Can Nuclear Energy Make a Major Contribution to Meeting the Climate-Change Challenge?

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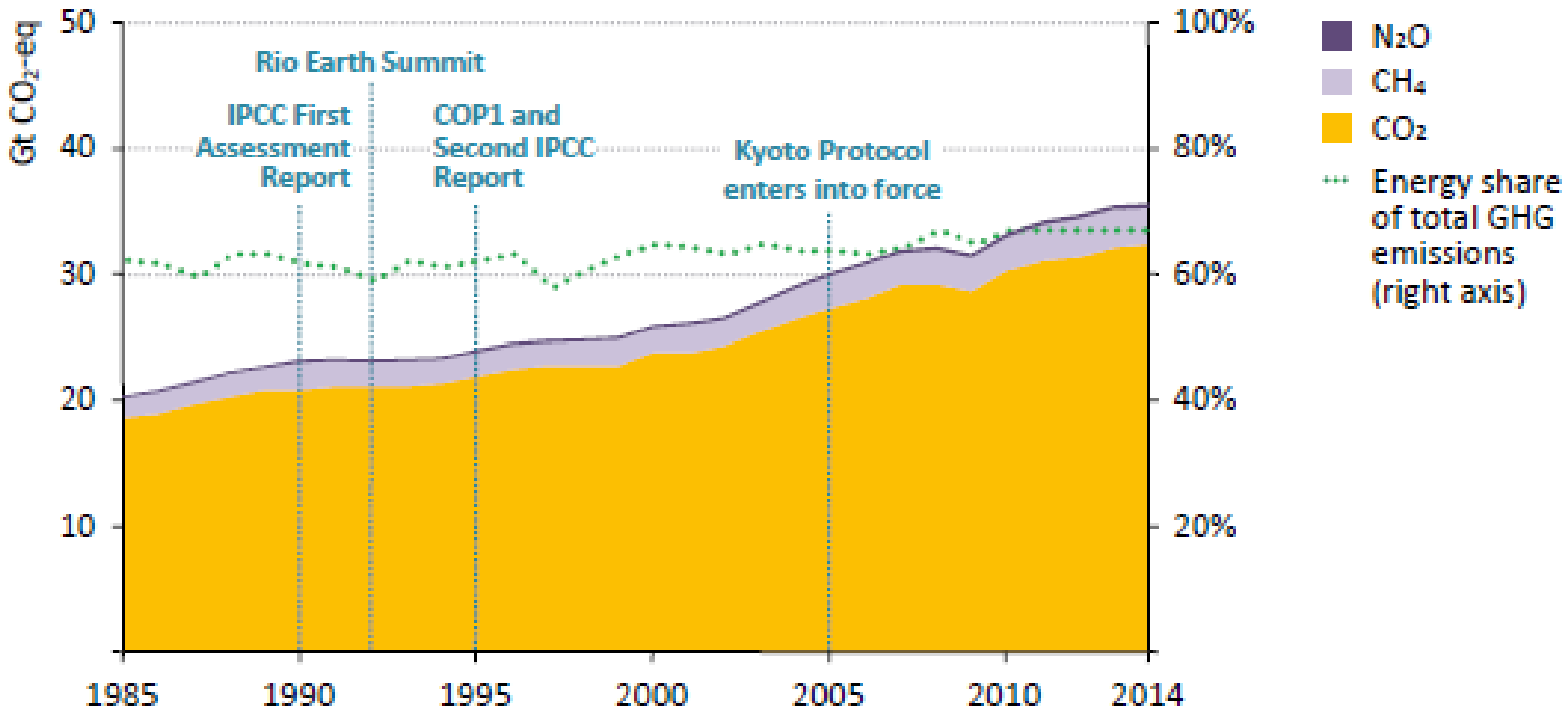
The Energy-Emissions Backdrop

Energy, economy, & CO_2 in 2015

	population (millions)	ppp-GDP (trillion $)	energy (EJ)	fossil E (percent)	fossil CO_2 (MtC)
World	7343	113.3	613	82%	9290
China	1371	19.4	139	84%	2570
USA	319	17.4	101	86%	1500
India	1311	7.9	39	74%	610
Russia	144	3.5	31	88%	420
Japan	127	4.9	20	92%	340

World Bank 2016, BP 2016

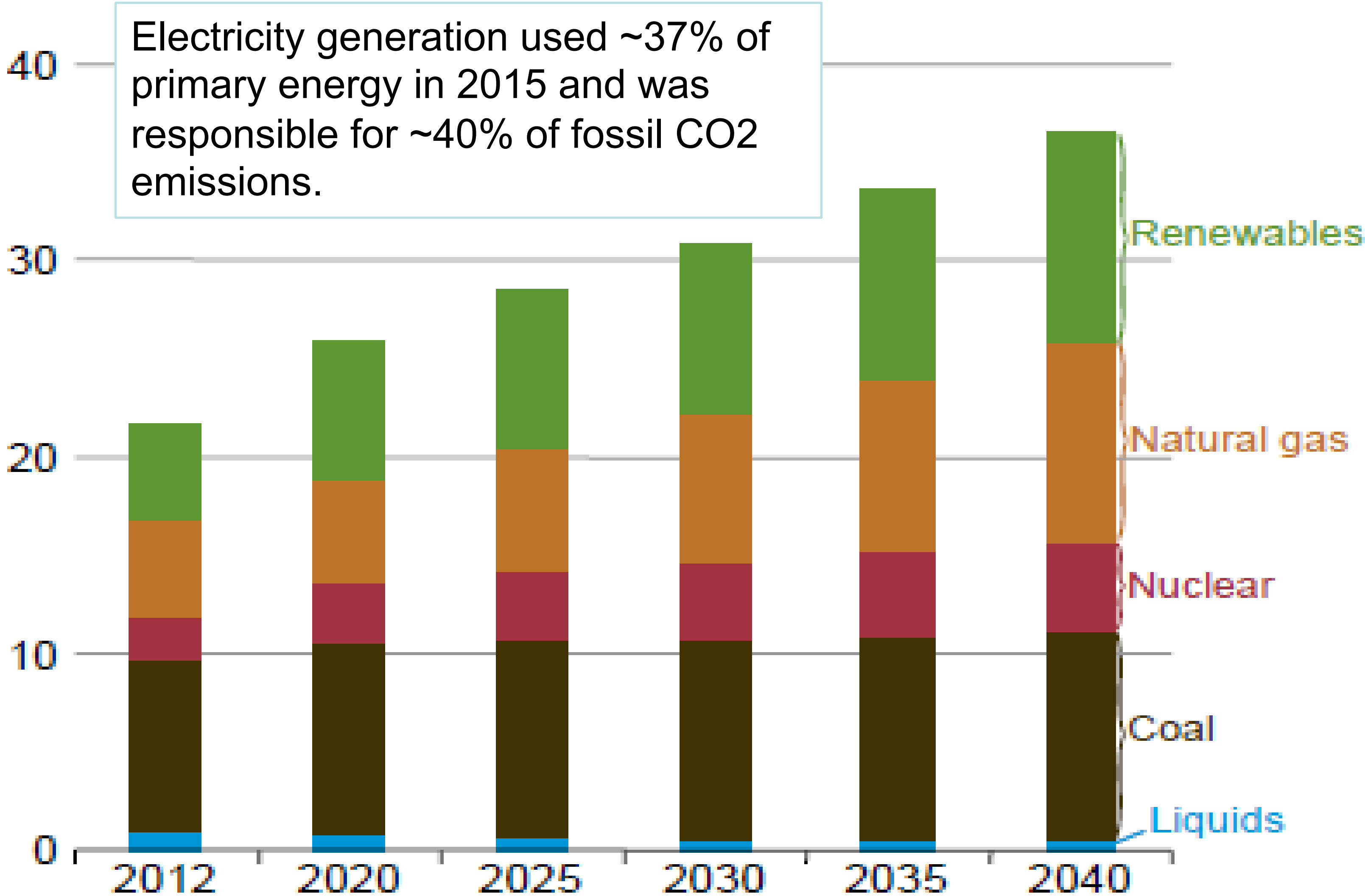
Global GHG emissions 1985-2014



The global energy system has accounted for 2/3 of global GHG emissions.

IEA World Energy Outlook Special Report, 2015

World electricity supply to 2040



Units are trillion kWh/yr

US EIA, World Energy Outlook 2016, Reference Case

Some realities about reducing emissions

- Stabilizing at 450 ppmv CO_2-e (50% chance of $\Delta T \leq 2°C$) means 2050 global CO_2 emissions must be at least ~7-9 GtC/yr below BAU (i.e., a cut of 50% or more from BAU).
- Ways to avoid 1 GtC/yr in 2050 include…

  - energy use in buildings cut 20-25% below BAU in 2050,

  - fuel economy of 2 billion cars ~60 mpg instead of 30,

  - carbon capture & storage for 800 1-GWe coal-burning power plants,

  -700 1-GWe nuclear plants replacing coal plants,

  -1 million 2-Mwe-peak wind turbines (or 2,000 1-Gwe-peak photovoltaic power plants) replacing coal power plants

Socolow & Pacala, 2004

How Much Could Nuclear Provide?

Current contribution of nuclear energy

WORLD

- 450 nuclear-fission power reactors* totaling 392 GWe of capacity in 29 countries generated 10.7% of world electricity in 2015 (down from 17% in 2000).
- 60 more reactors totaling 60 Gwe under construction in 15 countries will bring totals to ~500 reactors/~450 GWe.

UNITED STATES

- The 99 operating US power reactors have total capacity of 100 GWe and generated 19.7% of US electricity in 2016.
- As of November 2016, 4 more are under construction, totaling 4.5 Gwe.

* 350+ of the 450 reactors worldwide are light-water reactors (LWRs). The rest are mainly heavy-water reactors, gas-cooled reactors, and graphite-moderated light-water reactors.

Factors governing expandability of nuclear energy in the USA & worldwide

- Demand
  - economic growth, degree of electrification (esp transport), success of end-use efficiency improvements
  - ability of nuclear energy to deliver non-electric energy products (high-T process heat, hydrogen)
- Economics
  - cost of electricity, construction cost, risk premium, unit size (affects market size and investment “lumpiness”)
  - economics of competing sources
- Resource availability
  - uranium supply vs cost
  - effect on fuel-cycle choice and cost

Factors governing expandability in the USA & worldwide (continued)

- Safety & environment
  - comparison with alternatives in fact & perception
  - radioactive wastes, reactor safety *vs* air pollution, climate change, land use
- International security
  - energy dependence/independence
  - nuclear-weapon proliferation

Economics: Costs of nuclear vs fossil-fueled generation

Table 1.1 Costs of Electric Generation Alternatives

			LEVELIZED COST OF ELECTRICITY		
	OVERNIGHT COST	FUEL COST	BASE CASE	W/ CARBON CHARGE $25/TCO$_2$	W/ SAME COST OF CAPITAL
$2007	$/KW	$/MBTU	¢/KWH	¢/KWH	¢/KWH
Nuclear	4,000	0.67	8.4		6.6
Coal	2,300	2.60	6.2	8.3	
Gas	850	4/7/10	4.2/6.5/8.7	5.1/7.4/9.6	

MIT, Future of the Nuclear Fuel Cycle, 2010

- Carbon charges >>$25/tCO$_2$ highly likely by 2025
- Small modular reactors could drop unit cost, maybe COE

World uranium reserves & resources

kgU = kilogram of uranium; t = metric ton = 1,000 kg
RURR = remaining ultimately recoverable resources

Australian U Info Ctr (2002): RURR (<\$80/kgU) ~30 million t

Red Book (2009): RURR (<\$130/kgU) ~13 million t

MIT (2010): RURR (<\$260/kgU) ~100 million t

Extrapolation from US: RURR (<\$260/kgU) 60-180 million t

In a conventional light-water reactor (LWR) w once-through fuel cycle, 1 million t U yields 400 EJ = 13 TWy thermal energy = 4 TWy electricity = 36 trillion kWh electricity.

100 million t = 400 TWye; year 2100 with 3500 GWe is ~3.2 TWye/yr, so 100 Mt is 100+ years at this level.

Table 3.1 Alternative Reference Points for Nuclear Deployment in 2050 in GWe for Different Assumptions about Electricity Growth Rates and Nuclear Market Share[a]

	ALTERNATIVE AVERAGE ELECTRICITY GROWTH RATES 2000–2050 %		
NUCLEAR GENERATION MARKET SHARE %	1.5	2.0	2.5
17	650	838	1,060
20	770	970	1,235
25	880	1,235	1,545

a. We assume the global average capacity factor increases from 75% to 85%.

MIT, The Future of Nuclear Power, 2003

How much nuclear to get significant leverage in reducing CO_2 emissions?

- As another reference point in this vein, I calculated how much nuclear would be needed to double nuclear's share of world electricity from the 2000 figure of 17% to 33% by 2050, given business as usual electricity growth.
- The answer is ~1700 GWe of nuclear capacity in 2050, or roughly 1400 GWe more than existed in 2000.
- If these 1400 GWe of additional nuclear capacity all replaced what would otherwise have been coal-fired power plants lacking CO_2 capture, the avoided emissions would be 2 GtC/yr (C content of avoided CO_2).
- So this aggressive nuclear expansion goal yields 2 GtC/yr out of the 7-9 GtC/yr reduction from BAU that we need – an important contribution, but we'll also need renewables, CO_2 capture from fossil, and bigger efficiency increases.

Implications of nuclear at this scale

- Consider 1700 GWe of world nuclear capacity by 2050 (to make 1/3 of projected electricity and save 2 GtC/yr)
- If these were light-water reactors on the once-through fuel cycle, enrichment of their fuel would require ~250 million Separative Work Units (SWU).
  - Diversion of 0.1% of this enrichment to production of HEU from natural uranium would make ~20 gun-type or ~80 implosion-type bombs.
- If half the reactors were recycling their plutonium, the associated flow of separated, directly weapon-usable plutonium would be 170,000 kg per year.
  - Diversion of 0.1% of this quantity would make ~30 implosion-type bombs.
- Spent-fuel production in the once-through case would be 34,000 tonnes/yr. (Total production to date ~350,000 t.)

Safety and environment

- REACTOR SAFETY, in a world of 1,700 or more reactors, will probably be considered adequate if the probability of a major core-melt accident can be kept to the range of 10^{-6} per reactor per year. This is probably already achieved by the best current designs, at least absent deliberate attack/sabotage. Bolstering defenses against the latter may entail further effort.

- RADIOACTIVE WASTES must be shown to be manage-able without significant worker or public radiation exposure in the short to medium term, with the expectation of a problem-free permanent solution in the long term. This is surely achievable technically – relying on centralized engineered interim storage in the short to medium term – but public acceptance could remain challenging.

Proliferation

- PROLIFERATION RESISTANCE should be increased by a combination of technical and institutional means. In the short term, this will involve
  - avoiding use of highly enriched uranium,
  - minimizing horizontal proliferation of enrichment facilities by offering fuel on attractive terms (with take-back) & establishing fuel banks
  - minimizing inventories of separated plutonium (by minimizing reprocessing and maximizing disposition), and
  - improving protection and safeguards for all stocks of these materials.

  In the longer term, it might well require
  - foregoing plutonium recycle indefinitely (using, e.g., uranium from sea water and other very low-grade ores), <u>or</u>
  - developing recycle technologies that do not separate plutonium completely from fission products, <u>and/or</u>
  - placing all enrichment and reprocessing facilities in internationally operated and guarded complexes.

The Path Forward for Fission

2010 MIT Nuclear Fuel Cycle Study: Recommendations

Implementation of the first mover program of incentives should be accelerated for the purposes of demonstrating the costs of building new nuclear power plants in the U.S. under current conditions and, with good performance, eliminating the financial risk premium. This incentive program should not be extended beyond the first movers (first 7–10 plants) since we believe that nuclear energy should be able to compete on the open market as should other energy options.

For the next several decades, a once through fuel cycle using light water reactors (LWRs) is the preferred economic option for the U.S. and is likely to be the dominant feature of the nuclear energy system in the U.S. and elsewhere for much of this century. Improvements in light-water reactor designs to increase the efficiency of fuel resource utilization and reduce the cost of future reactor plants should be a principal research and development focus.

2010 MIT Nuclear Fuel Cycle Study: Recommendations (continued)

Planning for long term managed storage of spent nuclear fuel—for about a century—should be an integral part of nuclear fuel cycle design. While managed storage is believed to be safe for these periods, an R&D program should be devoted to confirm and extend the safe storage and transport period.

The possibility of storage for a century, which is longer than the anticipated operating lifetimes of nuclear reactors, suggests that the U.S. should move toward centralized SNF storage sites—starting with SNF from decommissioned reactor sites and in support of a long-term SNF management strategy.

We recommend an R&D program to improve existing repository options and develop alternative options with different technical, economic, geological isolation, and institutional characteristics.

2010 MIT Nuclear Fuel Cycle Study: Recommendations (continued)

The US and other nuclear supplier group countries should actively pursue fuel leasing options for countries with small nuclear programs, providing financial incentives for forgoing enrichment, technology cooperation for advanced reactors, spent fuel take back within the supplier's domestic framework for managing spent fuel, and the option for a fixed term renewable commitment to fuel leasing (perhaps ten years).

Integrated system studies and experiments on innovative reactor and fuel cycle options should be undertaken in the next several years to determine the viable technical options, define timelines of when decisions need to be made, and select a limited set of options as the basis for the path forward.

These are sound recommendations and track what the Obama Administration did.