Global Warming &
The Case for
Nuclear Power
Thermal Fission

- Slow neutron
- Fast neutron
- $^{235}$U
- $^{143}$Cs
- $^{90}$Rb
- Moderate $H_2O$ or $D_2O$
- $^{92}$Kr
- Fast Neutrons
- $^{235}$U
- $^{141}$Ba
Sunbathing on radioactive beaches
Guarapari, Brazil
The city of Pripyat in the Chernobyl zone
Chernobyl eco-system
Chernobyl

• 50 deaths
  – 31 radiation poisoning
  – 9 thyroid cancer
  – Rest from physical accidents (helicopter crash)

• 4000 deaths from cancer based on LNT model
  – Will be undetectable against background cancer rate (i.e., statistically equivalent to zero). Most doses are comparable to background doses.

• Greatest medical problems to survivors has been psychological not radiological.

• The eco-system is healthy and intact, although radioactive.
Chernobyl: the true scale of the accident

20 Years Later a UN Report Provides Definitive Answers and Ways to Repair Lives

As of mid-2005, however, fewer than 50 deaths had been directly attributed to radiation from the disaster, almost all being highly exposed rescue workers, many who died within months of the accident but others who died as late as 2004.

The estimated 4000 casualties may occur during the lifetime of about 600 000 people under consideration. As about quarter of them will eventually die from spontaneous cancer not caused by Chernobyl radiation, the radiation-induced increase of about 3% will be difficult to observe.

Alongside radiation-induced deaths and diseases, the report labels the mental health impact of Chernobyl as “the largest public health problem created by the accident” and partially attributes this damaging psychological impact to a lack of accurate information. These problems manifest as negative self-assessments of health, belief in a shortened life expectancy, lack of initiative, and dependency on assistance from the state.

Fukushima

• No deaths
• No projected deaths. WHO did not release such numbers. Increased cancer rates will be not detectable against the background cancer rate.
• Greatest medical problem for evacuees again is psychological not radiological
• Radiation released by Fukushima 1/5\textsuperscript{th} of Chernobyl. Presumably the eco-system is intact.
So Nuclear Power Is it safe?

Comparison of mortality rate from energy sources

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Mortality Rate (deaths/trillion kWhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>90</td>
</tr>
<tr>
<td>Hydro</td>
<td>1,400</td>
</tr>
<tr>
<td>Wind</td>
<td>150</td>
</tr>
<tr>
<td>Solar (rooftop)</td>
<td>440</td>
</tr>
<tr>
<td>Biofuel/Biomass</td>
<td>24,000</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>4,000</td>
</tr>
<tr>
<td>Oil</td>
<td>36,000</td>
</tr>
<tr>
<td>Coal-U.S.</td>
<td>15,000</td>
</tr>
<tr>
<td>Coal-China</td>
<td>280,000</td>
</tr>
<tr>
<td>Coal-global average</td>
<td>170,000</td>
</tr>
</tbody>
</table>

Data from: (Conca, 2012)
Future Fukushimas?

• Wheatley, Sovacool, & Sornette – 2015

• Probability of another Fukushima 50:50 in 50 years.

• They assumed GEN II reactors forever. If all reactors are replaced with GEN III+ (100 times safer), the probability of another Fukushima will be 50:50 in 5000 years.

• If Nuclear supplied all the world power (a factor of 20), then probability of another Fukushima is 50:50 in 5000÷20 = 250 years.
Future Fukushimas?

• In 40 years or less, more likely much less, GEN IV reactors will come on line. GEN IV reactors have no pressure vessels to blow up.

• The probability of a future Fukushima will then be zero
Open letter to policy makers
November 2013

• Hansen, Caldeira, Emanuel, and Wigley
• Asked all environmental policy makers to stop opposition to nuclear power
• Quantitative analyses show that the risks associated with the expanded use of nuclear energy are orders of magnitude smaller than the risks associated with fossil fuels.
• No energy system is without downsides. We ask only that energy system decisions be based on facts, and not on emotions and biases that do not apply to 21st century nuclear technology.
Open letter to policy makers

• While it may be theoretically possible to stabilize the climate without nuclear power, in the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power.
So why did they say this?

- For an 80% chance of **not** exceeding 2°C, global emissions must not exceed 565 Gt of CO$_2$
- (Gt = $10^9$ tonnes) (tonne = 1000 kg)
Consequences

- Permafrost melts, gases released
- Most of the world uninhabitable
- One-third of Bangladesh underwater
- Earth hotter than in 55 million years
- Mass extinction
- Up 5°C
- Up 6°C

Economics

- Global warming worse than
- Global GDP 20% lower
- Must invest 1% GDP
- Stern report
- Act now

War
- Famine
- Plague

Global nuclear war

Environmental refugees
- Environmental refugees
- Food shortages
- Amazon collapses
- Greenland melts
- Polar bears extinct
- Water supply affected

Predictions for 100 years
- Up 2°C
- Up 1°C
- Rare species extinct
- Coral reefs destroyed
- Island nations under water
- Increased earthquakes
- Extreme weather events

Heatwaves
- Oceans warming
- Arctic icecap melting
- Sea levels rising
So why did they say this?

- Bill McKibben “Global Warming's Terrifying New Math”
  *Rolling Stone* August 2, 2012
- For an 80% chance of not exceeding 2°C, global emissions must not exceed 565 Gt of CO₂
- (Gt = 10⁹ tonnes) (tonne = 1000 kg)
- In 2011 the world emitted 31.6 Gt of CO₂
- CO₂ emissions are climbing at about 3.2% per year.
- Do the math. That means we have 14 years emitting as we have been doing until our carbon budget is used up.
- That is by 2011 + 14 = 2025 !!!
## GHG Free Power

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Capacity factor (%)</th>
<th>Levelized Cost $/MWh</th>
<th>GHG emissions g(CO$_2$e)/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Nuclear</td>
<td>90</td>
<td>102.8</td>
<td>12</td>
</tr>
<tr>
<td>Geothermal</td>
<td>91</td>
<td>45.0</td>
<td>38</td>
</tr>
<tr>
<td>Advanced CCGT</td>
<td>87</td>
<td>57.2</td>
<td>490</td>
</tr>
<tr>
<td>Hydro</td>
<td>58</td>
<td>67.8</td>
<td>24</td>
</tr>
<tr>
<td>Wind</td>
<td>40</td>
<td>64.5</td>
<td>11</td>
</tr>
<tr>
<td>Wind - Offshore</td>
<td>45</td>
<td>158.1</td>
<td>12</td>
</tr>
<tr>
<td>Solar PV</td>
<td>25</td>
<td>84.7</td>
<td>48</td>
</tr>
<tr>
<td>Solar - Thermal</td>
<td>20</td>
<td>235.9</td>
<td>27</td>
</tr>
</tbody>
</table>

U.S. Energy Information Administration

GHG emissions from IPCC
First location, local

- Local only
- 40% renewable
- 60% CCGT
- $67/MWh
- 298 g\((\text{CO}_2e)/\text{kWh}\)

Second location

- Renewable
- Combined cycle gas turbine
- CCGT
- Transmission line

- Two locations
- 64% renewable
- 36% CCGT
- $87/MWh
- 190 g\((\text{CO}_2e)/\text{kWh}\)

- Three locations
- 78% renewables
- 22% CCGT
- $113/MWh
- 132 g\((\text{CO}_2e)/\text{kWh}\)
## Summary of Smart Grid

<table>
<thead>
<tr>
<th>No. of locations</th>
<th>% renewable</th>
<th>Cost $/MWh</th>
<th>GHG emissions g(CO$_2$e)/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.0</td>
<td>67.4</td>
<td>298</td>
</tr>
<tr>
<td>2</td>
<td>64.0</td>
<td>86.7</td>
<td>190</td>
</tr>
<tr>
<td>3</td>
<td>78.4</td>
<td>112.5</td>
<td>132</td>
</tr>
<tr>
<td>4</td>
<td>87.0</td>
<td>143.3</td>
<td>102</td>
</tr>
<tr>
<td>5</td>
<td>92.2</td>
<td>178.3</td>
<td>89</td>
</tr>
<tr>
<td>Advanced Nuclear</td>
<td>100.0</td>
<td>102.8</td>
<td>12</td>
</tr>
</tbody>
</table>
So What about Energy Storage?

40% renewable
45% batteries
15% CCGT
$176/MWh
107 g(CO$_2$e)/kWh

However
Batteries last only 8 years.
Over 40 years of a Wind Farm must be replaced 5 Times.

40% renewable
45% batteries
15% CCGT
$476/MWh
194 g(CO$_2$e)/kWh
## Summary of Renewables

<table>
<thead>
<tr>
<th>type</th>
<th>% renewable</th>
<th>Cost $/MWh</th>
<th>GHG emissions g(CO$_2e$)/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 station smart grid</td>
<td>78.4</td>
<td>112.5</td>
<td>114</td>
</tr>
<tr>
<td>300% infrastructure with batteries</td>
<td>85.0</td>
<td>176.4</td>
<td>107</td>
</tr>
<tr>
<td>same with battery replacement</td>
<td>80.0</td>
<td>476.4</td>
<td>194</td>
</tr>
<tr>
<td>Advanced Nuclear</td>
<td>100.0</td>
<td>102.8</td>
<td>12</td>
</tr>
</tbody>
</table>
Tom Murphy, physicist, UCSD
“Do the Math”

• The current mineral reserves of the entire planet for crucial elements like Lead and Lithium, necessary for the construction of batteries, will only supply <10% of the U.S. requirement for energy storage.

• The geological capacity of the U.S. can only supply <10% of the necessary pumped storage for U.S. requirements. This result should be the same for the world as a whole.

• All schemes for energy storage prove to be woefully inadequate when putting in the numbers to scale them up to the capacity that will be required. It will require a miracle in energy storage technology and none is currently on the time horizon.
So

- Non-dispatchable renewables cannot supply 100% of the power 100% of the time.
- Need dispatchable GHG emissions free power to cover the down time
- What choices are there?

- Hydro: Geographically limited
- Geothermal: Geographically limited
- Biomass: Competes with food and arable land and has air pollution
- Advanced Nuclear: There are no other choices
Nuclear Checklist

• Is it safe? ✓
• Is it economical? ✓
• Is it green? ✓
• What about nuclear waste? ... Not yet
Nuclear Waste Problem?

• Deep underground repositories in geological secure sites is an adequate solution.
• Yucca Mountain repository in Nevada for the U.S. waste was closed for political reasons not for technical reasons
• The world’s waste can be stored in areas the size of a couple of football fields.
Nuclear Waste Problem?

• Burn it!
Is It Abundant?

Distribution of Uranium in the Earth’s Crust

- Namibia 100 ppm
- The ratio between amount of high grade ore and low grade ore is ~100:1
- Cost of nuclear fuel mostly in the enrichment process
Is It Abundant?

They are referring to this figure

- Assume that nuclear instantaneously produced all the energy now produced by fossil fuels and nuclear
- There is enough high quality ore to last 5.2 years
- There is enough low quality ore to last 520 years
- If breeder reactors come on line there is enough fuel to last 300,000 years.
Nuclear Checklist

• Is it safe? ✔
• Is it economical? ✔
• Is it green? ✔
• What about nuclear waste? ... ✗
• Is it plentiful? ✔
Therefore, in order to make the human species use 100% renewable energies we would need:

A small percentage of these technologies are already in place.

1.7 billion
roof photovoltaic systems
(3-kW each)

3.8 million
wind turbines
(5-MW each)
50%

490,000
tidal turbines
(1-MW each)
1%
EROI

• Energy Return on Investment

\[
EROI = \frac{E_{out}}{E_{in}}
\]

EROI for U.S. Oil

data from Hall et al.
A Typical Gen IV Reactor

**Dual Fluid Reactor**

- **Photovoltaics**: 1.3
- **Biomass**: 3.5
- **Wind**: 3.9
- **Natural gas**: 28
- **Coal**: 30
- **Hydro power**: 35
- **Nuclear today**: 75

EROI
Nuclear energy is the only energy system where the EROI is increasing!
Conclusions

• We must transition from a fossil fuel economy to a greenhouse gas (GHG) emissions free economy as soon as possible.

• Modern nuclear technology exists and is ready to be implemented now.

• There is no credible path to climate stabilization that does not include a substantial role for nuclear power.

• Nuclear power is one of the safest, most economical, plentiful, and greenest sources of energy available.
Conclusions

• To mitigate global climate change we do not have the luxury of a priori eliminating one of the most potent GHG emissions free technology which has already been proven to do so.

The Case For Nuclear Power
If you want to know more

Google

Canada

pwalden
Fukushima Doses

IN THE ZONE

Most residents and nuclear workers in the Fukushima region received modest radiation doses from the power-plant meltdown, and in April the Japanese government lifted some restrictions on citizens’ access to their homes. But residents of Iitate and Namie may have received higher doses.

10–50 mSv
Estimated effective dose to evacuees after one year

Estimated effective doses after one year:

1–10 mSv
0.1–10 mSv
0.1–1 mSv

FUKUSHIMA PLANT–WORKER DOSES

- = 10 workers who received:
  - <10 mSv
  - 10–20 mSv (= a single full-body CT scan)
  - 20–50 mSv (= annual exposure limit for nuclear workers)
  - 50–100 mSv
  - 100–150 mSv (= slight increase in cancer risk)
  - 150–200 mSv
  - 200–250 mSv (= maximum allowed dose for emergency workers)
  - >250 mSv

mSv = millisievert
Radiation Risks

Cancer risk ~0.5%

1 Sv = 1 Joule/kg

Limits

TRIUMF continuous occupation
1 μSv/hr

TRIUMF yearly dose
10 mSv/y => 1.14 μSv/hr

Radiation Worker yearly dose
20 or 50 mSv/y

Dental Xray 0.15 mSv

Background ~4 mSv/y

CT scan 10 mSv

Radiation poisoning
First symptoms 400 mSv

Severe radiation poisoning
2 Sv

Death 4Sv or more
Brazil vs. Chernobyl

110 μSv

vs.

100 μSv

Brazil

500 μSv ± 20%

400 μSv

100 μSv

300 μSv

240 μSv

2d

18.25 mSv/y

43.8 mSv/y
A dark lining in a silver cloud
Is it safe?

16 years/TWh for nuclear due to estimates from LNT model
Is it safe?

Presumably no LNT estimates in this projection
Is it Green?
Is it Green?

Table A.II.4 | Aggregated results of literature review of LCAs of GHG emissions from electricity generation technologies as displayed in Figure 9.8 (g CO₂eq/kWh).

<table>
<thead>
<tr>
<th>Values</th>
<th>Bio-power</th>
<th>Solar</th>
<th>Geothermal Energy</th>
<th>Hydropower</th>
<th>Ocean Energy</th>
<th>Wind Energy</th>
<th>Nuclear Energy</th>
<th>Natural Gas</th>
<th>Oil</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>-633</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>290</td>
<td>510</td>
</tr>
<tr>
<td>25th percentile</td>
<td>360</td>
<td>29</td>
<td>14</td>
<td>20</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>422</td>
<td>722</td>
</tr>
<tr>
<td>50th percentile</td>
<td>18</td>
<td>46</td>
<td>22</td>
<td>45</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>469</td>
<td>840</td>
</tr>
<tr>
<td>75th percentile</td>
<td>37</td>
<td>80</td>
<td>32</td>
<td>57</td>
<td>7</td>
<td>9</td>
<td>20</td>
<td>45</td>
<td>548</td>
<td>907</td>
</tr>
<tr>
<td>Maximum</td>
<td>75</td>
<td>217</td>
<td>89</td>
<td>79</td>
<td>43</td>
<td>23</td>
<td>81</td>
<td>220</td>
<td>930</td>
<td>1170</td>
</tr>
<tr>
<td>CCS min</td>
<td>-1368</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>65</td>
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<tr>
<td>CCS max</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>245</td>
<td></td>
</tr>
</tbody>
</table>

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

From the IPCC Special Report on Renewable Energy Sources
Water Problems?

Dry cooling
i.e., like a car radiator

Wet cooling
i.e., cooling towers

Water use by power plants:

- Wind
- Solar thermal with dry cooling
- Solar photovoltaic
- Natural gas
- Nuclear
- Coal
- Solar thermal with wet cooling

- 0 gallons
- 26 gallons
- 26 gallons
- 198 gallons
- 672 gallons
- 687 gallons
- 786 gallons

Water consumed to produce one megawatt-hour of electricity, which is enough to power 1,000 homes for an hour.
Water Problems?

• Once through cooling.
  – Uses a tremendous amount of water
  – Ocean water: Diablo Canyon 2.2 GW, California

• Evaporative cooling.
  – Sewage water: Palo Verde 3.3 GW, Arizona (desert)
  – Largest nuclear station in U.S.

• Closed cooling like a car radiator
  – None yet.

• Liquid sodium cooling, molten salt cooling
  – Higher temperature, more efficient less cooling
  – Air turbines like a jet engine.
Fast Fission

fast neutron

Fast neutrons

$^{233}\text{U}$

$^{141}\text{Cs}$

Fast Neutrons

$^{233}\text{U}$

$^{232}\text{Th}$

$^{90}\text{Kr}$

$^{139}\text{Ba}$
Fertile to Fissile

Formation de l'uranium-233

Thorium-232 (90 p - 142 n) + Neutron → Thorium-233 (90 p - 143 n) → Protactinium-233 (91 p - 142 n) → 22 minutes → β⁻ → Uranium-233 (92 p - 141 n) → 27 jours → β⁻

Formation du plutonium-239

Uranium-238 (92 p - 146 n) + Neutron → Uranium-239 (92 p - 147 n) → Neptunium-233 (93 p - 146 n) → 23 minutes → β⁻ → Plutonium-239 (94 p - 145 n) → 2.3 jours → β⁻
Generation IV
Cashton Green Wind Farm
North Wind Turbine Installation

Installing Re-Bar and Anchor Bolts Before Cement Pour
(45 Tons of Re-Bar)

Marine Radioactivity 101

15,350,000 Peta-Becquerels of natural radioactivity (mostly Potassium-40)

~30 Peta-Becquerels of radioactivity from Fukushima Daiichi

Stating the obvious: There is about 500,000 times more natural radioactivity in the oceans than was added by Fukushima Daiichi

Notes: A Becquerel unit is equal to one nuclear (atomic) disintegration per second; Depending on the specific isotope, the disintegration may involve the emission of a gamma, beta, or alpha particle; Both natural and Fukushima isotopes are mostly gamma and beta emitters - biology does NOT distinguish between the isotopes of origin of these particles, be they natural or man-made; A Peta-Becquerel equals a thousand trillion Becquerels.
The Effect of Energiewende I
The Effect of Energiewende II

Graph by Clean Energy Wire, data from German Environment Agency (UBA) and Green Budget Germany
The Effect of San Onofre

closed 2013

Comparison Of Non-Hydro Low-Carbon Energy Sources In California
(for the last full year of operation)

<table>
<thead>
<tr>
<th>Source</th>
<th>2004</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>58%</td>
<td></td>
</tr>
<tr>
<td>Renewables</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>9%</td>
<td></td>
</tr>
</tbody>
</table>

Electricity Production (billion kWs/year)

- Nuclear (Diablo Canyon)
- Nuclear (SONGS)
- Wind
- Solar
- Biomass
- Geotherm