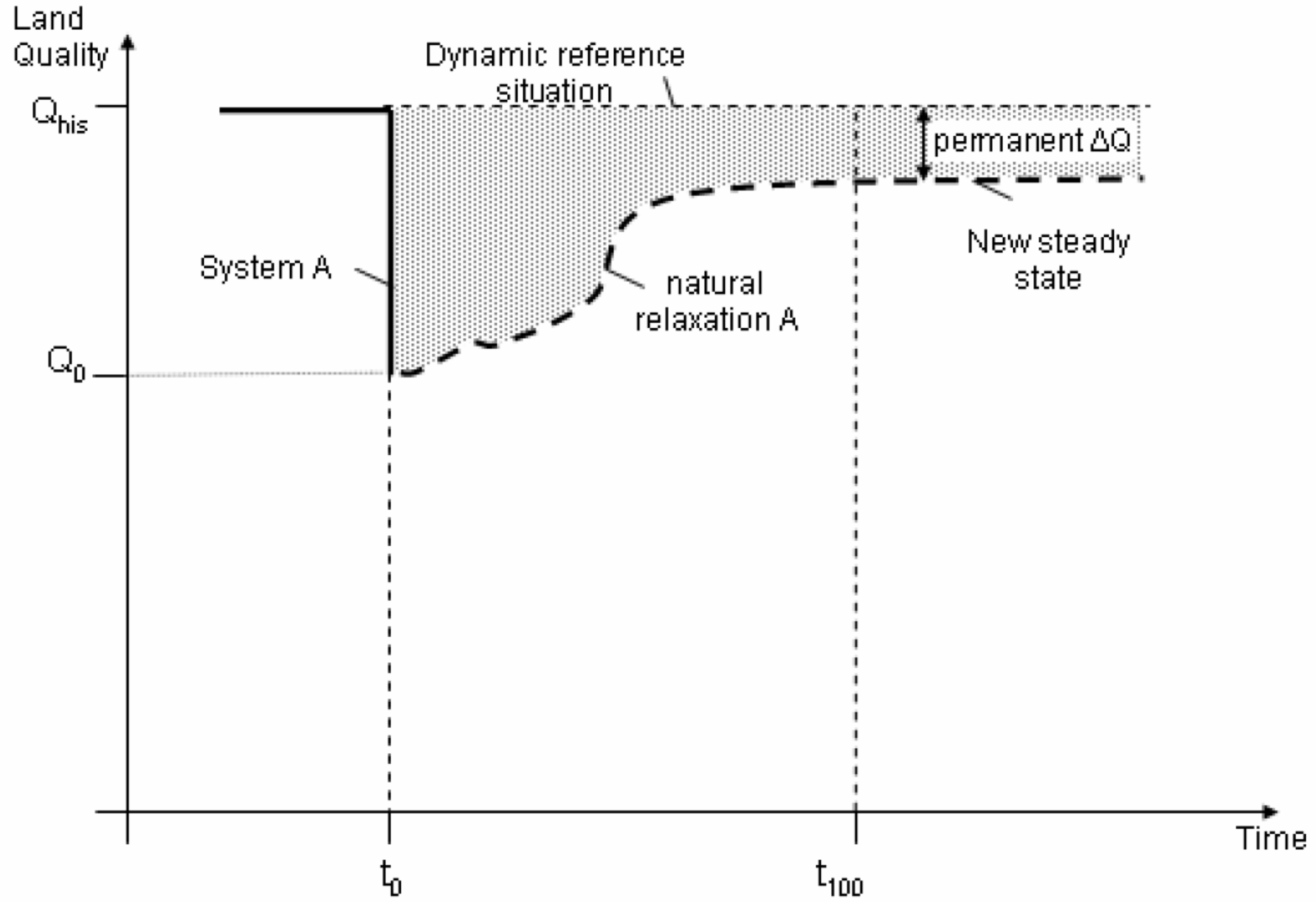
Site preparation, land disturbance, and stream-water quality

- Forest clearing and excavation for site preparation leaves soils unprotected leading to land-surface erosion

- Eroded soil and soil-bound contaminants are carried to streams and impair water quality

John Dickerson, USDA Soil Consv. Service

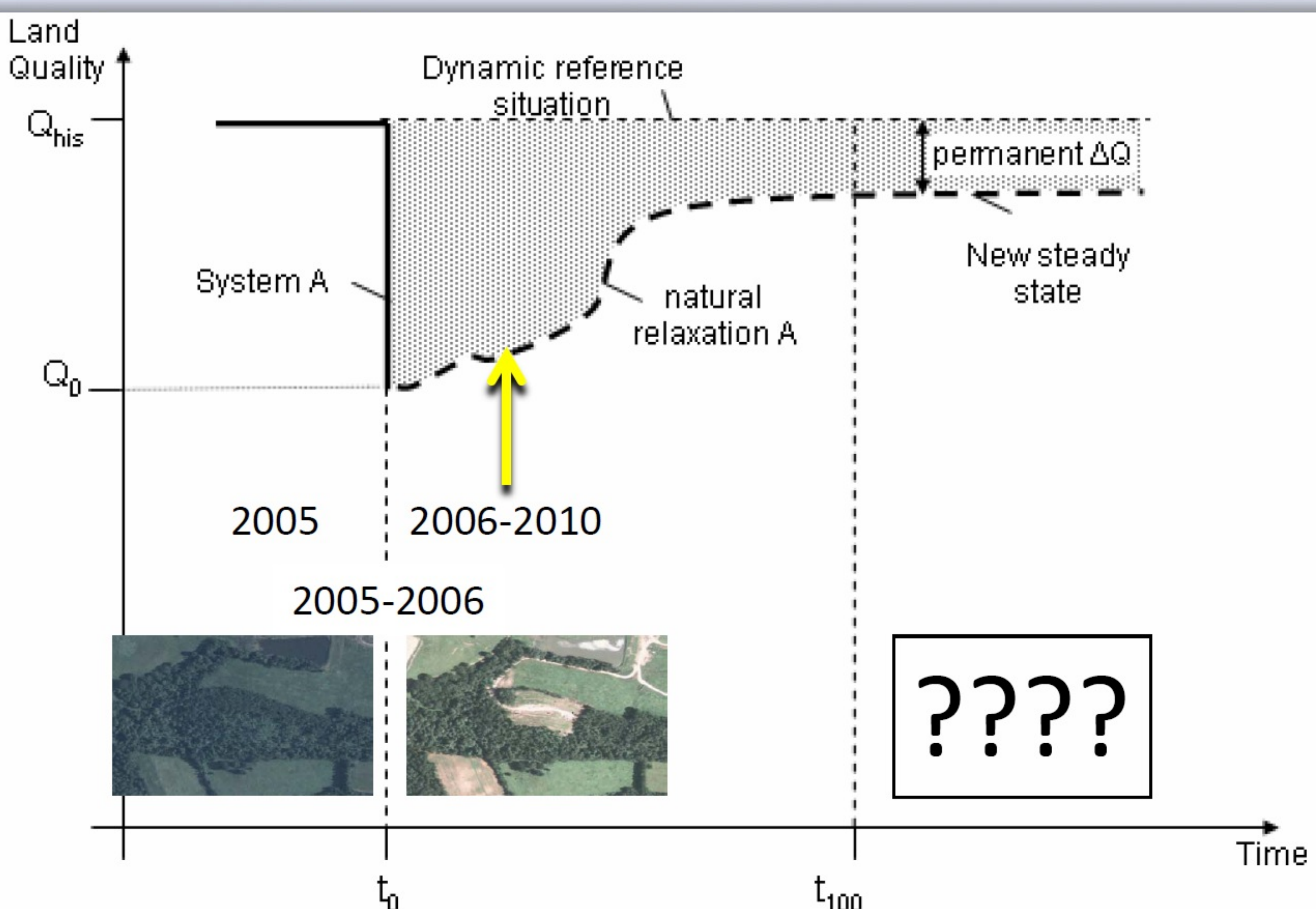
Land use and land change



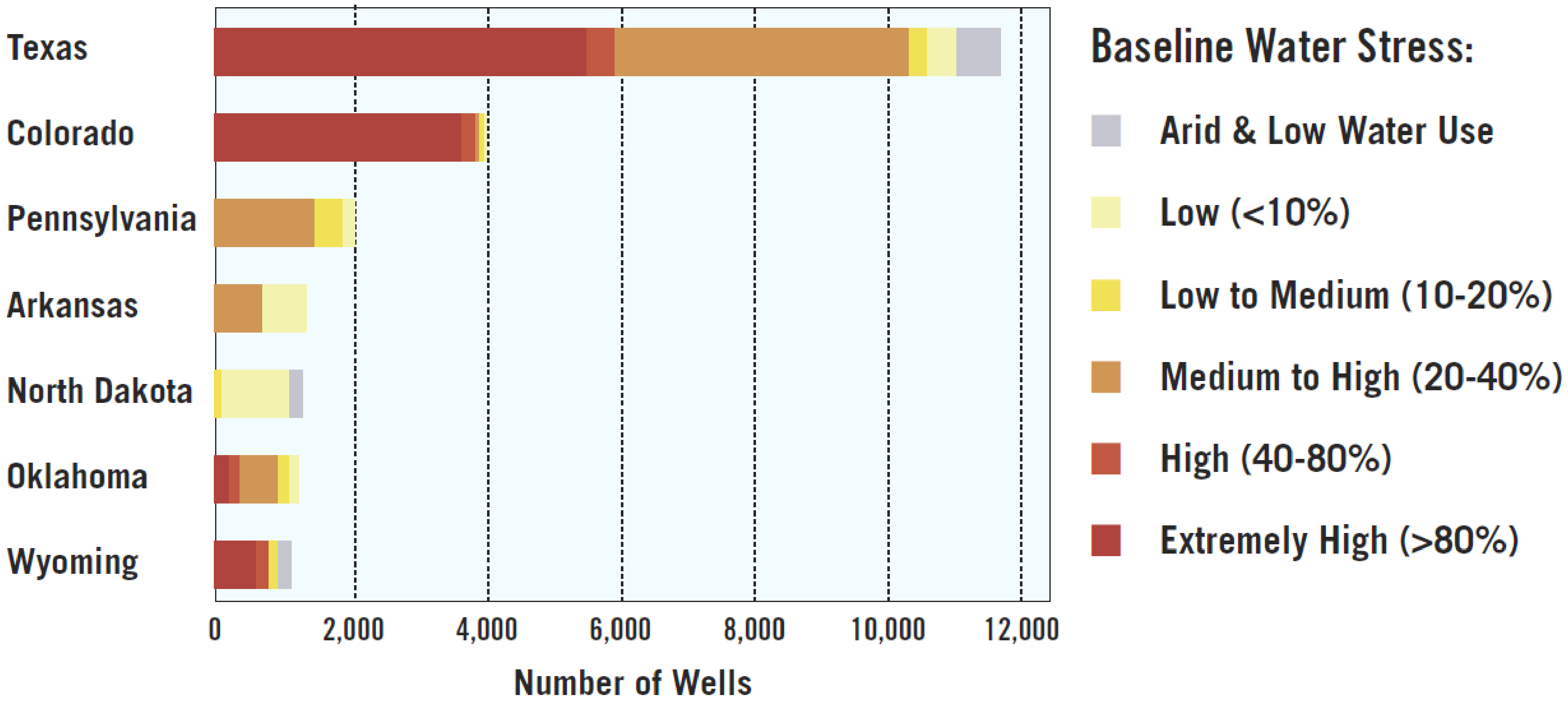
Adapted from Canals et al 2007

Land transformation

Land use and land change



Number of hydraulically fractured wells by state & water stress



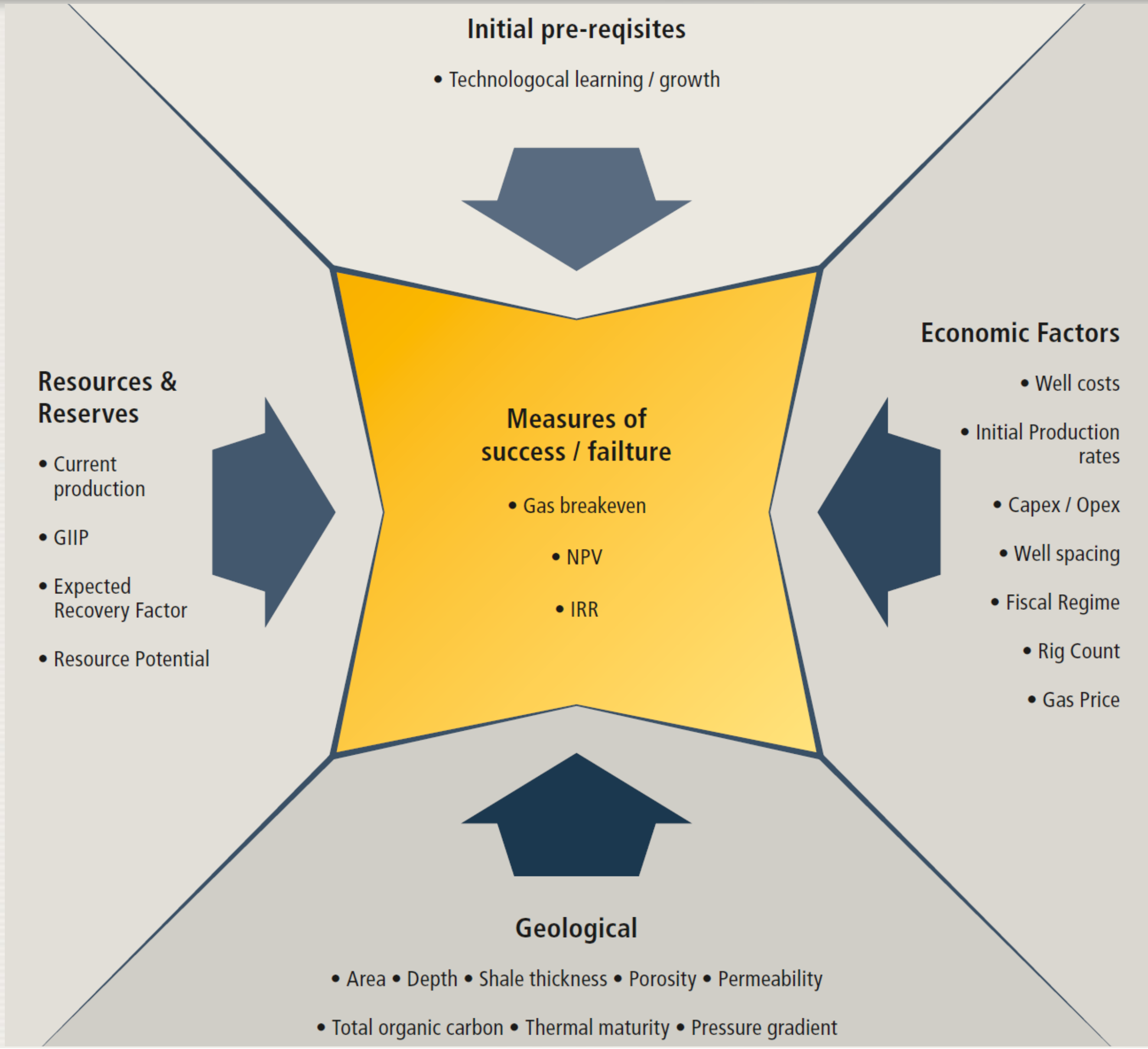
Numbers of wells in top seven shale energy producing states by water stress.

Source: CERES, 2013

Challenges

- Global shale deposits (source rocks) are abundant
- Potentially all sedimentary basins endowed with source rocks allover the world contain shale gas
- No two shale deposits are alike
- Information on deposits opaque
- Assessments often unclear – OGIP, URR, TRR, ERR or P1/P2/P3 related
- Result: Widely varying estimates for the same play
- Conventional gas occurrences still plentiful and growing globally – so are other unconventional gas occurences (CBM, Deep and Tight gas, hydrates)

Framework for key stages / prerequisites of successful unconventional plays



Source: Kuhn and Umbach, 2011)

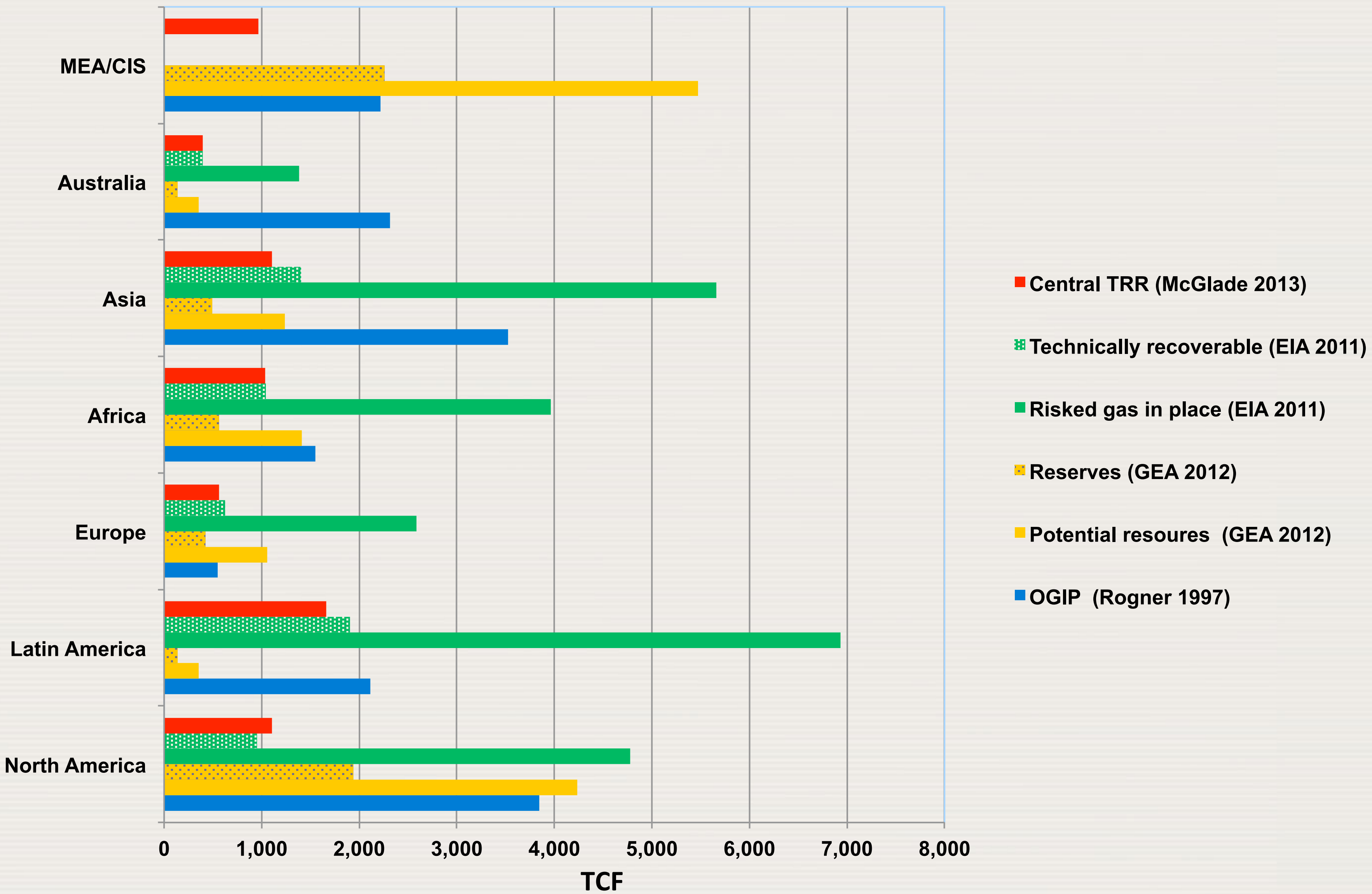
Challenge No 1: More precise resource assessments

- No other place as well delineated as the US
- High conventional gas prices stimulated shale gas development in North America – technology has existed for decades
- Other regions show a lot of enthusiasm but less action in F&D
- F&D technology still an American domain and not readily available abroad
- Not easily transferable due to
  - historical government – industry partnership
  - drilling service infrastructure
  - mineral-rights laws and lease structures
  - F&D costs
  - population density and, to a lesser extent
  - opposition from environmental groups
- All of which draw out resource assessments globally

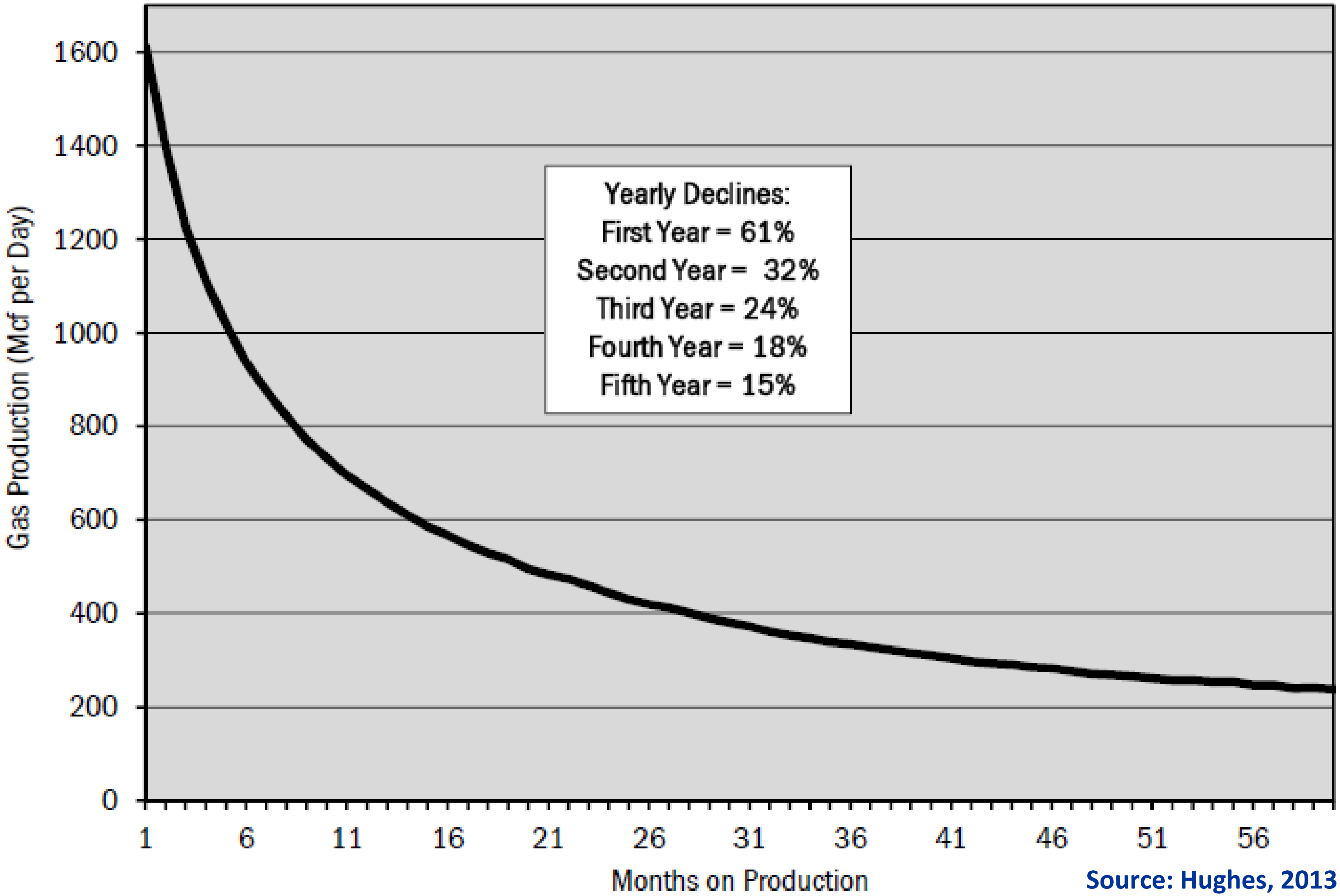
Shale gas resource estimates – the role of definitions

	OGIP (Rogner 1997) TCF	Potential resources (GEA 2012) TCF	Reserves (GEA 2012) TCF	Risked gas in place (EIA 2011) TCF	Technically recoverable (EIA 2011) TCF	Central TRR (McGlade 2013) TCF
North America	3,842	4,238	1,942	4,774	953	1,105
Latin America	2,117	353	141	6,935	1,906	1,660
Europe	549	1,059	424	2,587	624	562
Africa	1,548	1,413	565	3,961	1,042	1,035
Asia	3,528	1,236	494	5,661	1,404	1,102
Australia	2,313	353	141	1,381	396	396
MEA, CIS, etc.	2,215	5,474	2,260	-	-	964
Total	**16,112**	**14,126**	**5,968**	**25,300**	**6,325**	**6,823**

Shale gas resource estimates – the role of definitions

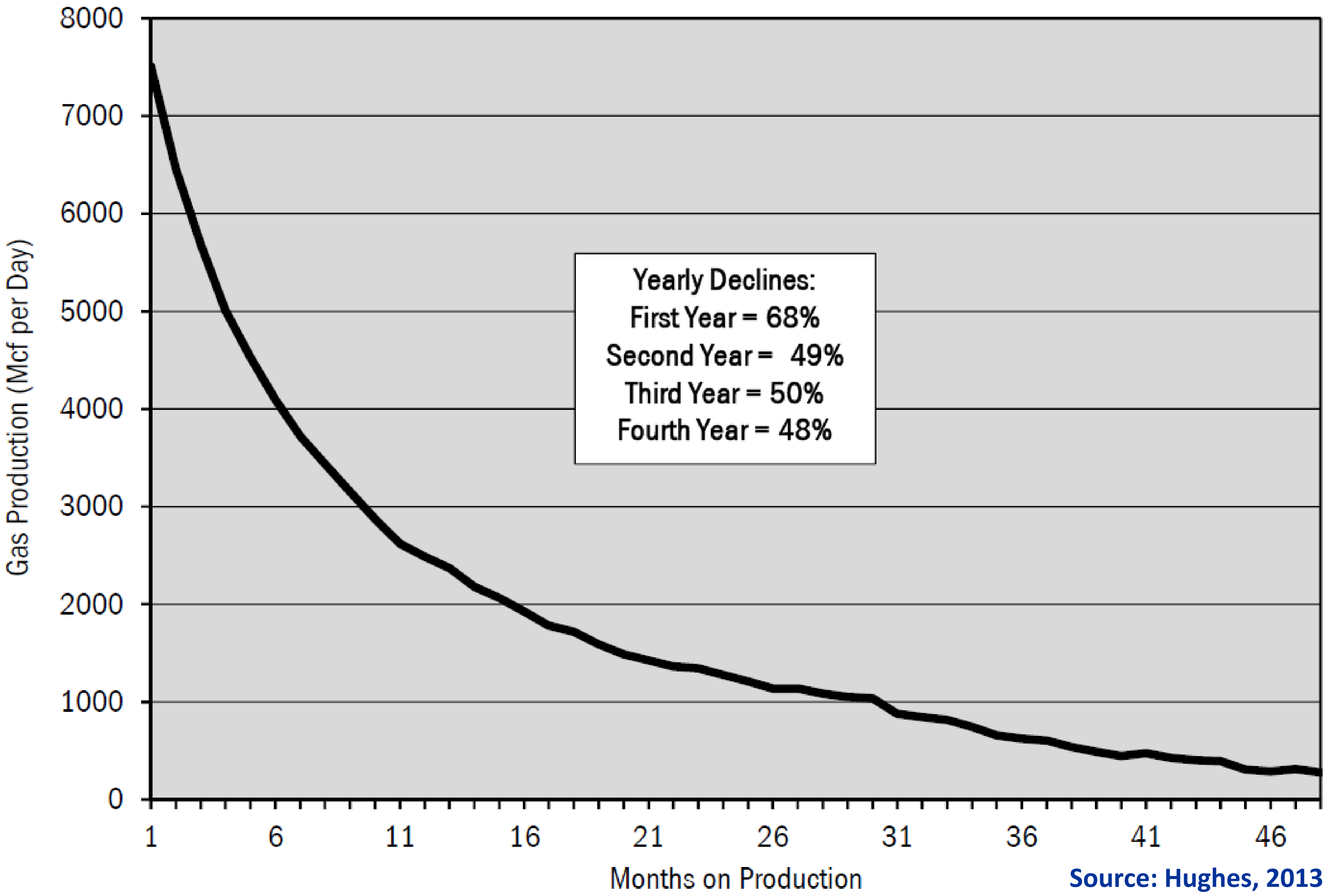


Type decline curve for Haynesville shale gas wells



Source: Hughes, 2013

Type decline curve for Haynesville shale gas wells

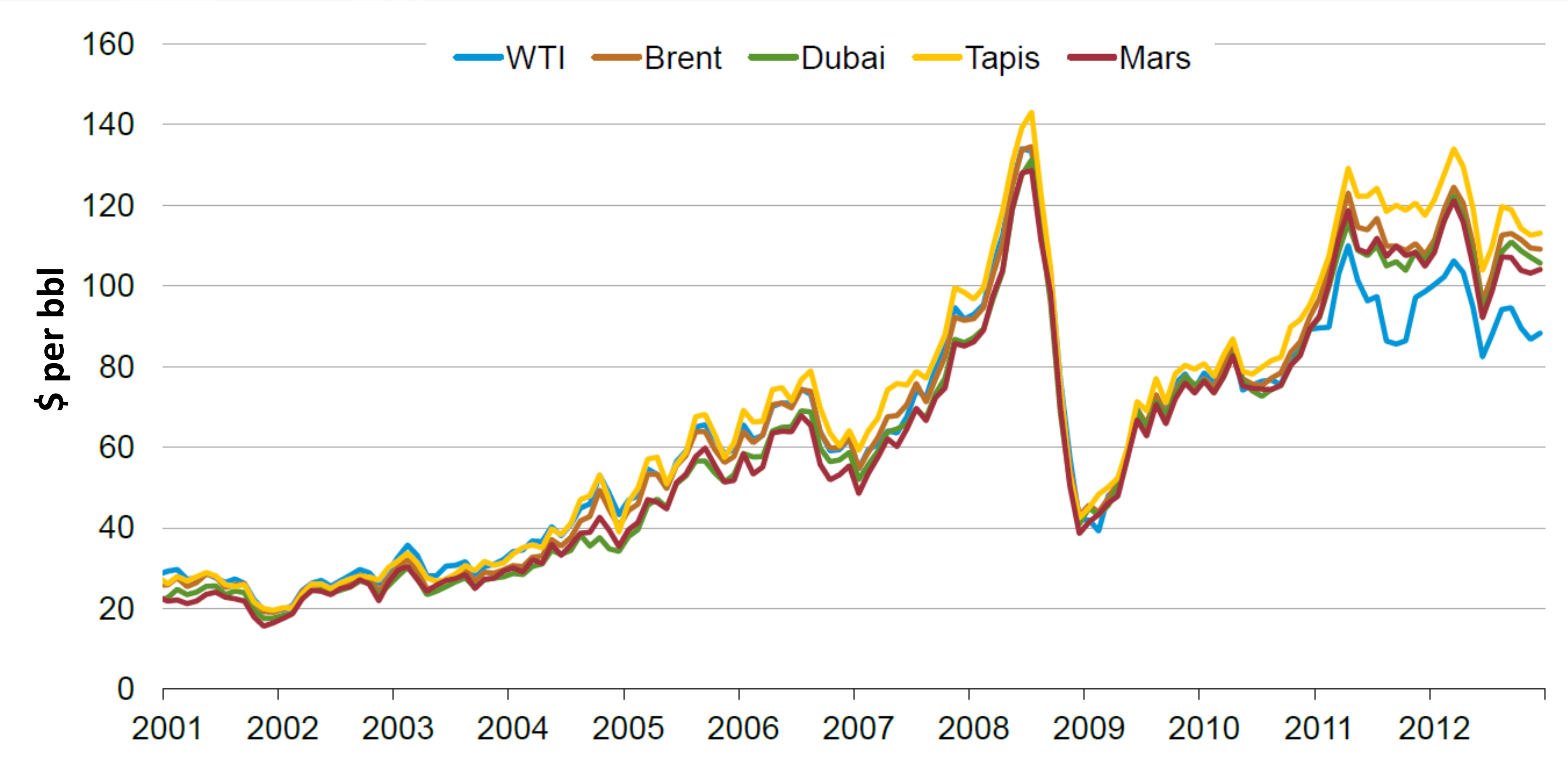


Source: Hughes, 2013

Challenge No 2: Full production costs

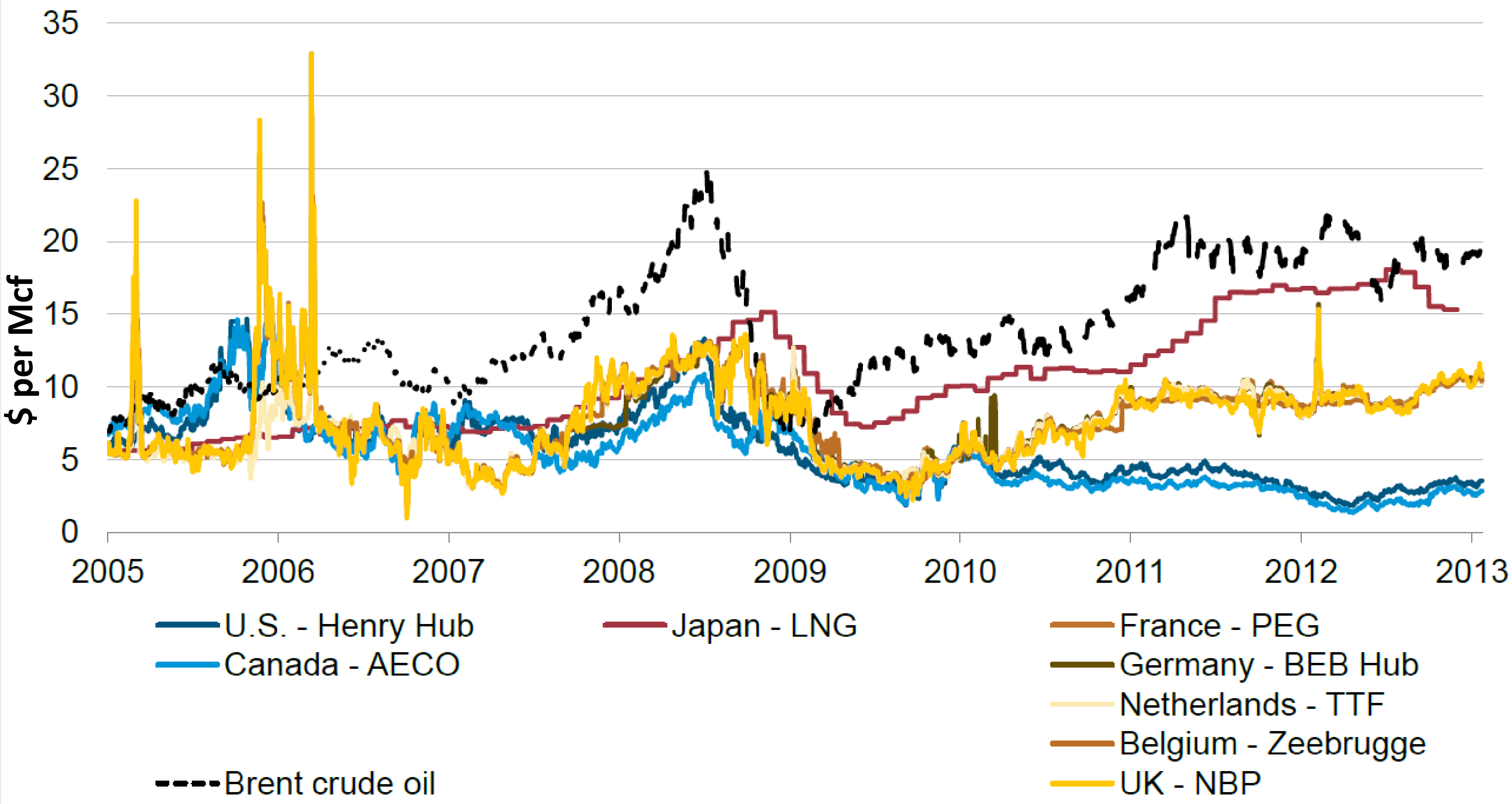
- Most regions outside NA with limited or no resources (not to speak of reserve) assessments and poor understanding of production costs
- Share of economically producible quantities (recovery rates) yet to be determined
  - Initially reserves are a small sub-set of resources but are dynamically changing
  - Reserves take years of development drilling and lots of $ before turning into supplies
  - Known reserves may never be developed
- Traps versus ‘continuous‘ basins’
- Current prices in the US are not sustainable unless cost reductions through technology progress
- Prices elsewhere should be a stimulus

Global crude oil prices



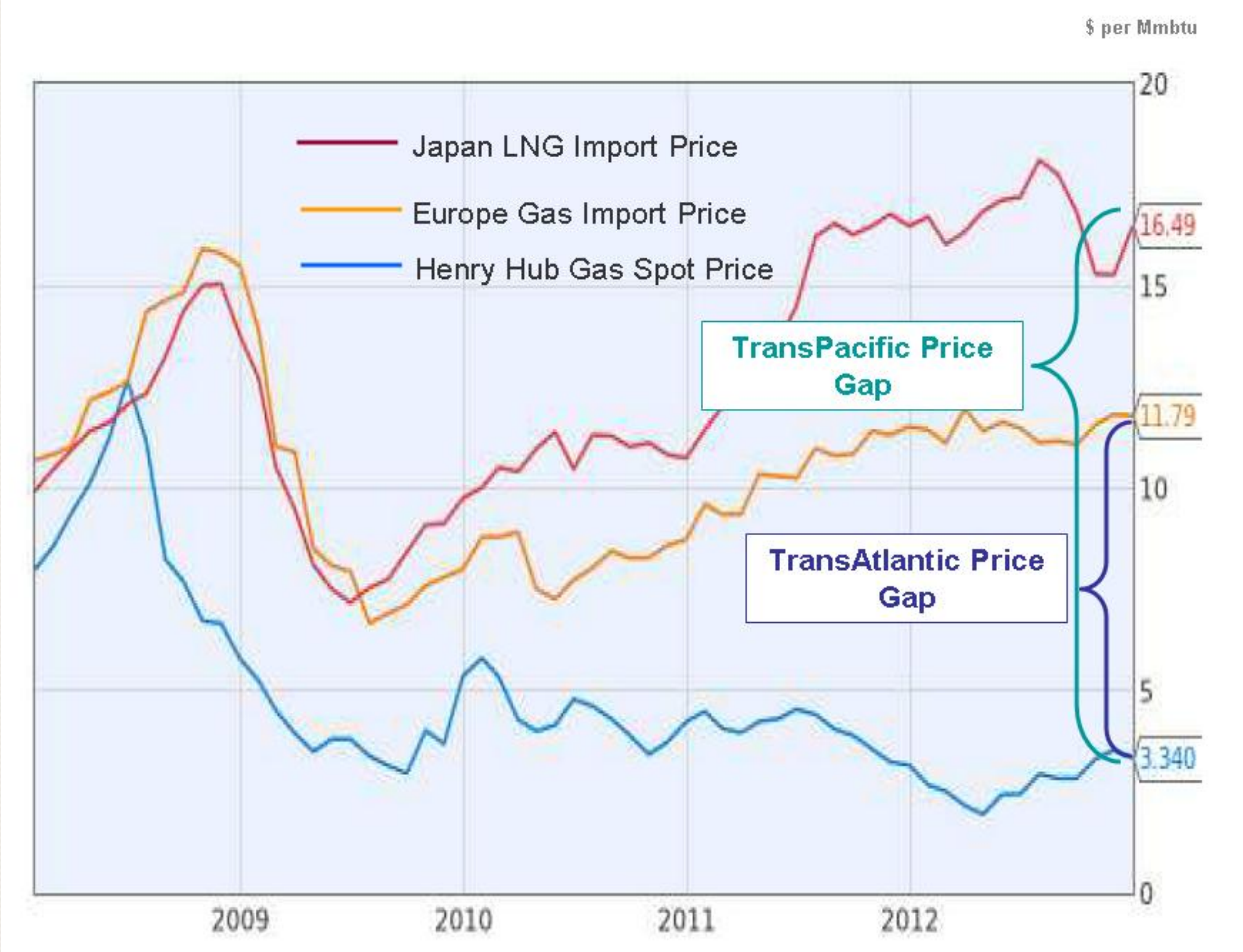
Source: Gruenspecht, 2013

Global spot natural gas, crude oil & LNG prices



Source: Gruenspecht, 2013

Interregional gas price gaps

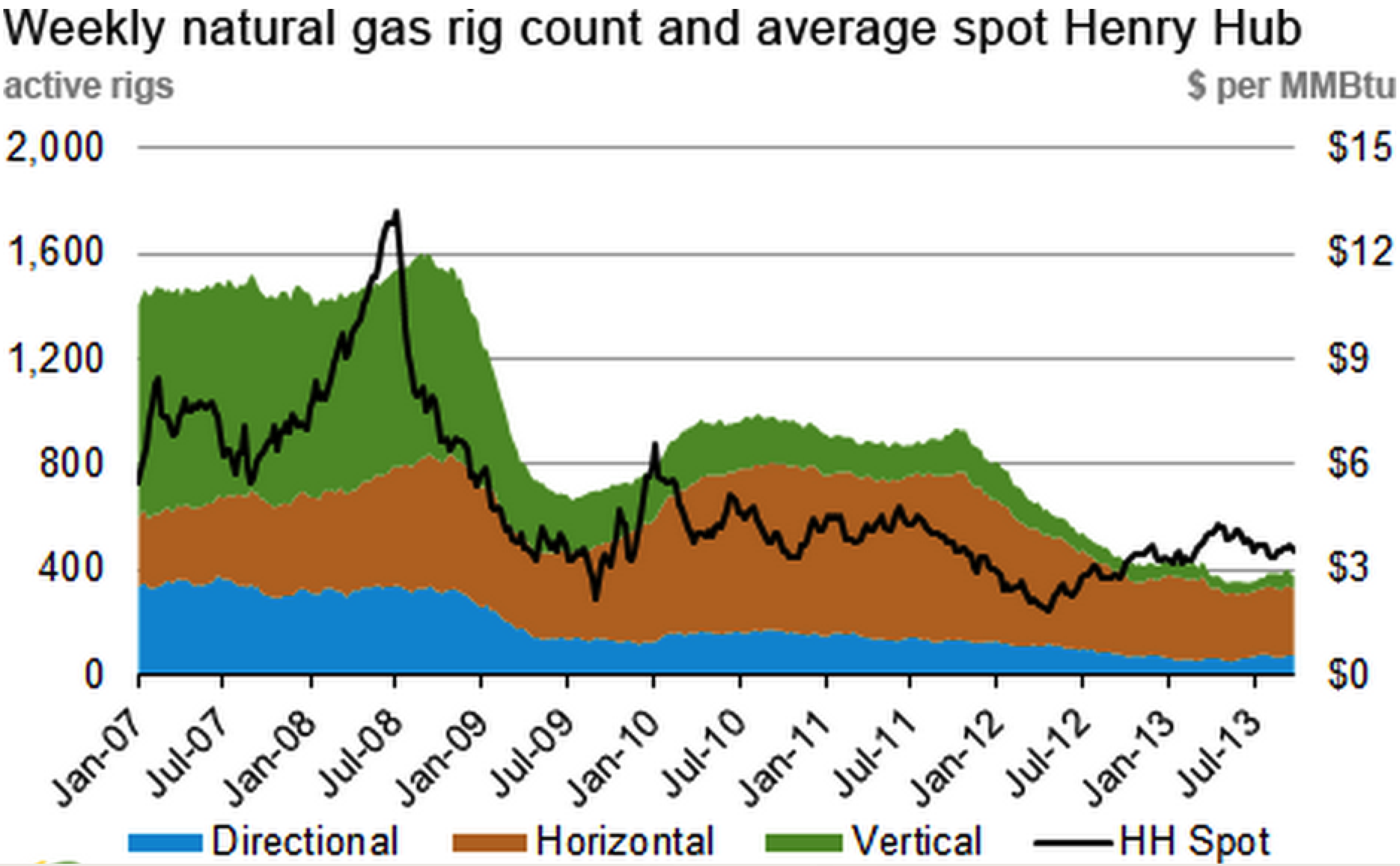


Source: Alboran Research

Henry Hub Gulf coast natural gas spot price

Source: EIA, 2013

Weekly natural gas rig count and average Henry Hub spot price

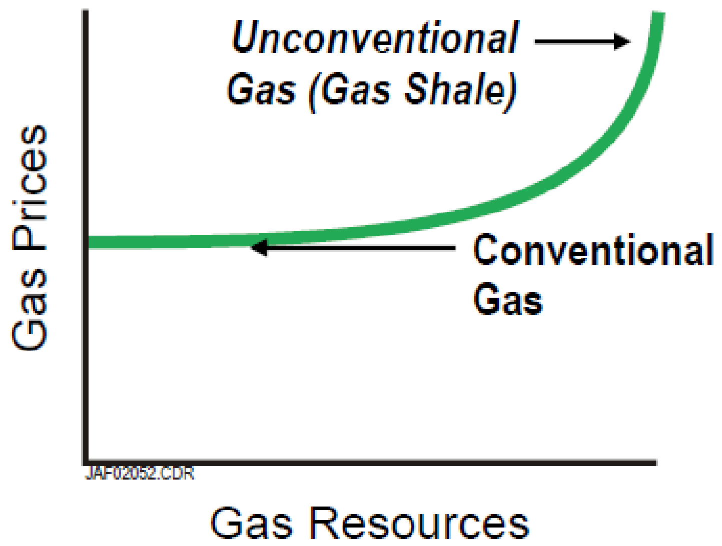


Source: EIA, 2013

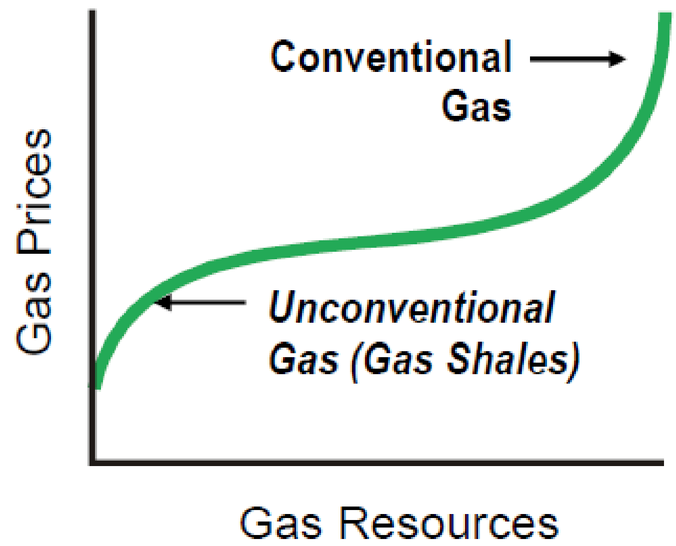
Shale gas impact on natural gas prices

Unconventional gas (particularly the higher quality gas shales) is today the low cost portion of the natural gas price/supply curve.

Prior Perception



New Understanding



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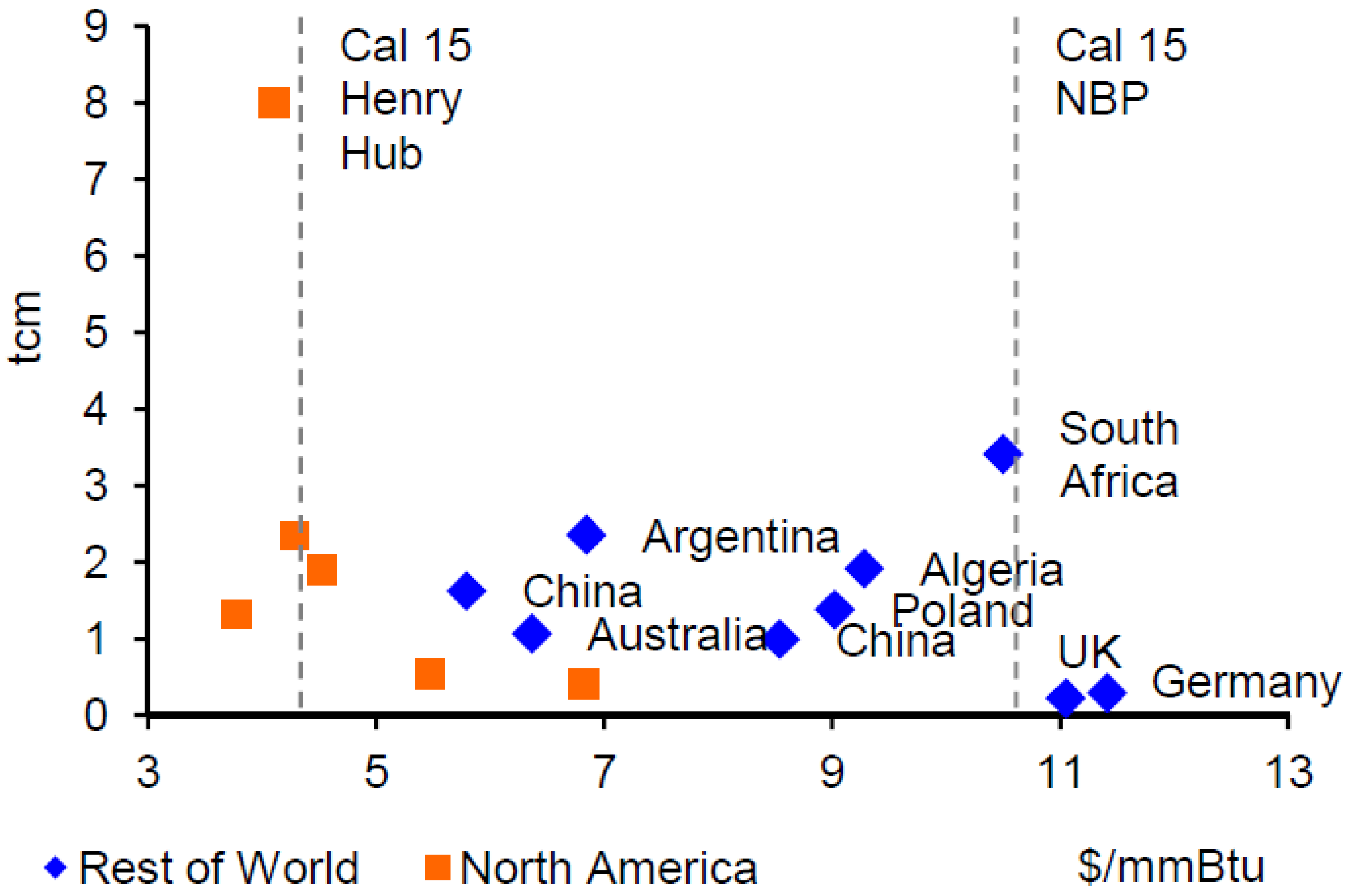
Economics of shale gas

- Shale gas requires continuous investment
- Typical lifespan of a well is 20 years but fracking may need to be repeated at intervals to maintain production levels
- More than 200,000 wells drilled in the US and counting….
- Estimated some 7000 wells need to be drilled per year to maintain current shale gas production
- Investments per well now approaching and at times exceeding $9 million per well (used to be $2 to $3 million)
- Additional innovation needed to contain costs

Haynesville

	Active	Undeveloped
Area (sq. miles)	3,574	5,426
EUR (Bcf/ well)	6.5	1.5
Well Spacing (wells/ sq. mile)	8	8
TRR (Tcf)	53.3	19.41
Wells drilled or to be drilled	8,200	12,940
Characteristics		
Depth (ft)	12,000	
Thickness (ft)	250	
Porosity (%)	8.5	
Total Organic Content (% wt)	2.25	

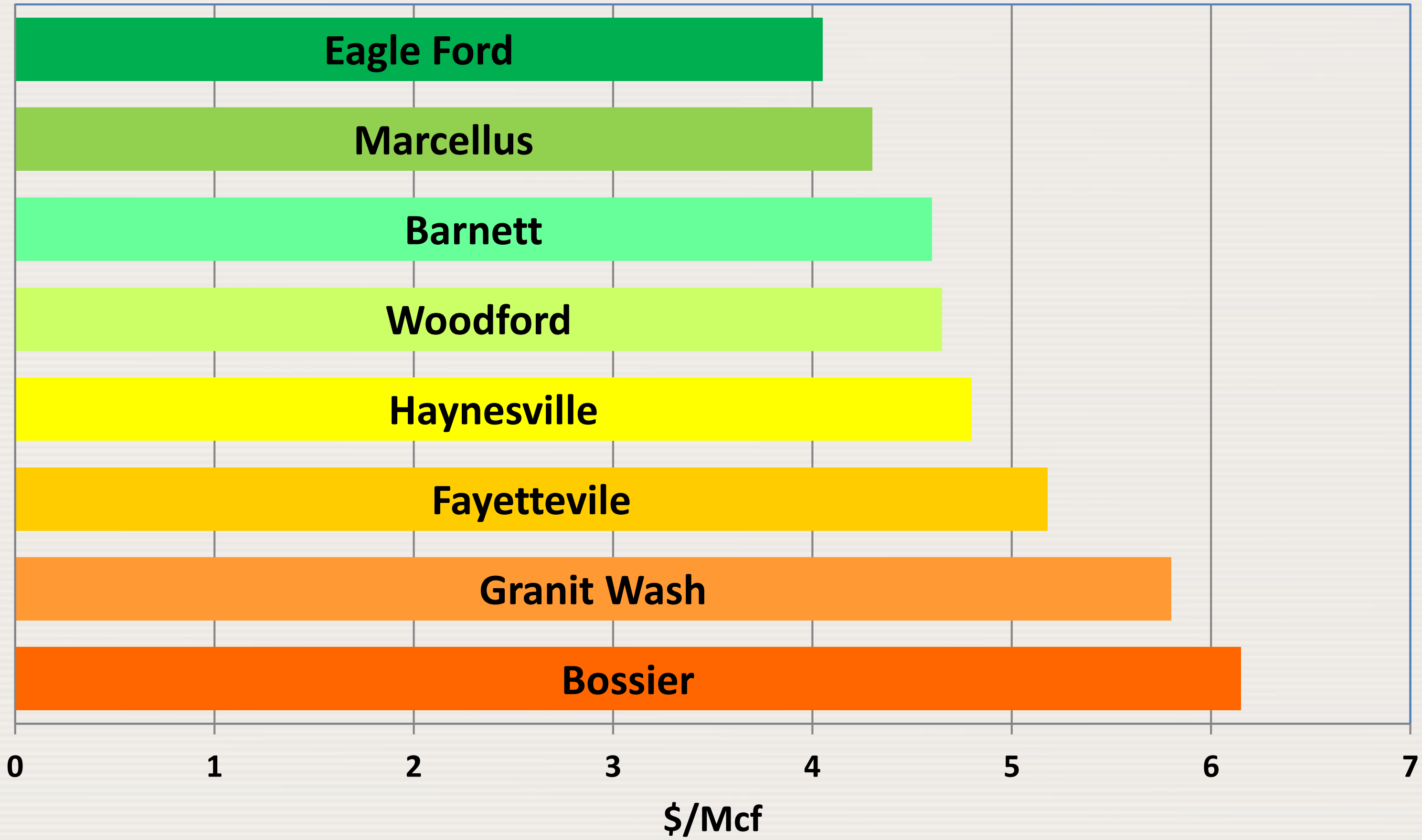
Shale-gas breakeven costs ($/mmBtu)*



Source: Wood Mackenzie, Deutsche Bank

**Discount rate of 10% applied; North American shale-gas resources plotted are Canada's Duvernay Shale, Marcellus, Barnett, Eagle Ford and Haynesville*

Breakeven marginal prices for major US shale gas plays

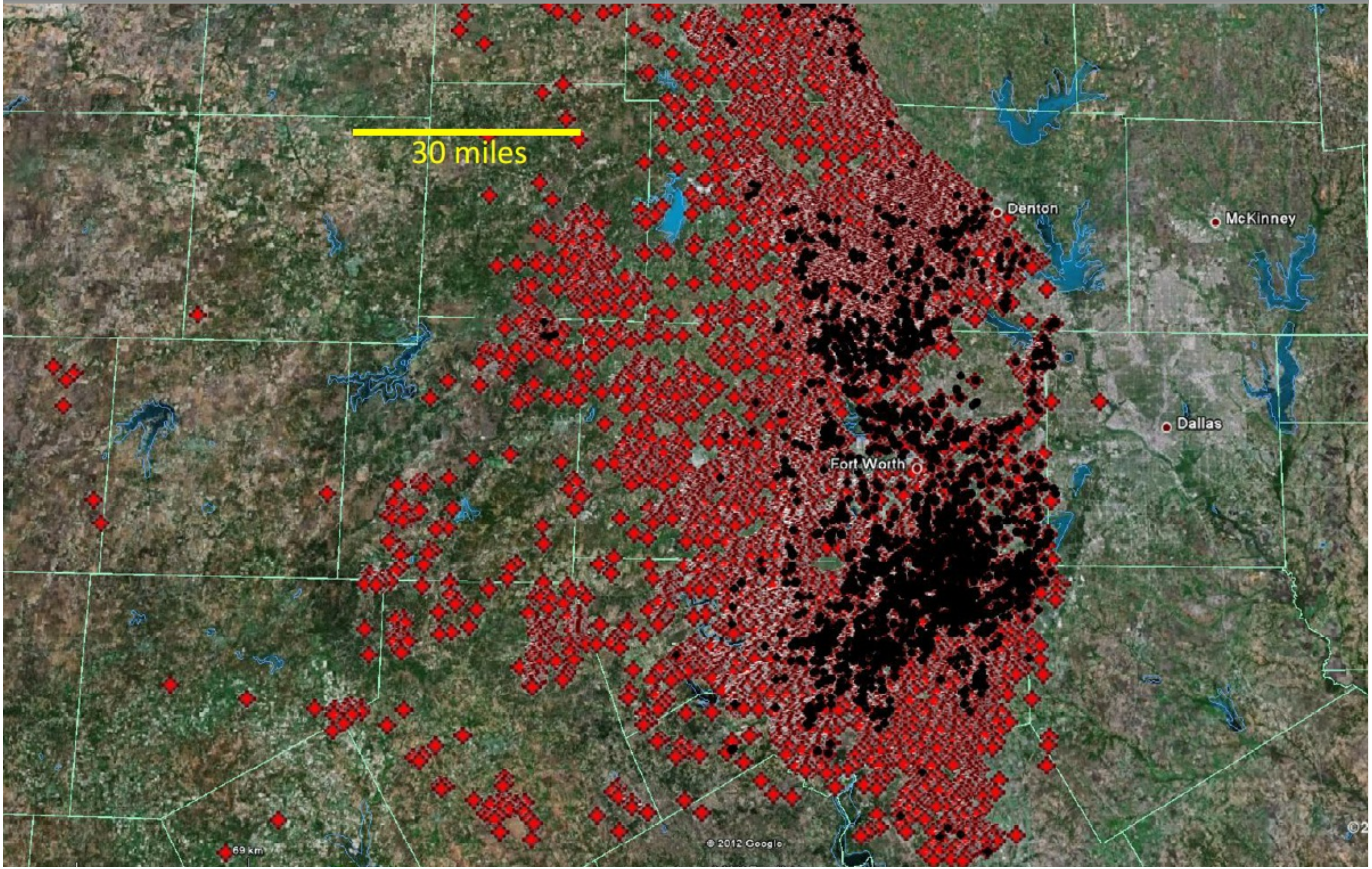


Source: Bloomberg & Credit Suisse, 2011

Challenge No 3: Balancing environmental risks and benefits

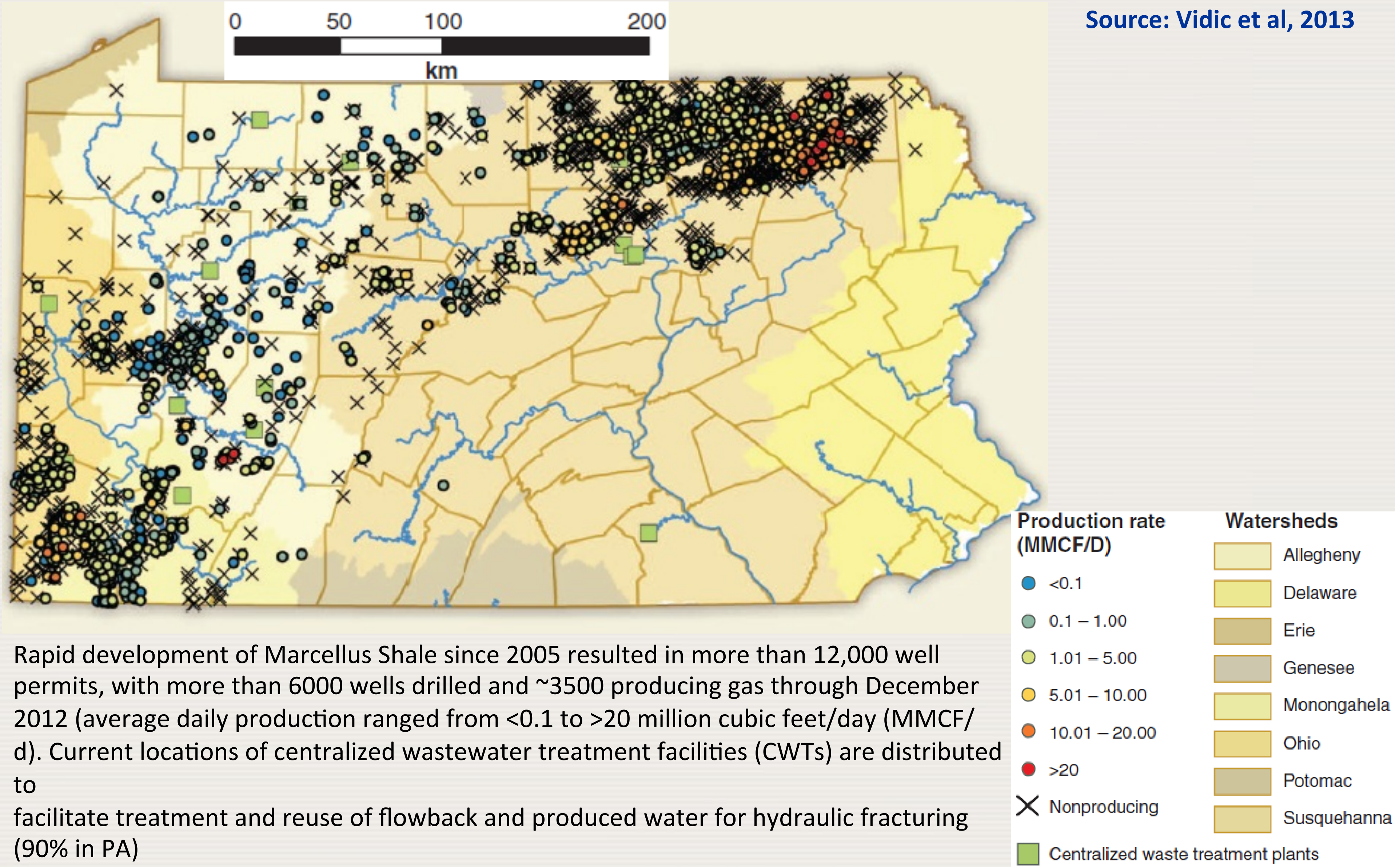
- Combustion of shale gas results in lower GHG emissions than coal and oil – climate change mitigation option
- Methane still a GHG
- Leakage during production
- Fracking impacts on local environment
- Water use and waste water disposal
- Development of fracking fluids without hazardous chemicals
- Impact on the market penetration of renewables with perceived higher environmental benefits

Distribution of wells in the Barnett play



Marcellus Shale wells in Pennsylvania

Source: Vidic et al, 2013



Rapid development of Marcellus Shale since 2005 resulted in more than 12,000 well permits, with more than 6000 wells drilled and ~3500 producing gas through December 2012 (average daily production ranged from <0.1 to >20 million cubic feet/day (MMCF/d). Current locations of centralized wastewater treatment facilities (CWTs) are distributed to
facilitate treatment and reuse of flowback and produced water for hydraulic fracturing (90% in PA)

Total hydraulic fracturing-related potential fugitive emissions from US shale gas wells brought online in 2010

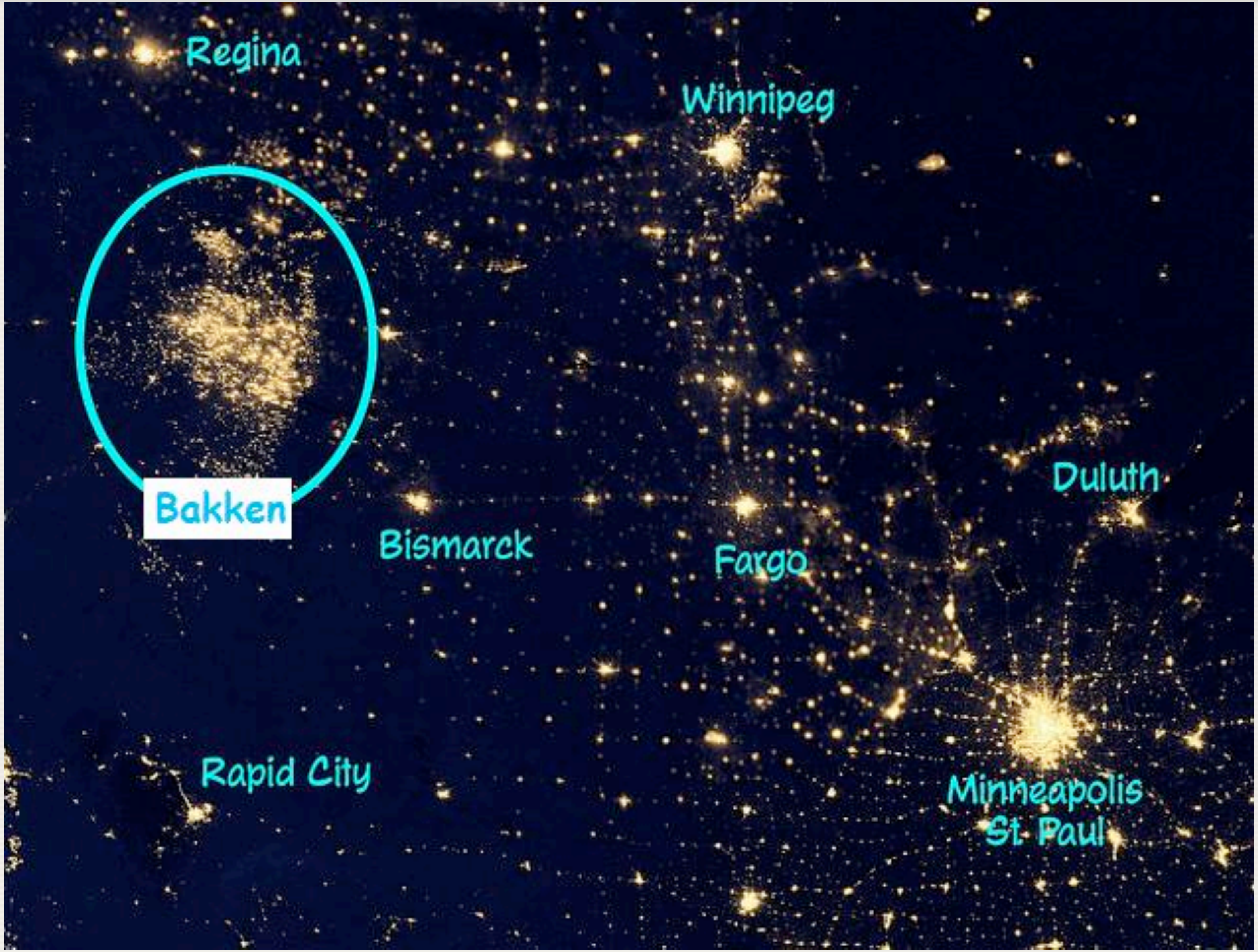
	Barnett	Fayetteville	Haynesville	Marcellus	Woodford	All plays
Mean per-well potential fugitive emissions: (10^3 m^3 of natural gas)	273	296	1177	405	487	—
No. of horizontal wells	1785	870	509	576	208	3948
Total potential fugitive emissions: (10^6 m^3 of natural gas)	487	257	599	234	101	1678
Total potential fugitive methane emissions: (Gg CH_4)	262	138	322	125	54	902

Shale gas hydraulic fracturing-related potential fugitive emissions as a percentage of estimated ultimate recovery assuming mean well production performance rates and 30 year and 15 year production lifetimes

	Barnett	Fayetteville	Haynesville	Marcellus	Woodford
30 year lifetime, %	0.39	0.39	0.78	0.39	0.39
15 year lifetime, %	0.54	0.52	0.99	0.53	0.52

Source: O'Sullivan and Paltsev, 2012

Gas flaring at Bakken

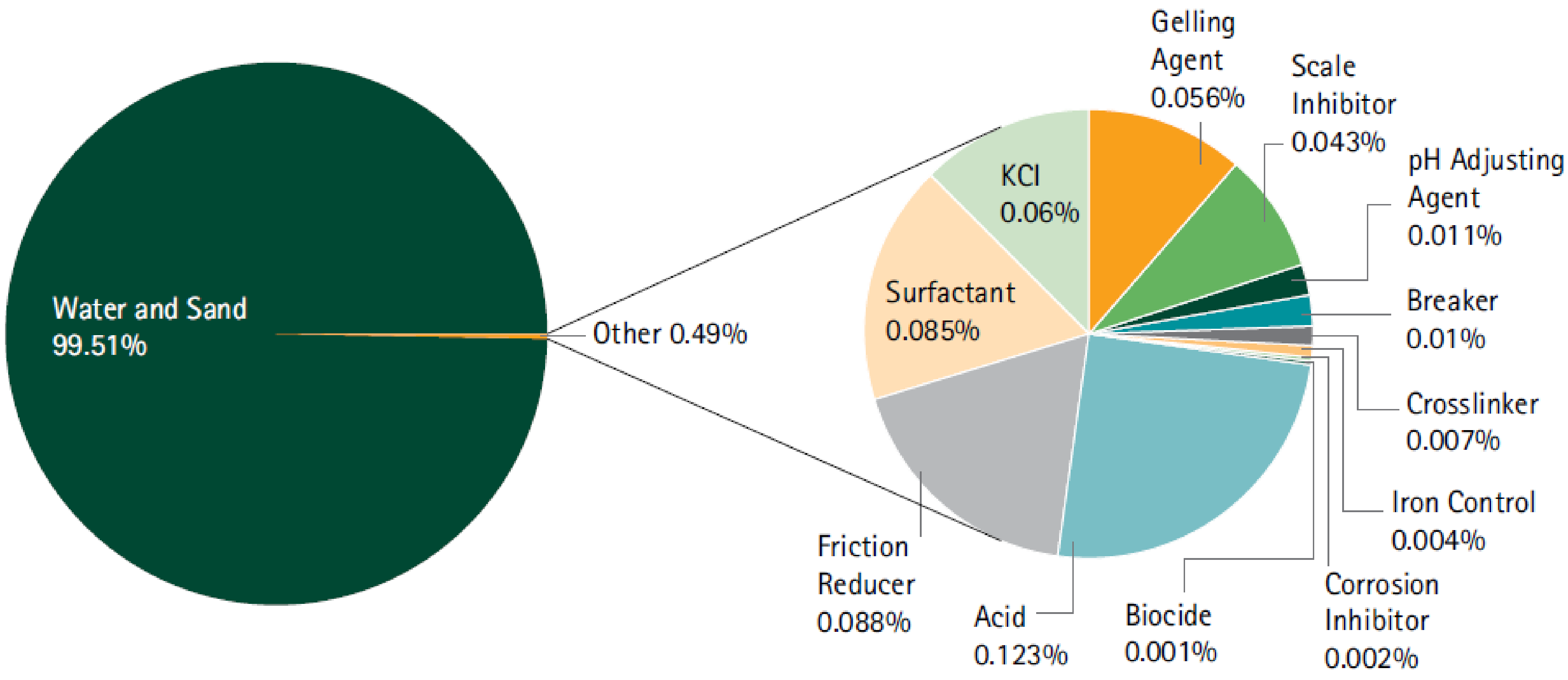


Common chemical additives for hydraulic fracturing

Additive type	Example compounds	Purpose
Acid	Hydrochloric acid	Clean out the wellbore, dissolve minerals, and initiate cracks in rock
Friction reducer	Polyacrylamide, petroleum distillate	Minimize friction between the fluid and the pipe
Corrosion inhibitor	Isopropanol, acetaldehyde	Prevent corrosion of pipe by diluted acid
Iron control	Citric acid, thioglycolic acid	Prevent precipitation of metal oxides
Biocide	Glutaraldehyde, 2,2-dibromo-3-nitrilopropionamide (DBNPA)	Bacterial control
Gelling agent	Guar/xantham gum or hydroxyethyl cellulose	Thicken water to suspend the sand
Crosslinker	Borate salts	Maximize fluid viscosity at high temperatures
Breaker	Ammonium persulfate, magnesium peroxide	Promote breakdown of gel polymers
Oxygen scavenger	Ammonium bisulfite, magnesium peroxide	Remove oxygen from fluid to reduce pipe corrosion
pH adjustment	Potassium or sodium hydroxide or carbonate	Maintain effectiveness of other compounds (such as crosslinker)
Proppant	Silica quartz sand	Keep fractures open
Scale inhibitor	Ethylene glycol	Reduce deposition on pipes
Surfactant	Ethanol, isopropyl alcohol, 2-butoxyethanol	Decrease surface tension to allow water recovery

Source: Vidic et al, 2013

Typical composition of a fracturing fluid



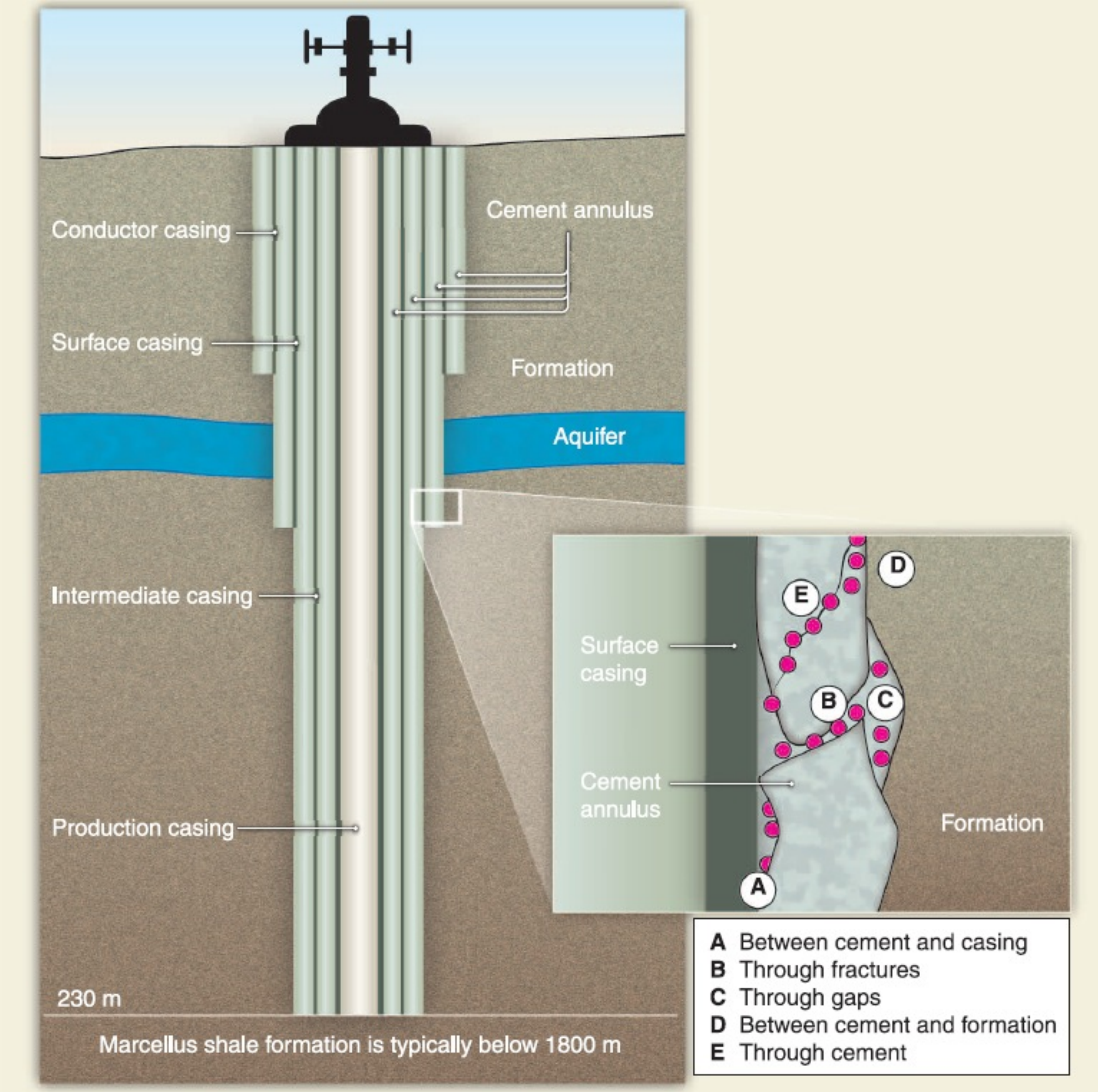
Source: Primer, 2009

Constituents of flow-back water

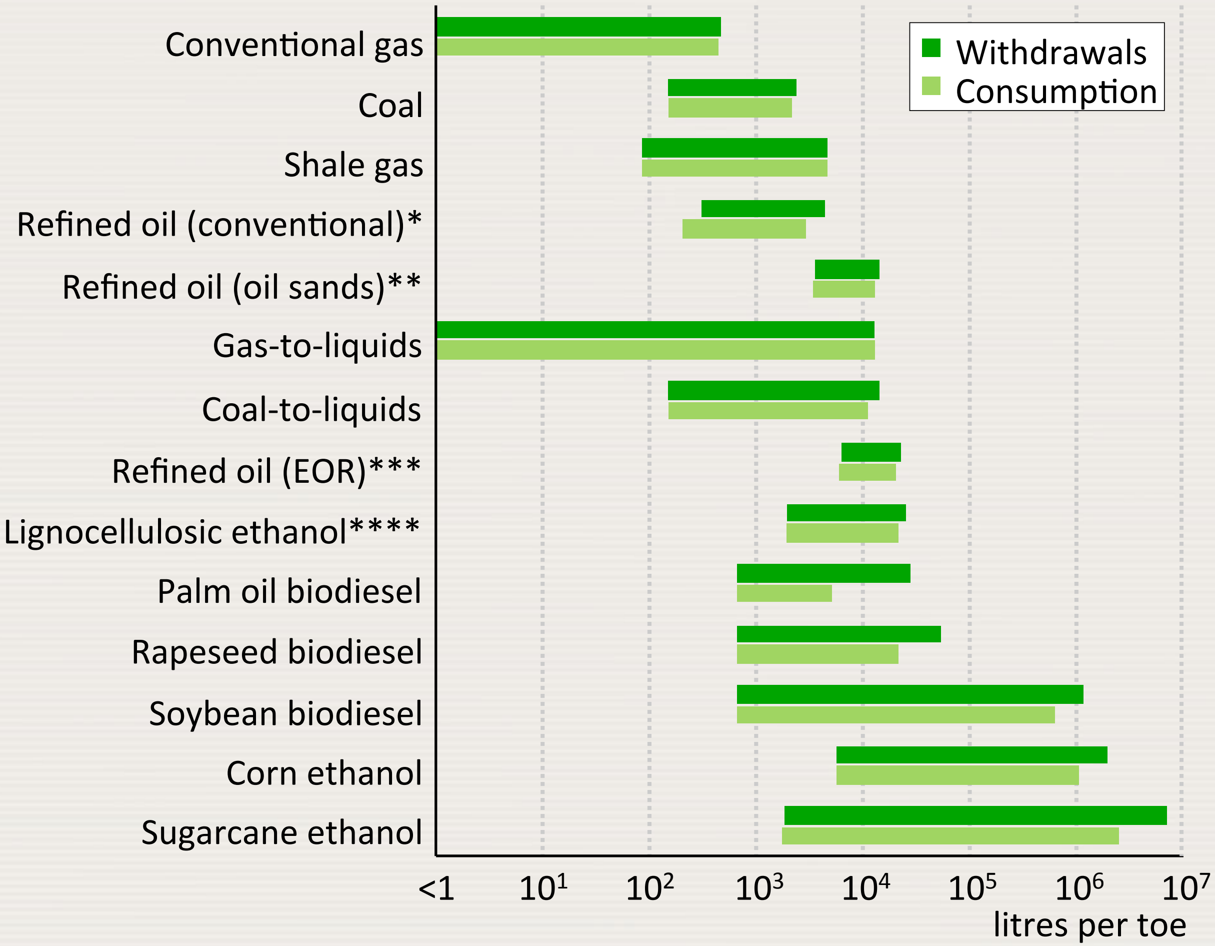
Constituent	Low (g/m^3)	Medium (g/m^3)	High (g/m^3)
Total dissolved solids	66,000	150,000	261,000
Total suspended solids	27	380	3,200
Chloride	32,000	76,000	148,000
Sulfate	ND	7	500
Sodium	18,000	33,000	44,000
Calcium	3,000	9,800	31,000
Strontium	1,400	2,100	6,800
Barium	2,300	3,300	4,700
Bromide	720	1,200	1,600
Iron	25	48	55
Manganes	3	7	7
Oil & grease	10	18	260

Source: Barbot and Peng, 2013

Typical Marcellus well construction



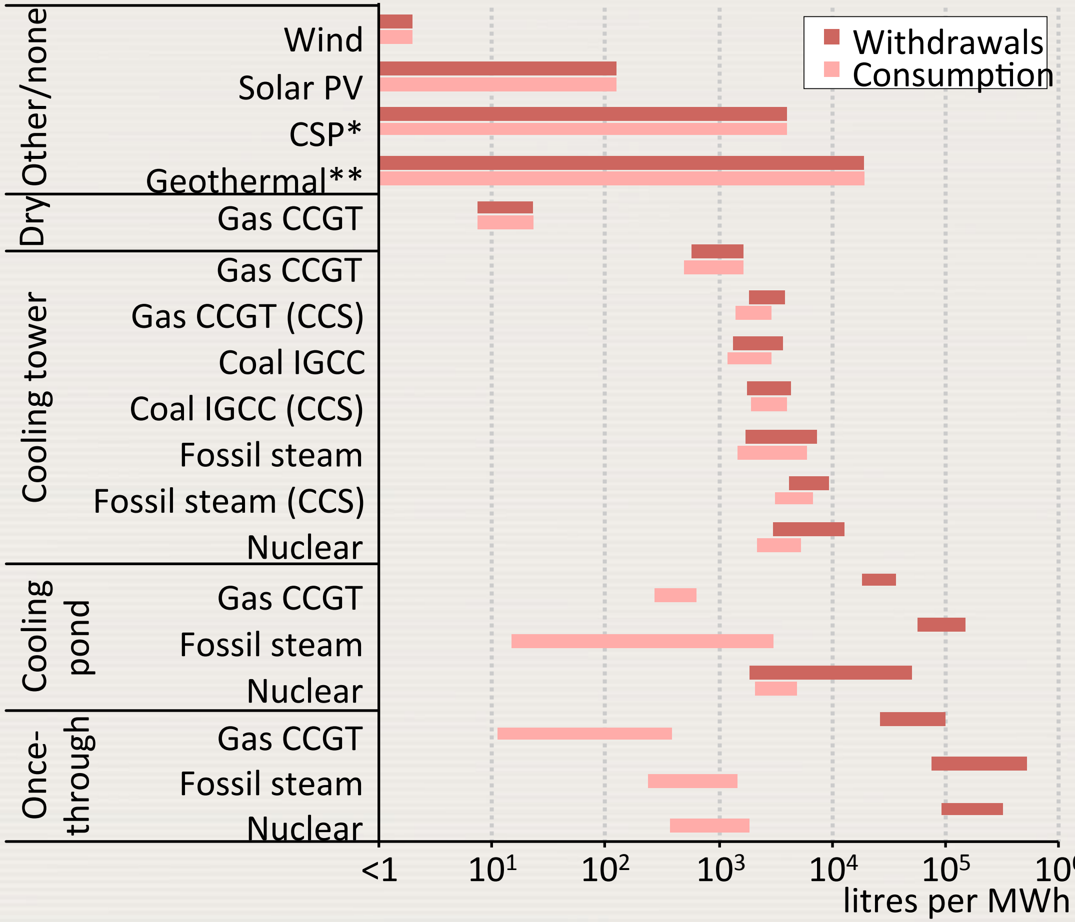
Water use for energy extraction or fuel production



Conventional natural gas entails minimal water use for drilling & processing & is generally much less water-intensive than producing other fossil fuels or biofuels

Source: IEA, World Energy Outlook 2012

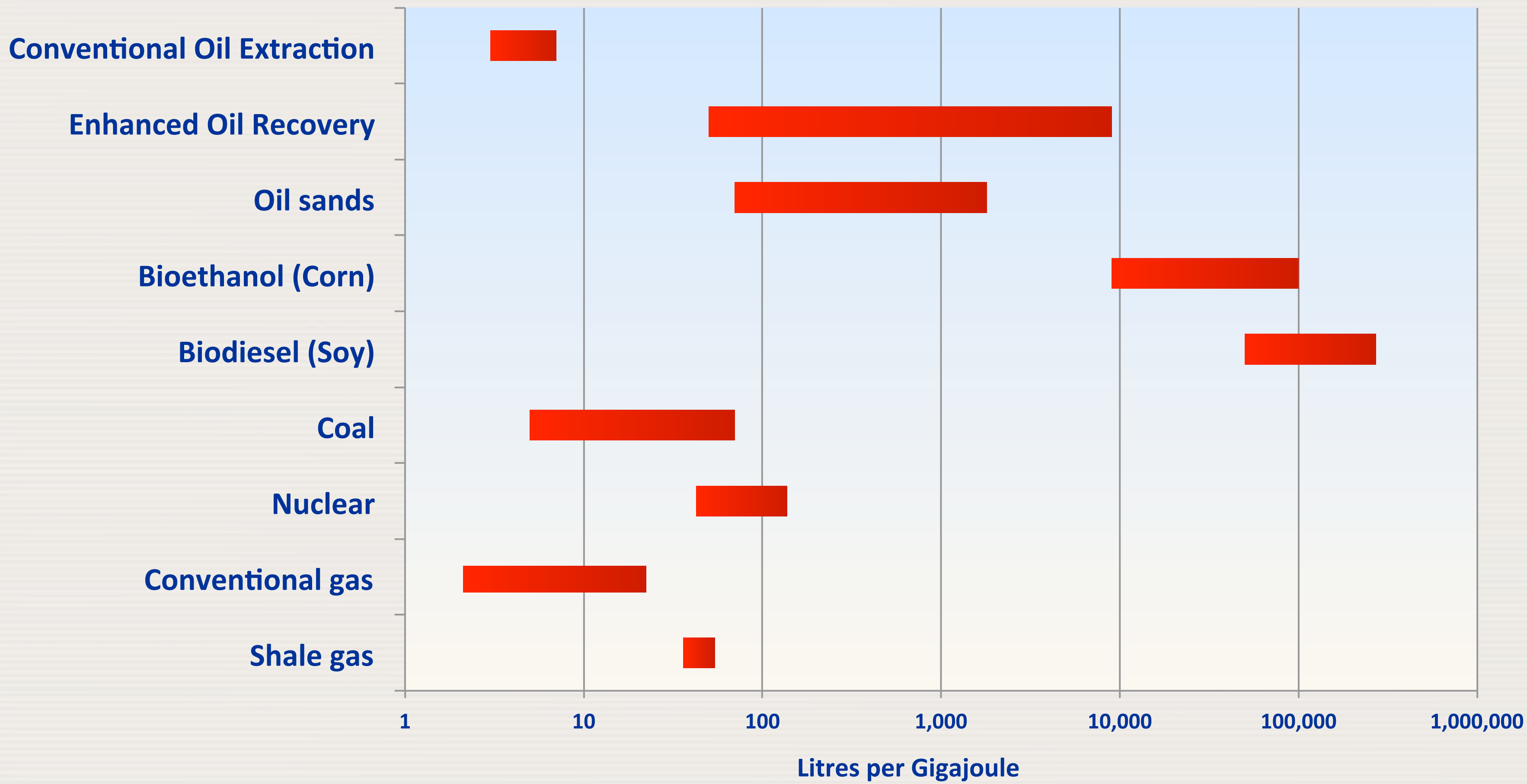
Water use for electricity generation by cooling technology



Water withdrawals per unit of generation are highest for coal-, gas- & oil-fired plants operating on a steam-cycle & nuclear plants with once-through cooling

Source: IEA, World Energy Outlook 2012

Water use for energy production



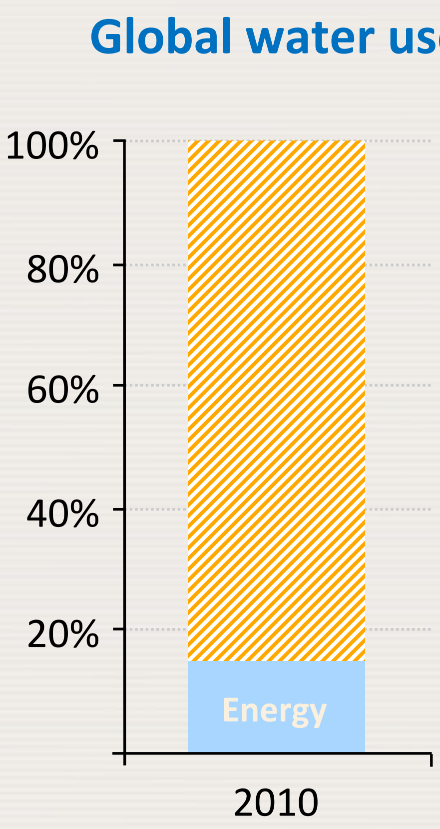
Source: Adapted from US DOE, "Energy Demand on Water Resources, Report to Congress on the Interdependence of Energy and Water", 2006 Cambridge Energy Research Associates

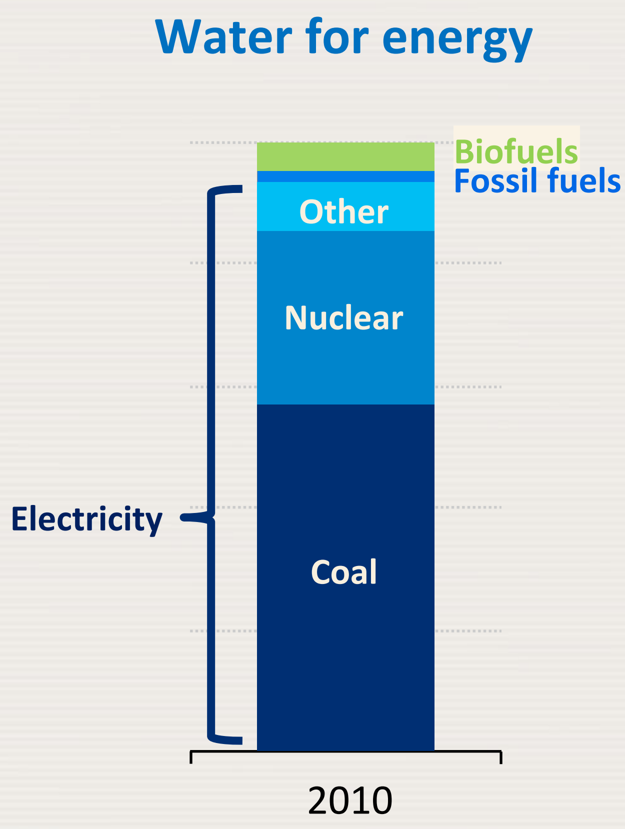
Consumptive freshwater use for ethanol and petroleum gasoline production

Fuel (feedstock)	Net water consumed[a]	Major factors affecting water use
Corn ethanol	10–324 gal/gal ethanol[d]	Regional variation caused by irrigation requirements due to climate and soil types
Switchgrass ethanol	1.0 –9.8 gal/gal ethanol[d]	Production technology
Gasoline (U.S. conventional crude)[b]	3.4–6.6 gal/gal gasoline	Age of oil well, production technology, anddegree of produced water recycle
Gasoline (Saudi conventional crude)	2.8–5.8 gal/gal gasoline	Same as above
Gasoline (Canadian oil sands)[c]	2.6–6.2 gal/gal gasoline	Geologic formation, production technology

Source: Wu et al, 2008

Energy is becoming thirstier in the face of growing water constraints

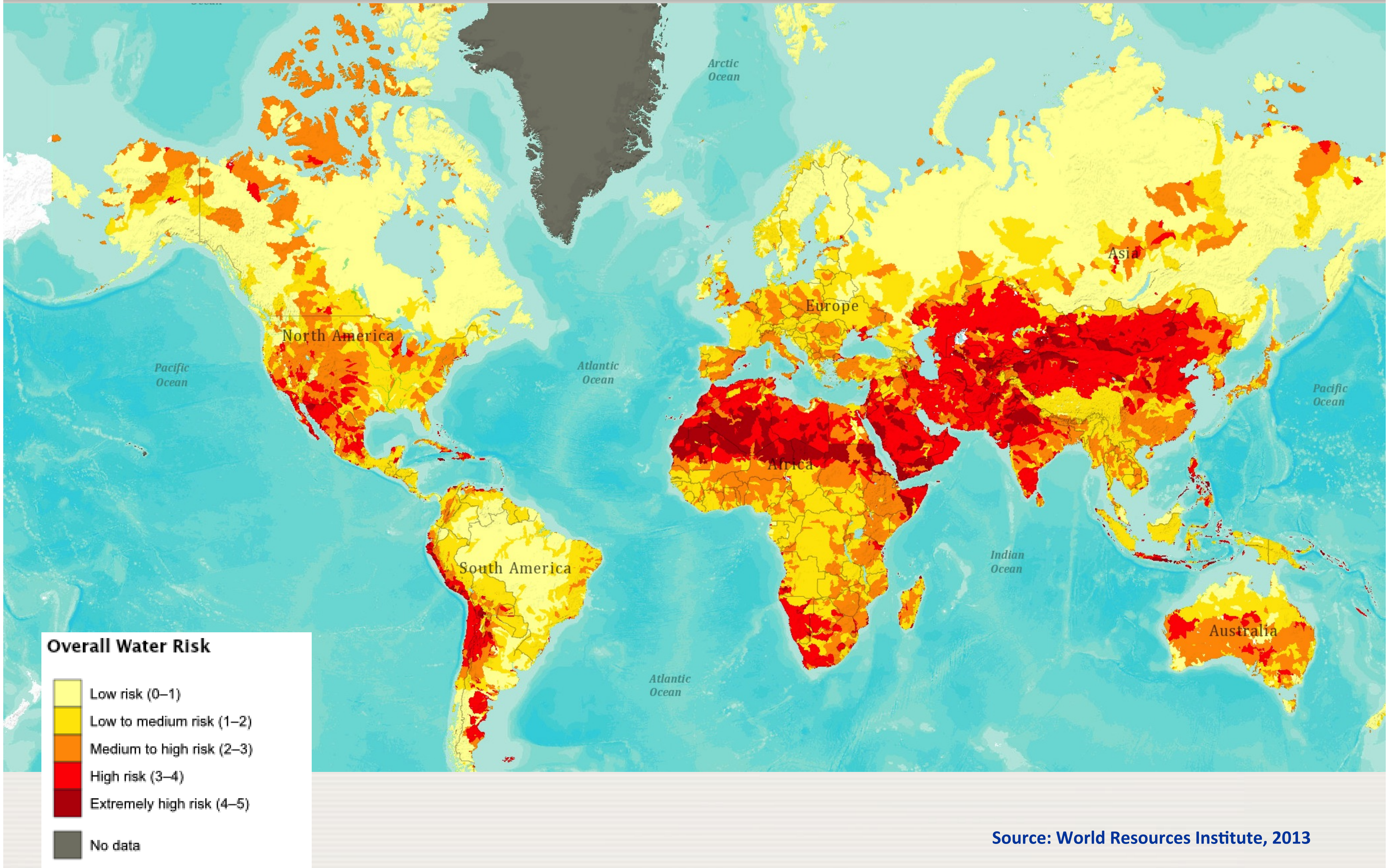




The energy sector's water needs are set to grow, making water an increasingly important criterion for assessing the viability of energy projects

Source: IEA, World Energy Outlook 2012

World water stress



Source: World Resources Institute, 2013

Water Resources and Scarcity

- The total volume of water on Earth is about 1.4 billion km^3 of which 97% is salt water, and of the remaining 3 per cent fresh water (~35 million km^3), some 70 per cent is frozen in the polar icecaps. (UNEP; U.S. Geological Survey, 2009)
- Less than 1 per cent of the world's fresh water is readily accessible for direct human uses. (U.S. Geological Survey, 2009)
- The global volume of stored groundwater is poorly known; estimates range from 15.3 to 60 million km^3. (4th UN World Water Development Report, 2012)
- Around 20 per cent of total water used globally is from groundwater sources (renewable or not), and this share is rising rapidly, particularly in dry areas. (Comprehensive Assessment of Water Management in Agriculture, 2007)
- Freshwater lakes and rivers contain an estimated 105 000 km^3 or around 0.3 percent of the world's freshwater

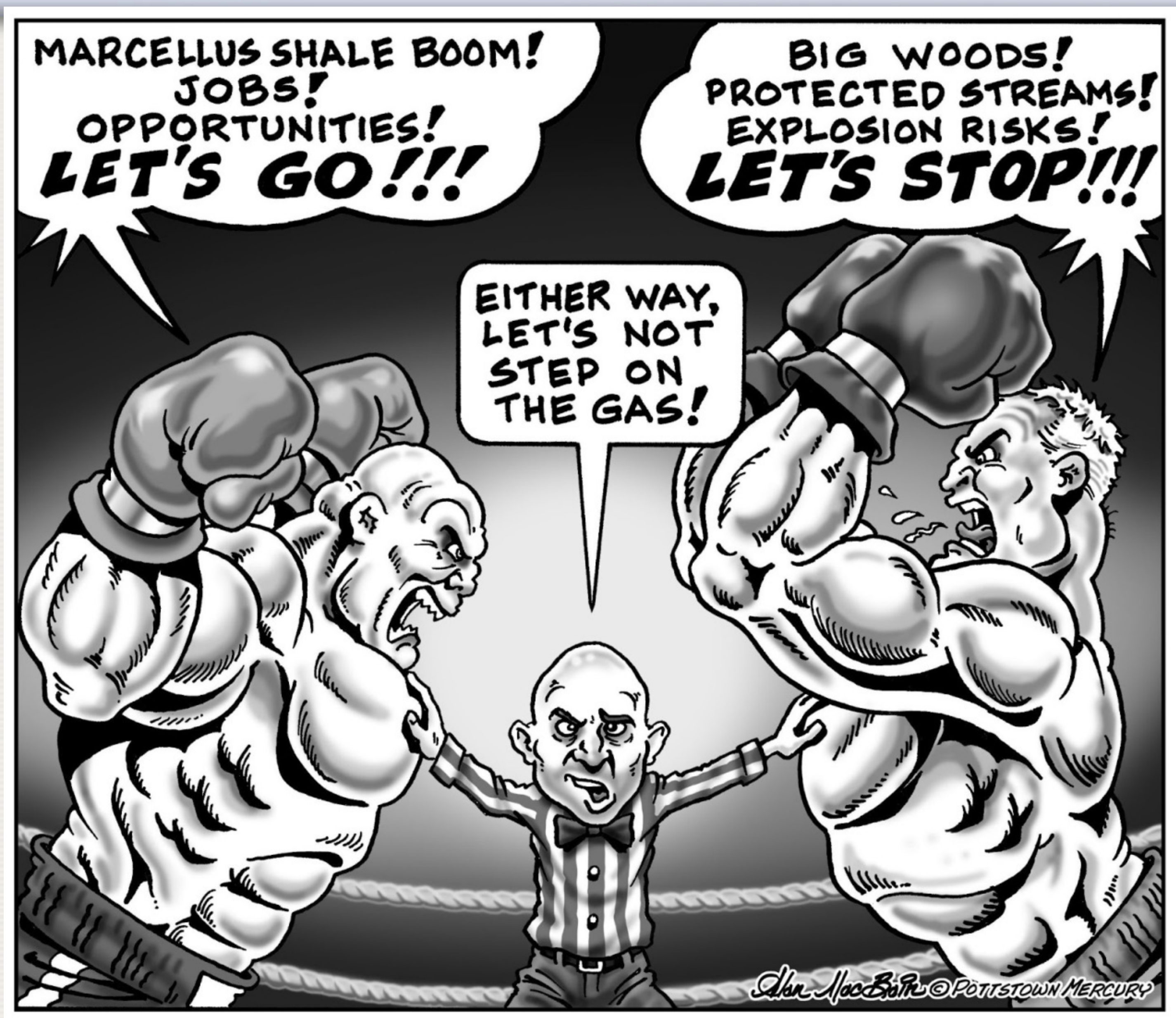
Water Resources and Scarcity

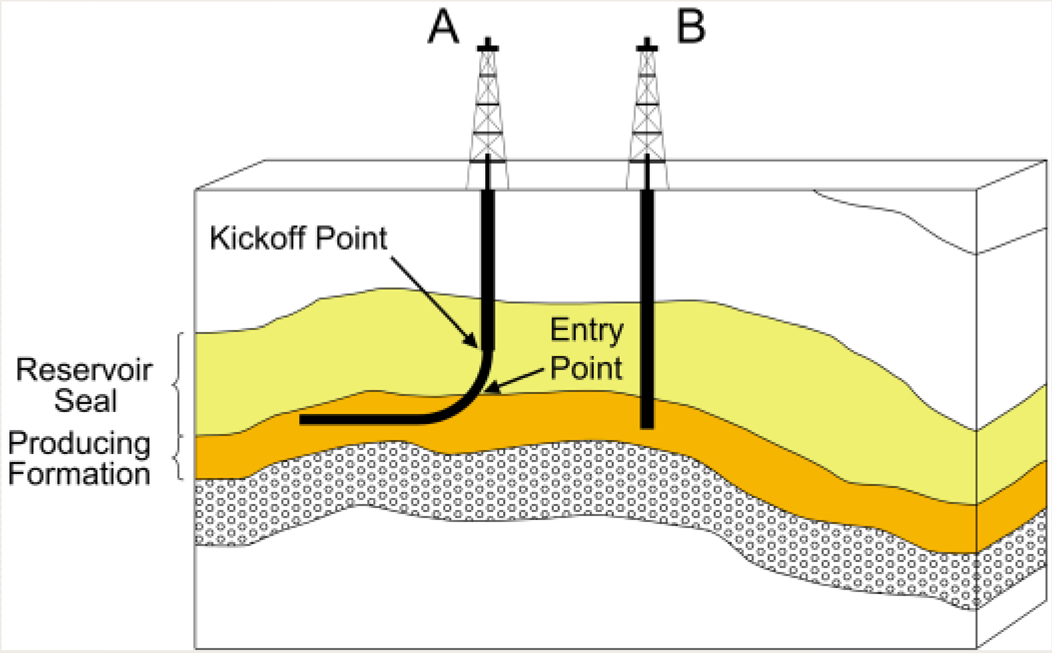
- **Global aggregated groundwater use: Irrigation 67 per cent, industry 11 per cent, domestic use 22 per cent.** **(4th UN World Water Development Report, 2012)**
- **Total global water withdrawals are about 4,300 km^3 per year**
- **Water withdrawals for energy production in 2010 are estimated at 583 km^3 or some 14% of the world's total water withdrawals.**
- **Energy related water consumption – the volume withdrawn but not returned to its source – was 66 km^3.**

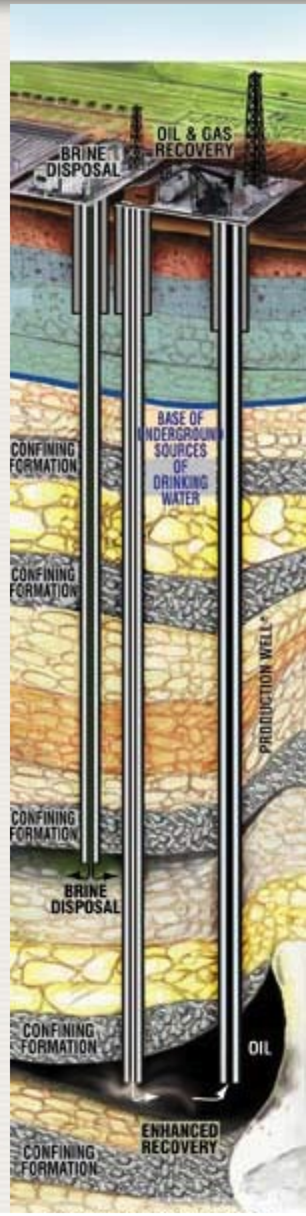
What to do now…

'Wonderful news, Prime Minister. They've found shale gas!'

The jury is still out……




A
B
Kickoff Point
Entry Point
Reservoir Seal
Producing Formation


BRINE DISPOSAL
OIL & GAS RECOVERY
BASE OF UNDERGROUND SOURCES OF DRINKING WATER
CONFINING FORMATION
CONFINING FORMATION
PRODUCTION WELL
CONFINING FORMATION
BRINE DISPOSAL
CONFINING FORMATION
OIL
ENHANCED RECOVERY
CONFINING FORMATION