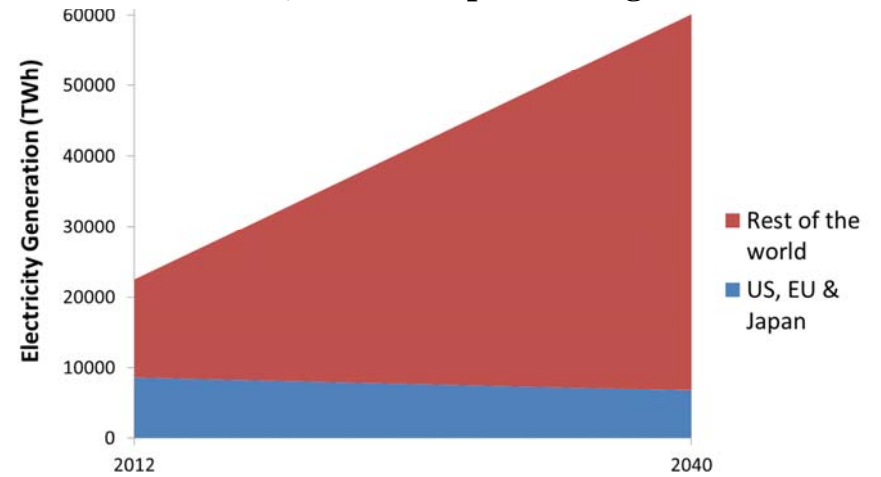


# Rethinking Nuclear

## Can We Change the World's Cumulative Carbon Emissions Soon Enough?

Joseph B. Lassiter, III  
 Senator John Heinz Professor of Management Practice  
 In Environmental Management  
 &  
 Faculty Chair, Harvard Innovation Lab  
 Harvard Business School  
 January 2015

### A Thought Experiment: Are Energy Efficiency & Renewables in the US, EU and Japan Enough?



Source: UN WPP 2012, EIA

Note: Following Hargraves (2012) presentation. Estimates require energy use per capita in 2040 to become approximately 50% of US levels in 2012 i.e. 6.65 MWh per person per year for the whole world.

## How “Safe” and “Secure” Are We in a Rapidly Changing World?

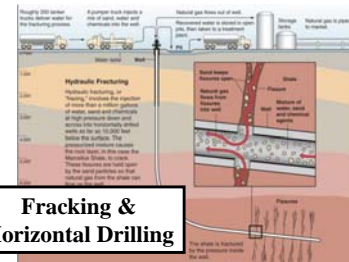
EU View of the Problem



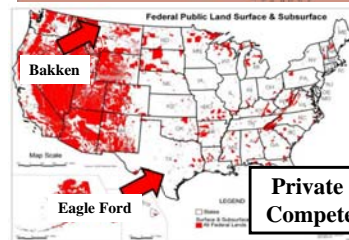
US View of the Problem



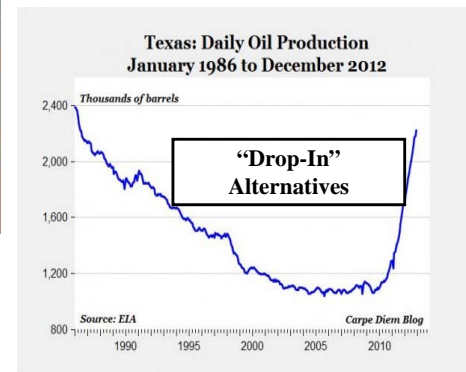
### Energy System Solutions Can Scale Rapidly When the Technology, Politics and Economics Are “Proven”



Fracking & Horizontal Drilling



Private Ownership & Competent Regulation

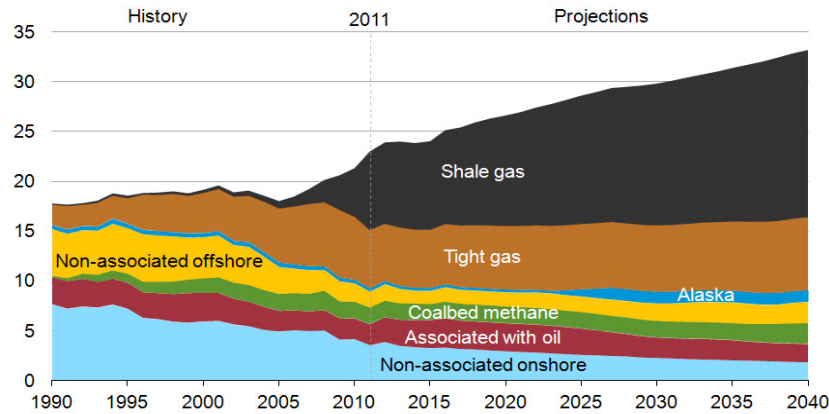


Source: EIA

Carpe Diem Blog

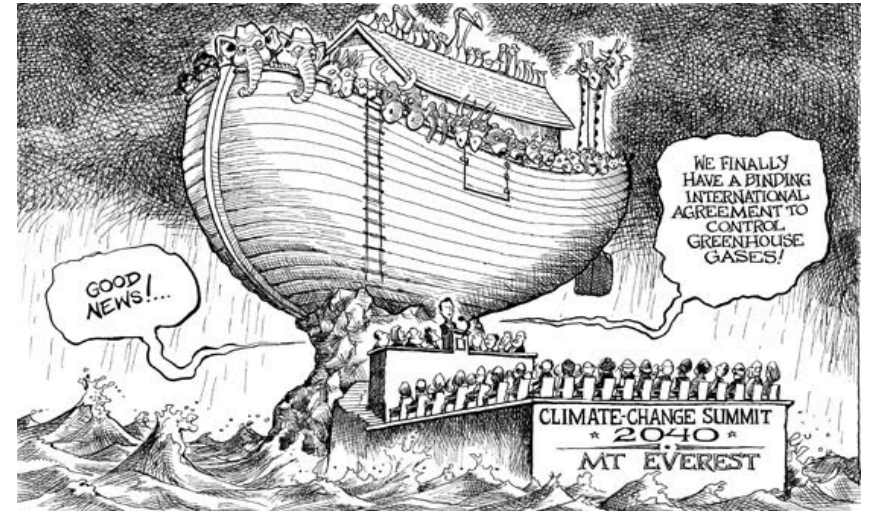
## Shale Gas Cuts CO2 Emissions More Than All Renewables Combined

U.S. dry natural gas production  
trillion cubic feet



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2013 Early Release*

## And, How **Can and Will** We Govern in a Rapidly Changing World?

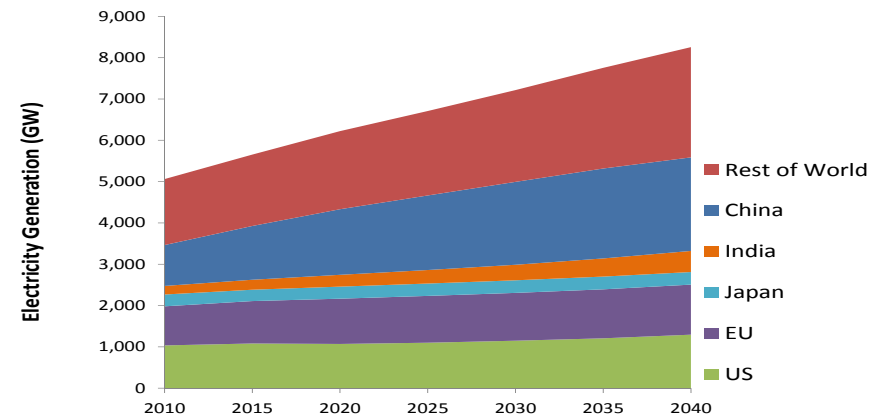


## So, What Do We Know?

It's tough to make predictions,  
especially about the future.

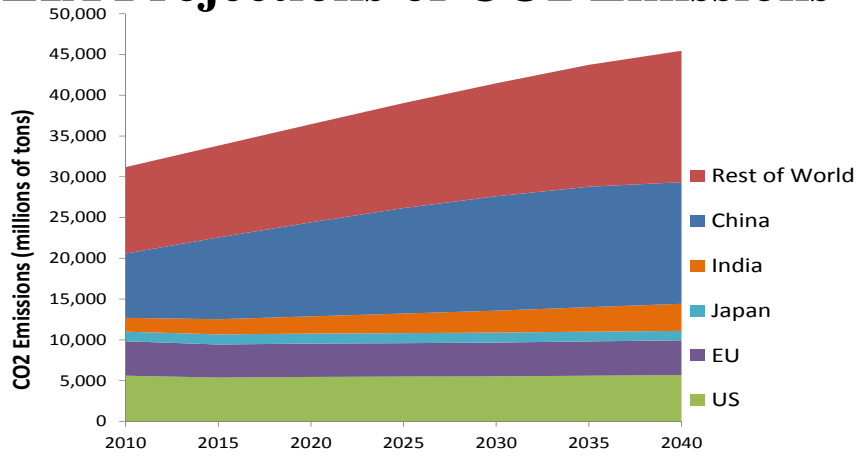
Yogi Berra

## EIA Projections of Energy Generation Capacity



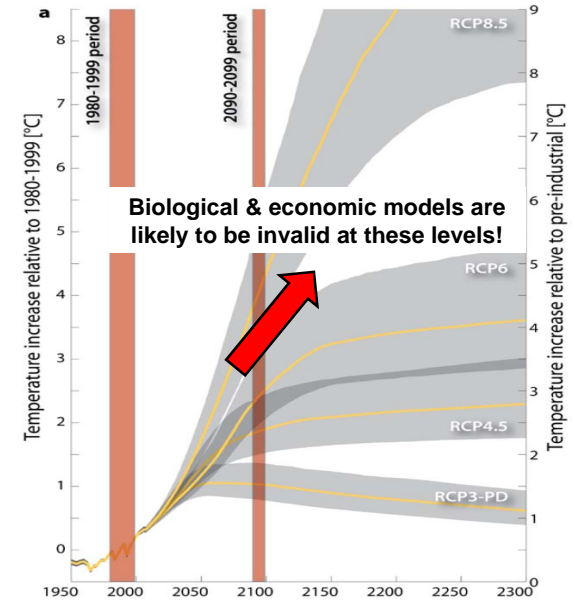
Source: EIA  
Note: 2010 reflects historical data, whereas 2015-2040 are EIA projections.

# EIA Projections of CO2 Emissions

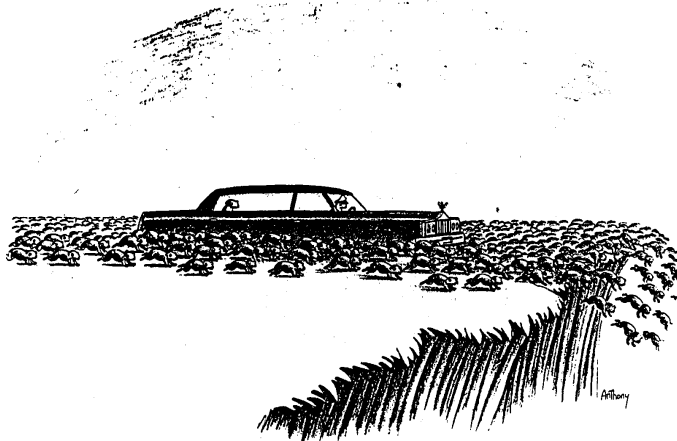


Source: EIA  
Note: 2010 reflects historical data, whereas 2015-2040 are EIA projections.

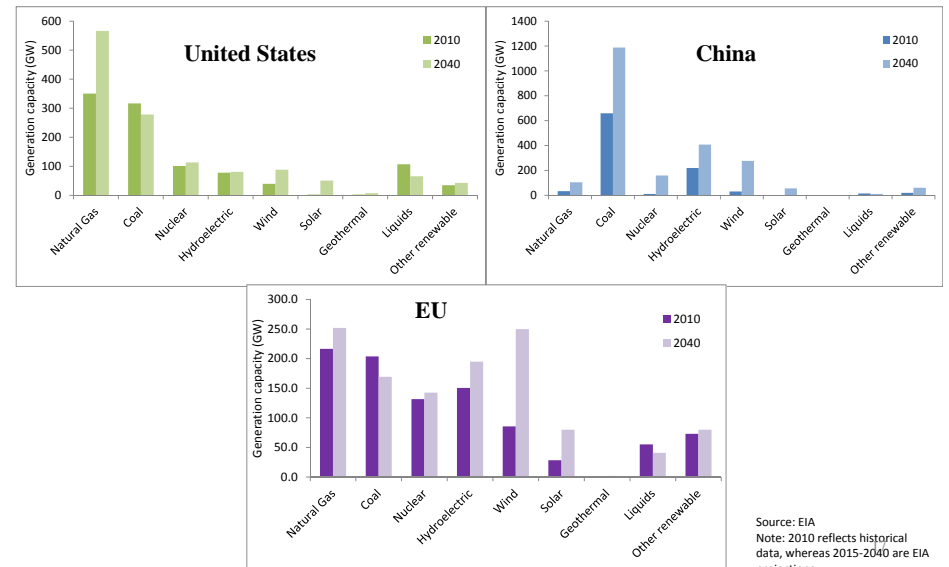
# Probabilistic Temperature Estimates for Magnitude and Timing of AR5 IPCC scenarios



Source: Rogelj, Meinshausen et al. 2012

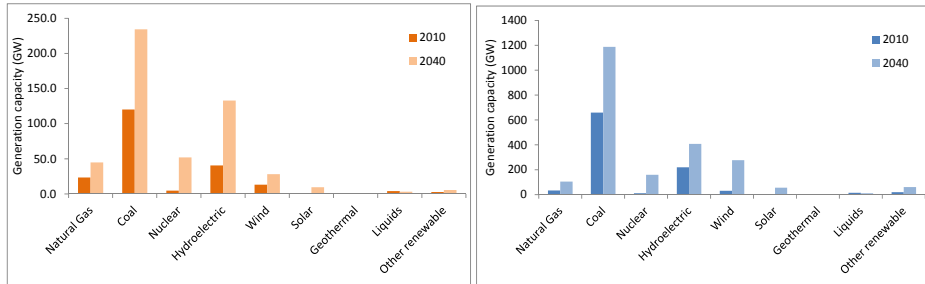


# Alternatives, Economics & the Choices of Nations



Source: EIA  
Note: 2010 reflects historical data, whereas 2015-2040 are EIA projections.

# EIA Projections Alternatives, Economics & the Choices of Nations

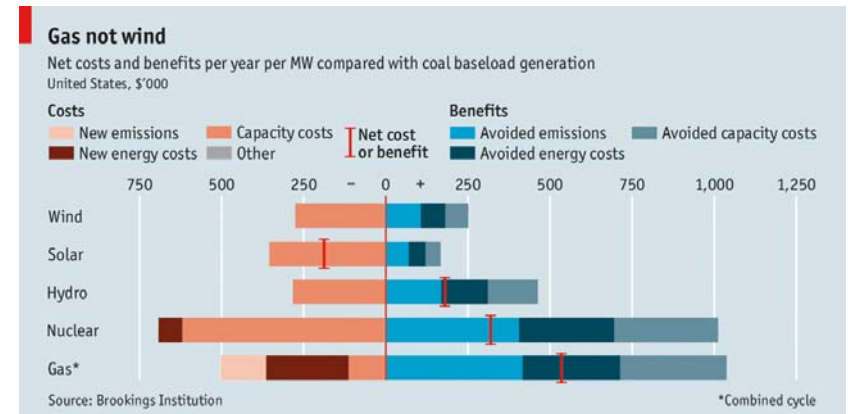


India

China

Source: EIA  
Note: 2010 reflects historical data, whereas 2015-2040 are EIA projections.

# The Net Benefits of Low and No-Carbon Electricity Technologies



"The Net Benefits of Low and No-carbon Electricity Technologies", by Charles Frank, Brookings Institution, May 2014

# The Net Benefits of Low and No-Carbon Electricity Technologies Updated September 2014

TOTAL NET BENEFITS	Wind	Solar	Hydro	Nuclear	Gas CC
Original Calculations	(\$25,333)	(\$188,820)	\$180,378	\$318,569	\$535,382
Recent Capacity Factors (1)	32,591	(161,941)	156,830	261,262	476,636
Higher Nuclear Costs (2)	32,591	(161,941)	156,830	80,138	476,636
Capacity Factor Variability (3)	(45,069)	(194,114)	156,830	80,138	476,636
Fugitive Emissions (4)	(44,188)	(193,359)	158,235	82,850	475,863

Alternative Energies Debate—All Things Considered on the Net Benefits of Low and No-Carbon Electricity Technologies,  
Charles Frank, Brookings Institute September 2014.

# The Legacy of Coal Mining, Burning and Waste

Coal Has Low-Level Radioactive Emissions

Table 12.1 Typical yearly radiation doses

Source	Radiation dose (mR/year)
Natural radiation	240
Natural in body*	29
Medical (average)	60
Nuclear plant (1 GW electric)	0.004
Coal plant (1 GW electric)	0.003

\*Included in the natural total for a 75 kg person.  
Source: National Council on Radiation Protection Report 160 (2009)

Coal Has Long-Term Ash Waste At Times with Leachable Heavy Metals



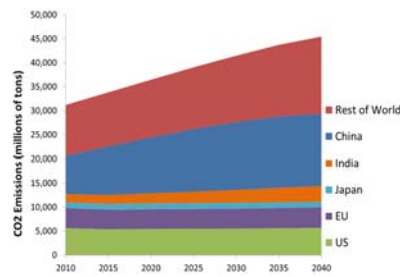
Sources: US Nuclear Regulatory Commission, World Health Organization and Wikipedia

# Nuclear Proliferation by Nation States and Terrorists Are Serious Issues Requiring International Management

Who Has the Social Stability to Manage Nuclear Powers Risks at Scale?

No Nuclear Weapons No Nuclear Power	No Nuclear Weapons Nuclear Power																								
160+ countries	<table border="0"> <tr><td>Argentina</td><td>Armenia</td><td>Belgium</td></tr> <tr><td>Brazil</td><td>Bulgaria</td><td>Canada</td></tr> <tr><td>Czech Republic</td><td>Finland</td><td>Germany</td></tr> <tr><td>Hungary</td><td>Iran</td><td>Japan</td></tr> <tr><td>Mexico</td><td>Netherlands</td><td>Romania</td></tr> <tr><td>Slovakia</td><td>Slovenia</td><td>South Africa</td></tr> <tr><td>South Korea</td><td>Spain</td><td>Sweden</td></tr> <tr><td>Switzerland</td><td>Taiwan</td><td>Ukraine</td></tr> </table>	Argentina	Armenia	Belgium	Brazil	Bulgaria	Canada	Czech Republic	Finland	Germany	Hungary	Iran	Japan	Mexico	Netherlands	Romania	Slovakia	Slovenia	South Africa	South Korea	Spain	Sweden	Switzerland	Taiwan	Ukraine
Argentina	Armenia	Belgium																							
Brazil	Bulgaria	Canada																							
Czech Republic	Finland	Germany																							
Hungary	Iran	Japan																							
Mexico	Netherlands	Romania																							
Slovakia	Slovenia	South Africa																							
South Korea	Spain	Sweden																							
Switzerland	Taiwan	Ukraine																							
Nuclear Weapons No Nuclear Power	Nuclear Weapons and Nuclear Power																								
<table border="0"> <tr><td>Israel</td></tr> <tr><td>North Korea</td></tr> </table>	Israel	North Korea	<table border="0"> <tr><td>China</td></tr> <tr><td>France</td></tr> <tr><td>India</td></tr> <tr><td>Pakistan</td></tr> <tr><td>Russia</td></tr> <tr><td>United Kingdom</td></tr> <tr><td>United States</td></tr> </table>	China	France	India	Pakistan	Russia	United Kingdom	United States															
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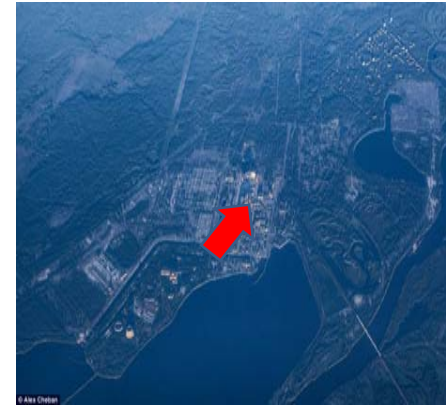
Who Has the "Competence" to Deploy Nuclear Power at Scale Soon Enough?



# The Legacy of Nuclear Three-Mile Island, Chernobyl and Fukushima

Chernobyl RMBK NPP Complex 1986- 2013

Partial Accounting of the Impacts

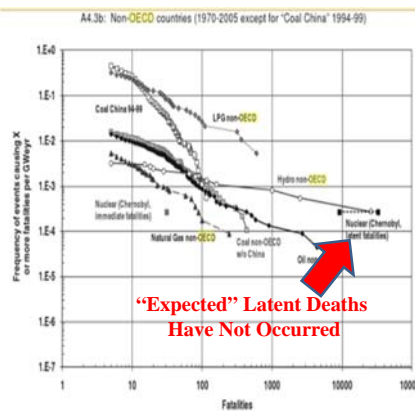


- 31 direct deaths and 106 severe radiation effects
- 15 deaths of children and adolescents from 6000 incremental cases of thyroid cancer due to I-131/Cs-137 in dairy products in FSU
- Evidence of learning impairment due to immediate to fetal exposure to I-131/Cs-137 as far away as Sweden
- Still limited evidence for longer-term evidence of leukemia and other cancers due to on-going, low-level radiological exposure
- About 20 mile radius isolated by regulators with 1000 sq mi still excluded, abandoned reactor complex and support city of Pripyat
- 350,000 people displaced and 200,000 workers received (1-100 REM doses vs 0.6 nominal)
- Direct economic loss estimated at US\$15 Billion - FSU governments estimated 30 year claims of US\$100s of Billions

Sources: US Nuclear Regulatory Commission, World Health Organization and Wikipedia

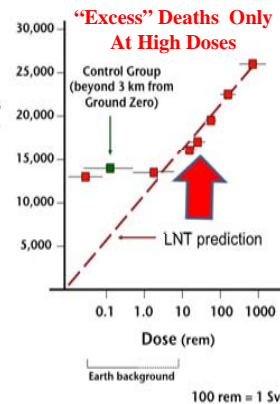
# The Legacy of Nuclear Low-Level Doses Have Not Proven Harmful, Damage Appears Largely DNA Repairable

1930's Radioactive Theory Has Led To 2010 Regulations That Cost Human Lives



Japanese Atomic Bomb Survivors

normalized per 100,000	dose range
13,748	> 3 km from Grd0
12,806	< 0.1 rem
13,494	0.5-10 rem
15,476	10-20 rem
16,752	20-50 rem
19,094	50-100 rem
23,949	100-200 rem
26,808	> 200 rem



Sources: OECD, ICRP

# There Are Tragic Casualties In Our Energy System, Even With Regulatory Oversight

PAUL SCHERRER INSTITUT  
FSI

The Energy Departments  
Laboratory for Energy Systems Analysis  
Technology Assessment

Severe accidents with at least 5 fatalities (1970-2005)

Energy chain	OECD		EU 27		non-OECD	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	81	2123	41	942	144	5360
Oil	174	3388	64	1236	308	17'990
Natural Gas	103	1204	33	337	61	1366
LPG	59	1875	20	559	61	2636
Hydro	1	14	1	116 (b)	12	30'007 (c)
Nuclear	—	—	—	—	1	31 (d)

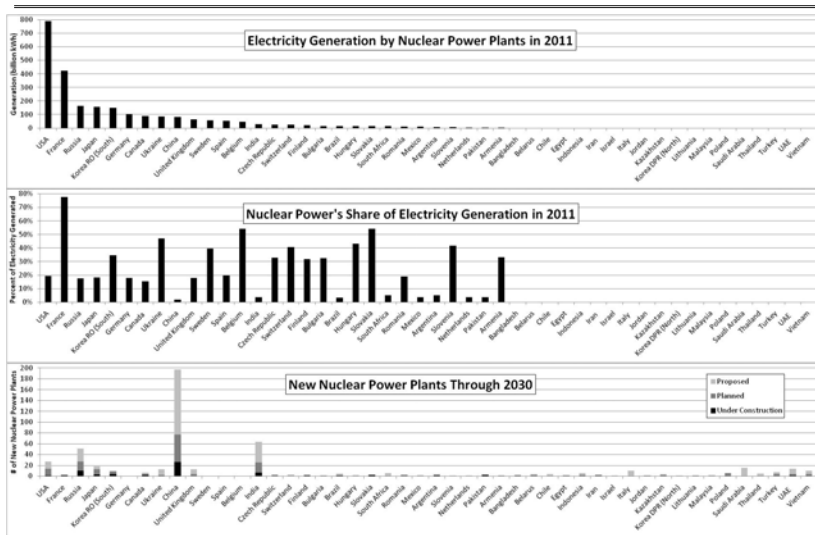
- (a) First line: coal non-OECD without China; second line: coal China  
 (b) Belci dam Romania (1991)  
 (c) Banqiao and Shimantan dam failures alone caused 26'000 fatalities  
 (d) Latent fatalities treated separately

Reported as 75 by Devaney (2013), Including 1 Death at Fukushima

Burgherr & Hirschberg, 2008

IDRC, 25 - 29 August 2008, Davos, Switzerland

## Electricity Generation by Nuclear Power Plants in 2011, and Proposed New Nuclear Reactors Through 2030, by Country



Source: Compiled by case writer. Data from <http://www.world-nuclear.org/info/reactors.html>, accessed October 2012.

## Key Criteria in NPP Design & Selection

- Safety (Likelihood & Nature of Radioactive Release)
- Cost (Relative to National Fuel Standard)
- Environment (Nuclear Waste)
- Proliferation Resistance (Uranium Bomb Making)
- Energy Security (Cut Off of Fuel & Service)
- Licensing (National Reactor Standard & Test Reactors)

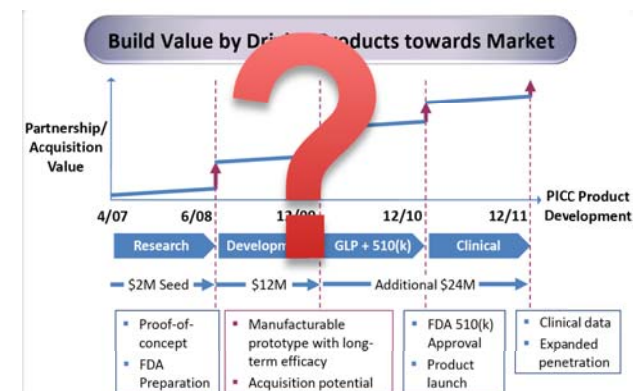
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## Licensing Constraints

- The US only licenses LWR derivatives
- In the US, you can't test without a license and you can't get a license without testing... unlike drugs or airplanes
- Other nations recognize "Test Reactors"
  - "The KLT-40S (Russia), the HTR-PM (China) and the CAREM (Argentina) were given permission to begin building by their national regulators under special provisions that allow demonstration plants to be built and initially operated. The ACP100 (US design) will be built in China by early 2016 under those same provisions. The timing for US reactor vendors to submit their design certification applications will depend in large part on customer commitments."
  - If the US wants to play a lead role in nuclear power innovation then they have to allow test reactors. The NRC has not done this in 40 years, they aren't likely to start to do it this year. We need Congress to define a way for the US to do test reactors. Perhaps under supervision of an appropriate national lab (ORNL for MSRs for example).
- Other nations even allow the sale of electricity from "Test Reactors" until or unless that the reactor fails to be licensed.

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## The Investor's Context... Staged Capital Supply Chain... Probably "Variants" of Biotech for "New Nuclear" Money-Time-Information-Value



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# FDA Approval Process

Stage	Elapsed Time (years)	Capital Required (\$ million USD)	Purpose and Objective	Market Value (\$million USD)	Historical Success (probability)
Pre-clinical	1 – 5	10 – 50	Pre-human validation	10 – 20	10%
Phase I	1 – 2	5 – 20	Safety	10 – 50	65%
Phase II	2 – 3	20 – 50	Efficacy and dose	50 – 100	50%
Phase III	3	40 – 100	Registration Trial	200 – 400	65%
New Drug Application	1	20 – 50	Manufacturing and FDA Approval	500 – 1000	90%

Ray Rothrock, Blue Ribbon Panel Testimony, August 2010

# A “New Nuclear” Approval Process

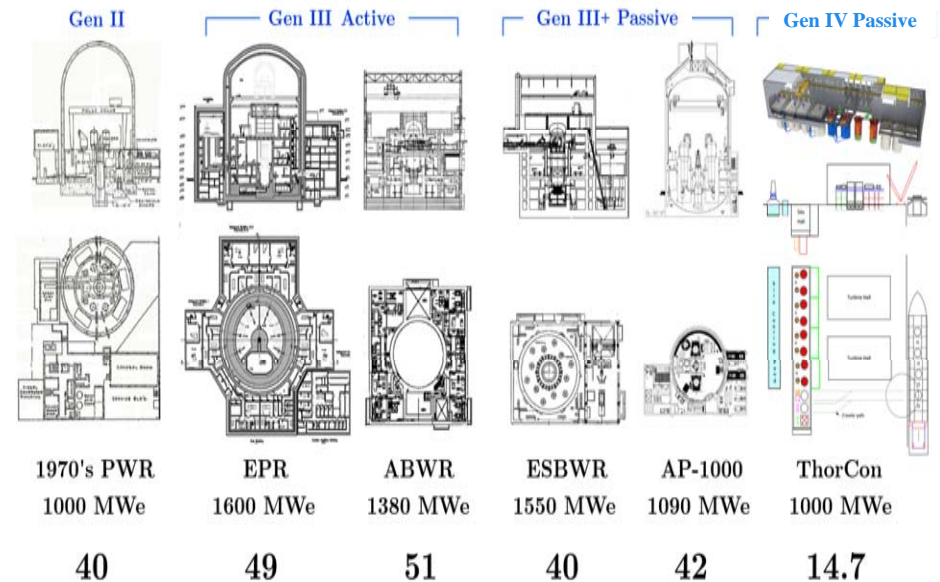
Discussion with Ray Rothrock

Stage	Elapsed Time (years)	Capital Required (\$ USD)	Purpose and Objective	Market Value (\$million USD)	Historical Success (probability)
<b>Science &amp; Economics</b>	1 – 3	<b>\$5-10M</b>	Economic and technical concept, computer simulation, critical materials or neutronics assessments		<b>1st Option to Abandon</b>
<b>Phase I Viability</b>	2 – 3	<b>\$10 – 150M</b>	Sub-critical pile to test neutronics, thermal hydraulics test Update economics, NRC prelim review.		
<b>Phase II Scalability</b>	2 – 5	<b>\$200 – 500M</b>	Build, characterize and test critical pile. NRC review.		
<b>Phase III Full Power</b>	2	<b>\$500M</b>	Small scale reactor for power. Produce steam only (at DOE facility), but full run and final modelling, economics, control, and training process. Full NRC approval	<b>1st Utility Evaluation</b>	<b>1st Option for Financial Exit</b>
<b>Approved NPP IPP</b>	<b>Total 5-7 yes</b>	<b>\$1B Including Licensing</b>	Site-Specific Licensing, Training & Supply-Chain Audit		

## Nuclear Entrants

	Gen III+ Passive LWRs	Gen IV Passive SFRs	Gen IV Passive MSRs
<b>Classic On-Site Construction</b>	Westinghouse AP-1000 Variants	TerraPower TWR	Site Excavation Only
<b>Factory Manufacture</b>	NuScale (Reactor Module Only)	GE-Prism (Reactor Module Only)	ThorCon / Transatomic (Whole Power Plant)
<b>Service &amp; Fueling</b>	Repair w/ Centralized Fuel Processing	Repair Limited Refueling & Little Waste	Upgrade & Repair w/ Centralized Fuel Processing
<b>Reactor Design Impact</b>	Hi P/ Lo T Water	Atm P/ Hi T Liquid Metal Sodium	Atm P/ Hi T Na/Be/Li Salts

## Metric Tonnes of Steel per MW of Electricity



# The Curse of Cost Escalation US vs French Reactor Costs

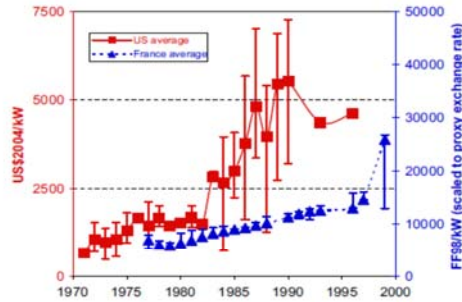


Fig. 12. Comparison of French (FF\$9/kW, this study) and US (US\$94/kW, Koomey and Hultman, 2007) nuclear construction costs, average and min/max per reactor completion year (year of entering into service in US, year of first criticality in France, cf. Fig. 9). The different metrics are scaled in proportion to yield an approximately correct exchange rate, but the customary caveats of technology cost comparisons across countries and different currencies apply (adopting alternative exchange rates might increase the French costs in US terms by <20%). In both data sets, average costs refer to the specific construction costs of all reactors completed in that particular year. Min/max values show the respective highest/lowest reactor in the US (therefore there are no uncertainty bands for those years where only a single reactor was completed) and the min/max - 2 uncertainty ranges for the inferred reactor specific cost data in France (see text for explanation).

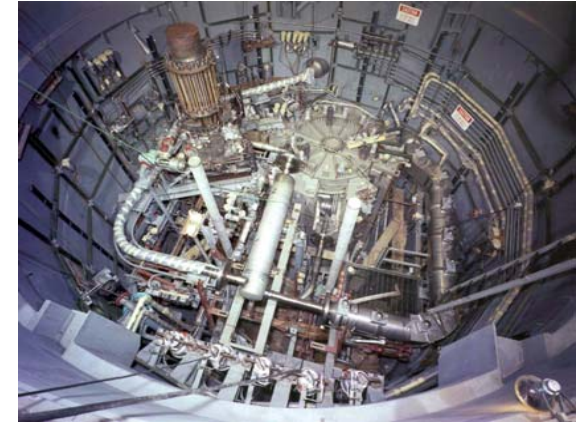
Gruber, Energy Policy 2010

## ThorCon is based on Oak Ridge Labs' proven nuclear power technology.

Uranium and Thorium in molten salt.

ThorCon redesign:  
- modular production  
- 50 years of science  
- modern materials  
- fast computers

Result:  
- rapid production  
- cheaper than coal



**Oak Ridge molten salt reactor ran from 1965 to 1969.**

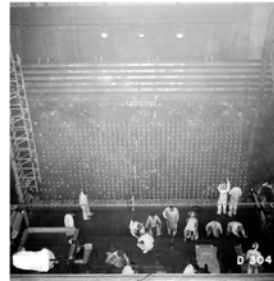
## A prototype nuclear power plant can be built quickly.



**Camp Century**  
Greenland glacier 77°N  
2 MWe  
American Locomotive  
factory modules  
1959 + 2 years



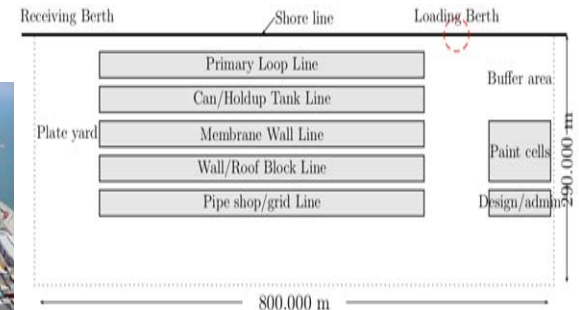
**Nautilus**  
First ever PWR  
10 MWe  
Electric Boat  
full scale prototype  
1949 + 4 + 2 years



**Hanford**  
Pu production  
250 MWt  
DuPont, GE  
1942 + 2 years

## Build everything on an assembly line

- Reactor yard produces 150--500 ton blocks. About 100 blocks per 1GWe plant.
- Blocks are pre-coated, pre-piped, pre-wired, pre-tested.
- Focus quality control at the block and sub-block level.
- Blocks barged to site, dropped into place, and welded together.



10 GWe/year yard block diagram; 200,000 tons steel per year

## “New Nuclear” Approval Process

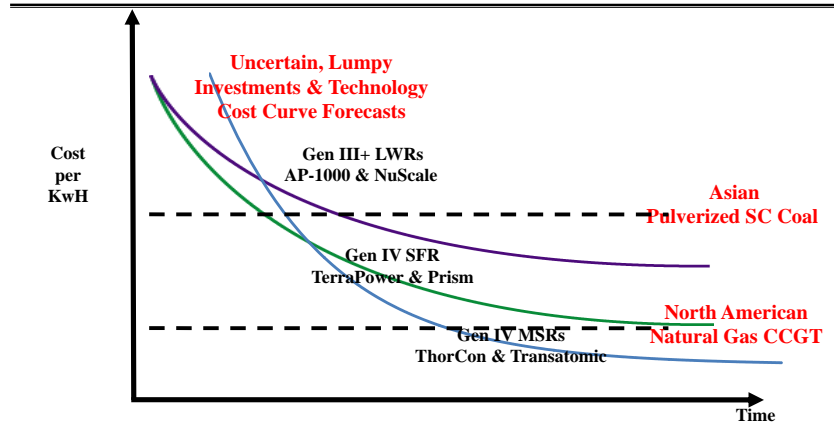
Discussion with Jack Devaney

Martingale’s ThorCon Reactor A Simple 250 MWe MSR Converter

“No New Technology” & “Physical Testing-Based-Development & Licensing”

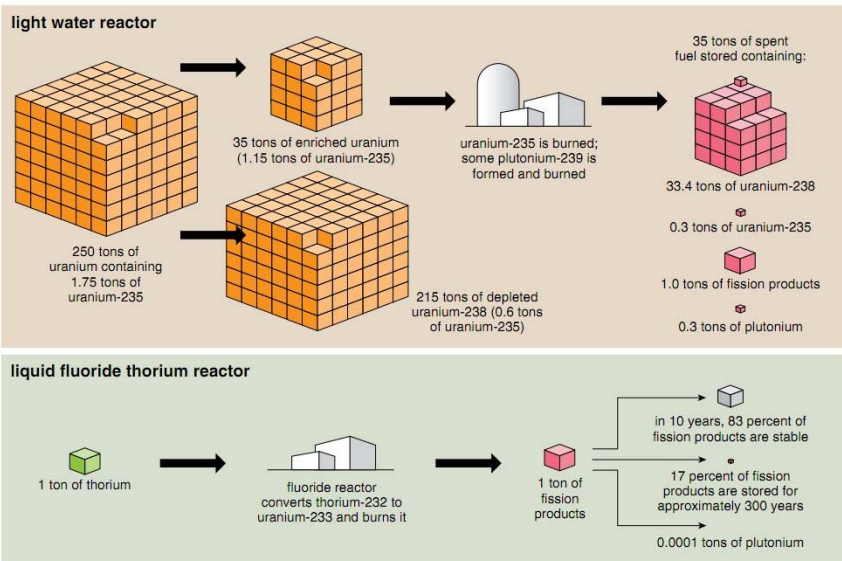
Stage	Elapsed Time (years)	Capital Required (\$ USD)	Purpose and Objective	Market Value (\$million USD)	Historical Success (probability)
“90%” @ Full-Scale Prototype Bidding & Vendor Selection	1	\$10M	Prepare Specs for Yard / Vendors , Get Quotes & Execute Selected Experiments. Raise Phase I Round		
Phase I Non-Nuclear “90%” @ Full-Scale Prototype	1 - Build 1- Non-Nuclear Test	\$50-100M	Build, commission, then full scale pre-nuclear tests, Confirm thermo-hydraulics, stresses at operating temperature, exercise instrumentation, safety, replacement systems. Approval of zero power tests. Raise Phase II Round		
Phase II Critical “100%” @ Full-Scale Prototype	1	\$100-150M	Ramp-Up by “Must Pass” Test Stages to Full Power then Characterization Approval of Design Basis Casualty Tests. Raise Phase III & IV Round		
Phase III “100%” FOAK Nuclear Plant w/ Steam Generator	1	\$50-\$100M	Staged Physical Testing of Design Basis Casualties , Training & Supply Chain Audit		
Approved NPP IPP	Total 4-5 yrs	\$250-350M <i>Supporting Licensing</i>	Site-specific Licensing 10GWe/yr Reactor Yard		

## The Entrepreneur's Context Probably a Variant of Strategic Technology Leapfrogging

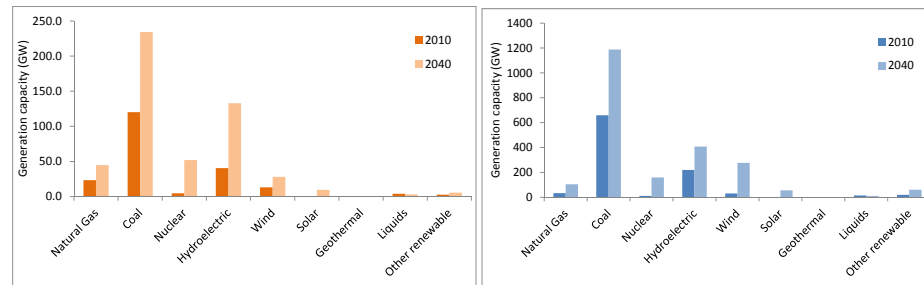


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## LWR Uranium v. LFTR Thorium



## EIA Projections Alternatives, Economics & the Choices of Nations



India

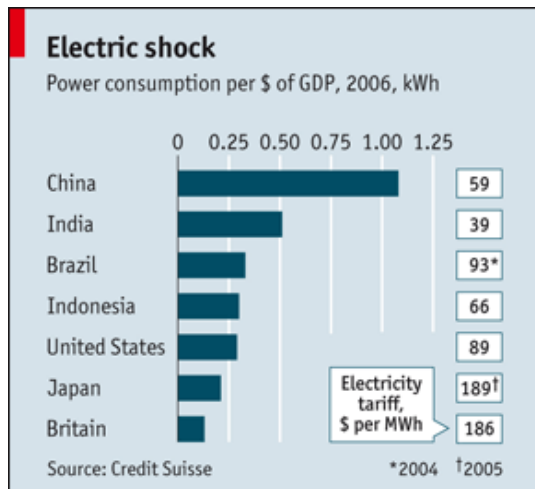
China

Source: EIA

Note: 2010 reflects historical data, whereas 2015-2040 are EIA projections.

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## Chindia Economic Growth Defines the Standards for Power Generation

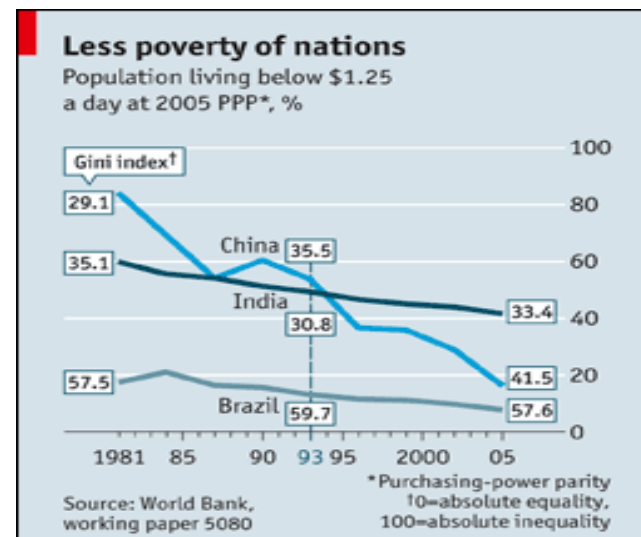


China's endless power-plant construction boom has accounted for 80% of the world's new generating capacity in recent years and will continue to do so for many years to come

**By 2020, China's goal is to build advanced reactors and advanced renewable power systems entirely by itself, and to export its prowess abroad. China subsidies focus on promoting Chinese manufacturing exports, not increasing domestic Chinese renewables usage.**

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## China Leads and India Follows in Reducing Poverty & Increasing Disparity



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## Premature Deaths, Air Pollution & the Choices of Nations

Chart 7: Premature deaths from all pollution, 2002

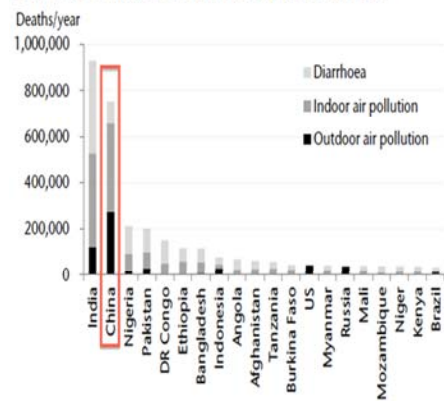
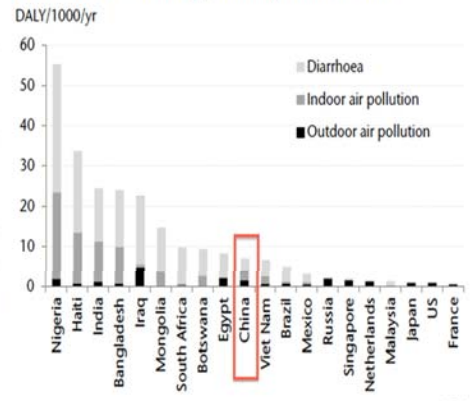


Chart 9: DALY caused by pollution, select nations



Source: Jeffries, <http://www.businessinsider.com/jefferies-chinas-epic-pollution-is-saving-lives-2013-1>  
Note: Uses WHO Public Health Statistics

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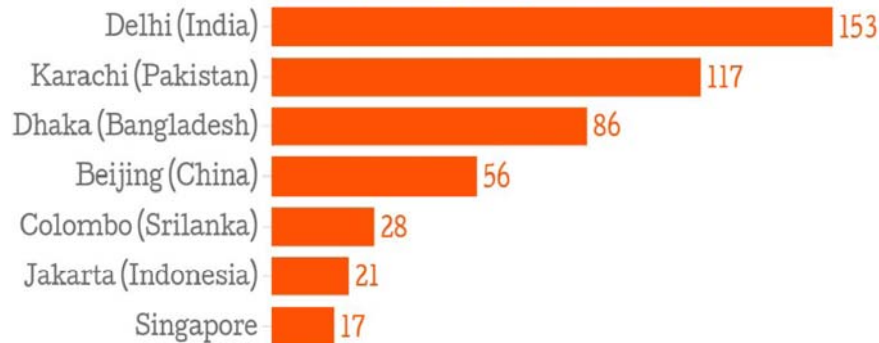
## World Health Organization 2012 Worst Twenty Cities for 2.5 PM Air Pollution

1. Delhi, India: 153
2. Patna, India: 149
3. Gwalior, India: 144
4. Raipur, India: 134
5. Karachi, Pakistan: 117
6. Peshawar, Pakistan: 111
7. Rawalpindi, Pakistan: 107
8. Khoramabad, Iran: 102
9. Ahmedabad, India: 100
10. Lucknow, India: 96
11. Firozabad, India: 96
12. Doha, Qatar: 93
13. Kanpur, India: 93
14. Amritsar, India: 92
15. Ludhiana, India: 91
16. Igdir, Turkey: 90
17. Narayonganj, Bangladesh: 89
18. Allahabad, India: 88
19. Khanna, India: 88
20. Agra, India: 88

45

## World Health Organization 2014 Comparison Across Asia

PM 2.5 (micrograms per cubic metre)

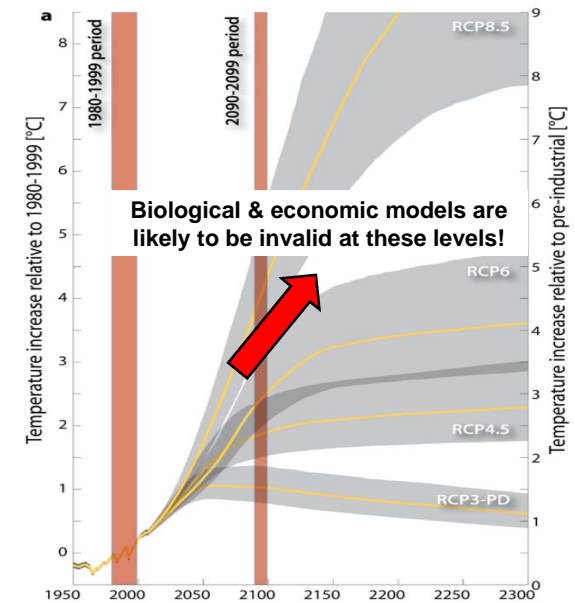


Scroll.in

Data: WHO Report 2014

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## Probabilistic Temperature Estimates for Magnitude and Timing of AR5 IPCC scenarios



Source: Rogelj, Meinshausen et al. 2012

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## So, What Do We Do Now?

When you come to a fork in the road, take it.

Yogi Berra

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## To Materially Change The World's Climate Future, Cleantech & "New" Energy Alternatives Must Be Cheaper Than Coal In China and In India

- The Chinese and India governments are committed to raising the standard of living in their countries to "Western per capita economic and public health standards"...
- The Chinese and Indian government actions say that the certain short-run benefits of low-cost coal energy are likely to offset the uncertain long-run costs of coal's climate change impacts to their citizens.
- The Chinese and perhaps Indian government actions say that they will build green supply chains if needed for export sales to Europe and North America while serving themselves and their ROW exports with brown supply chains. The Chinese and perhaps the Indian governments will clear up local pollution that impacts their own citizens directly even if that energy required for that clean-up increases their net CO2 emissions.
- The world will need to adapt to their choice...In my opinion, there is a material likelihood that our world is very already changed "forever" ..
- In my opinion, most of the "rich" will not materially feel these changes...But, many of the "poor" will materially suffer from these changes
- **In my opinion, we need to use "markets" to drive efficient, effective change by "fully-pricing" each unique source of energy to consumers, utilizing tax-revenue neutral escalating carbon taxes, catastrophe/remediation taxes and security-of-supply taxes, enforced with international border tariffs**
- **In my opinion, all nations should encourage the hunt for an "energy miracle" that can significantly impact Indian and Chinese energy choices and CO2 emissions as well as their own within 5-10 years ..No nation is in the lead.. It is an open game for the bold.... That "energy miracle" is probably \*new\* nuclear**
- In the end, in my opinion, we will all need to move to zero net carbon emissions as well as quite possibly supporting carbon dioxide removal and solar radiation management "miracles" in the next 10-20 years. And, we all need to prepare for adaptation to what quite possibly is an already very changed and rapidly changing world.

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## Where Do You Watch for the “Next” Black Swan?

**\*New\* Nuclear?  
Carbon Capture?  
Human Behavior & Energy Use?  
Biofuels?  
Batteries?  
Solar Microgrids?  
Carbon Trade Tariffs?  
Government “Supported” Cartels?  
Or, Something Totally Unknown?**

## Entrepreneurship

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- HBS Working Definition:

The relentless pursuit of opportunity  
beyond the constraints of the resources  
currently controlled

- A complete process for pursuing opportunity from  
identification to harvesting
- A way of managing

Howard Stevenson

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