Nuclear Energy & Sustainable Development

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Executive Committee of the Global Energy Assessment (IIASA, Laxenburg, Austria; 2007-2012)

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## Global Energy Assessment

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### GEA chapters dealing with renewable and nuclear energy

- **Chapter 7: Energy Resources and Potentials** - CLA: Hans Holger Rogner (IAEA)

- **Chapter 11: Renewable Energy** - CLA: Wim Turkenburg (Utrecht University)

- **Chapter 14: Nuclear Energy** – CLA: Frank von Hippel (Princeton University)

- **Chapter 17: Energy Pathways for Sustainable Development** – CLA: Keywan Riahi (IIASA)

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## World Primary Energy Supply in 2009

*(using GEA substitution method to calculate contribution from renewables)*

| Fossil fuels: | 412 EJ (78%) |
| - oil | 167 EJ |
| - gas | 106 EJ |
| - coal | 139 EJ |
| Renewables: | 89 EJ (17%) |
| - large hydro | 30 EJ (*) |
| - traditional biomass | 39 EJ |
| - ‘new’ renewables | 20 EJ (*) |
| Nuclear: | 27 EJ (5%) |
| Total: | 528 EJ (100%) |

*) Assuming for hydro, wind, solar and geothermal electricity: 1 EJ(el) = 2.85 EJ savings on fossil fuels, and for solar and geothermal heat: 1 EJ(th) = 1.17 EJ savings on fossil fuels
• Some remarks on status renewables
## Contribution ‘modern renewables’ to World Primary Energy Supply in 2009 *)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Amount</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower</td>
<td>32</td>
<td>EJ</td>
</tr>
<tr>
<td>Modern biomass energy</td>
<td>12.1</td>
<td>EJ</td>
</tr>
<tr>
<td>Wind electricity</td>
<td>3.7</td>
<td>EJ</td>
</tr>
<tr>
<td>Geothermal energy</td>
<td>1.2</td>
<td>EJ</td>
</tr>
<tr>
<td>Low temp. solar thermal energy</td>
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<td>EJ</td>
</tr>
<tr>
<td>Solar PV electricity</td>
<td>0.33</td>
<td>EJ</td>
</tr>
<tr>
<td>Solar thermal electricity (CSP)</td>
<td>0.02</td>
<td>EJ</td>
</tr>
<tr>
<td>Ocean energy</td>
<td>0.005</td>
<td>EJ</td>
</tr>
</tbody>
</table>

**Total:** 49.9 EJ

*) Assuming for hydro, wind, solar, geothermal, and ocean electricity: 1 EJ(el) = 2.85 EJ savings on fossil fuels, and for solar and geothermal heat: 1 EJ(th) = 1.17 EJ savings on fossil fuels

Annual New Clean Energy Investments by Asset Class

2004-2010

2004 – 2010: 29% CAGR

Source: Bloomberg/Deutsche Bank, 2 May 2011

Note: CAGR = Compound Annual Growth Rate; PE = Private Equity; VC = Venture Capital
Renewable energy technology learning curves

Renewables: some conclusions and trends

• The renewable resource based is sufficient to meet several times the present world primary energy demand, and potentially even 10 to 100 times this demand.

• Since 1990 energy provided by renewables has risen with 2% a year, but in recent years with 5% a year.

• Many renewable technologies have experienced a high annual growth rate – some (biofuels, wind, solar electricity, solar thermal, and geothermal heat) even experiencing two-digit growth.

• At present more than $230 bln investments a year ($-2005) in renewables.

• Contribution to energy supply in 2009: 17% (89 EJ); contribution to electricity supply: 19% (3800 TWh).

• Renewable power capacity additions now represent more than one-third of all global power capacity additions.

► Renewables are beginning to change the energy paradigm!

• Some remarks on status nuclear power
Nuclear Power Sites of the World

Number of reactors operable in 2010: about 440
Total installed capacity in 2010: about 375 GWe
Reactors under construction: about 65 (60 GWe)
Generated electricity in 2010: nearly 2650 TWh
- about 14 % of global electricity production
- about 5 % of global primary energy demand
Nuclear reactors operating in the world, 1954-2011

Source: IAEA-PRIS, MSC, 2011
Production of Electricity from Nuclear from 1971 to 2009 (TWh/y)

Source: IEA, Key World Energy Statistics, 2011
Nuclear Reactor Startups and Shutdowns, 1956-2011

Source: IAEA-PRIS, MSC², 2011
Generation of Nuclear Electricity in the World in 2010

Total World 2,630 TWh

Source: IAEA-PRIS, MSC, 2011
Europe: Share of Nuclear in National Electricity Generation in Europe in 2009

In 2009, 15 Member States produced electricity from nuclear energy, with the highest share in France (76%) and the lowest in the Netherlands (4%)

Source: Eurostat, May 2011 (Market Observatory for Energy)
Age of nuclear reactors operating in the world, as of 1 April 2011

Source: IAEA-PRIS, MSC, 2011
(15 March 2012)

IAEA concerned about aging nuclear plants

• The International Atomic Energy Agency (IAEA) says it's concerned about the safety of the world's nuclear power plants as 80 percent are more than 20 years old.

• The UN nuclear watchdog sent a draft of its annual report to member countries. The draft says 80 percent of the 435 facilities in operation were more than 2 decades old at the end of last year.

• Forty-three percent are between 20 and 29 years old. Thirty-two percent are 30 to 39 years old, and 5 percent are older than 40 years.

• IAEA Director General Yukiya Amano said nuclear power should remain a major energy resource as long as safety of facilities is strictly monitored.

• The agency wants cooperation from member countries to examine their nuclear plants in a bid to reinforce safety standards.

Source: NHK, Thursday, March 15, 2011 01.44+0900 (JST)
Negative experience curve of French nuclear reactors

• On the GEA Sustainable Development Energy Scenario, and its pathways
Objectives GEA Sustainable Development Energy Scenario till 2050

- Support economic growth at recent historic rates (2% a year on average).
- Almost universal access to electricity and cleaner cooking by 2030 (diffusion of clean technology; extension of grids).
- Reduce air pollution impacts on health, adhering to WHO guidelines (reduced premature death due to air pollution by 50% by 2030).
- Avoid dangerous climate change; stay below +2 °C above pre-industrial global mean temperature with more than 50% likelihood (CO2 emission peak by 2020; 35-75% reduction in 2050; negative emissions later).
- Improve energy security through enhanced diversity, limited energy trade and resilience of energy supply by 2050 (reduce share oil import in primary energy by 30-80%; increase local energy supply options; infrastructure expansion; storage and back-up capacity).
- And in the process, address issues like peak oil and nuclear proliferation challenges

Allowable CO2 emission budget and required CO2 price in GEA

• In the period 2010-2100: 940-1460 GtCO2 in total.

*Note: This budget is achieved in 30-45 years if we stay at present level of CO2 emissions!

• CO2 price in GEA: at least 15-45 $/tCO2 in 2010; up to 110 $/tCO2 or above in later years.

*Note: In April 2012, the CO2 price on the spot market was about 6 Euro per tonne CO2.
Global population projections
(stabilization at about 9 billion in GEA)
Economic development projections

(developing countries 3.5% a year on average; developed countries 1.2% a year in GEA)
Branching points and GEA pathways

- **Branching point 1**: *What is the level of energy demand?* (GEA-Efficiency; GEA-Supply; GEA-Mix // range eff. improv.: 1.5%-2.2% a year).

- **Branching point 2**: *What are the dominant transportation fuels and technologies?* (Conventional; Advanced).

- **Branching point 3**: *How divers is the portfolio of supply-side options?* (Full portfolio – all options available; Restricted portfolio – excludes or limits particular options).
Global Energy Assessment (GEA) Pathway Taxonomy

Branching point: Efficiency

Branching point: Demand

Branching point: Supply

Supply-side flexibility

Demand-side flexibility

Intermediate demand

Low demand

High demand

Feasible supply-side transitions (primary energy by 2050)
Composition of global primary energy supply in 2005, 2030 and 2050
(across pathway groups, under unrestricted supply portfolio and Conventional Transportation set-up)
Development of primary energy
(In the GEA-Supply pathway with a nuclear phaseout shortly after 2050)
Cumulative discounted total energy cost for all scenarios (2010-2050)
GEA: robust conclusions on sustainability

• At least the historical rate of improvement of the energy efficiency a year should be achieved.
• Low carbon energy shares in primary energy at least at 60-80% by 2050.
• Strong growth in renewable energy, beginning immediately and reaching 165-650 EJ a year by 2050 - about 30-75% of primary energy demand (and in some regions it could exceed 90% of this demand in 2050).
• Increasing requirement for storage technologies, apart from other measures, to support system integration of intermittent renewable.
• Growth in bioenergy to 80-140 EJ a year by 2050. Strong growth of liquid biofuels in the short to medium term. Thereafter, the mix of liquid and gaseous fuels depends on transportation system choices.
• Nuclear energy may play an important role, but it is also possible to phase out nuclear, still meeting the GEA sustainability targets.
• Fossil CCS as an optional bridge in the medium term; contribution from biomass plus CCS to achieve negative CO2 emission in longer term; cumulative storage of CO2 up to 250 GtCO2 by 2050, depending on pathway.
• On Nuclear Energy & Sustainable Development
Nuclear Energy and Sustainability

“Under what conditions may nuclear energy qualify as a viable option to fulfill the need for energy services of present and future generations in a sustainable manner”
Nuclear Energy & Sustainable Development

1. Climate change & scarcity of resources.
2. Public acceptance.
5. Proliferation (fissile materials; weapons).
6. Accumulation of radio-nuclides (Kr-85).
7. Investment costs and kWh costs of nuclear power.
8. Impact on development and application of alternatives (energy efficiency; renewables; CCS).

Source: Wim C. Turkenburg, 1996
Natural Uranium: is produced from Uranium ore. If the ore is rich, the percentage of Uranium can be 10-15%. In general ores are used having a concentration of 0.1-0.5%.

Natural Uranium reserves: are estimated at about 5 million tonnes (costs: 80-130 $/kg). Ultimately the recoverable reserves can be estimated at 10-30 million tonnes (maybe up to 100 million tonnes).

Uranium in sea water: Total amount in sea water: 4.5 billion tonnes. Concentration: less than 3. $10^{-3}$ ppm. Therefore high extraction costs (200-300$/kg). However, the impact of nuclear fuel costs on kWh production costs is small (compared with e.g. coal or gas fired plants).

Composition Natural Uranium: 0.006% U-234; 0.712% U-235; en 99.282% U-238.

U-238: difficult to fission. U-238 absorbs neutrons; then it becomes U-239. This isotope will decay (half-life 23 minutes) towards Np-239. Thereafter (half-life 2.3 days) it becomes Pu-239.

Pu-239: half-life 24.000 years. Like U-235, Pu-239 is a fissile material.
# Natural Uranium use of some reactor types (tonne per GW(e)-year)

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Description</th>
<th>Without Reprocessing</th>
<th>With Reprocessing</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWR</td>
<td>Without Reprocessing</td>
<td>212 tonne</td>
<td>129 tonne</td>
</tr>
<tr>
<td></td>
<td>With Reprocessing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HWR</td>
<td>Natural Uranium</td>
<td>174 tonne</td>
<td>119 tonne</td>
</tr>
<tr>
<td></td>
<td>Enriched Uranium</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>With Reprocessing</td>
<td></td>
<td>87 tonne</td>
</tr>
<tr>
<td>FBR</td>
<td>Uranium-Plutonium cycle</td>
<td>1.5 tonne</td>
<td></td>
</tr>
</tbody>
</table>

**Source:** H. van Dam, 1982

**Conclusion:** Nuclear power can contribute substantially to the reduction of CO2 emissions, taking into account the reserves and resources of Uranium (and Thorium) and limited *indirect* CO2 emissions from nuclear energy use.
Nuclear energy and public acceptance

Research in the 1980’s and 1990’s indicated, that public acceptance requires:

1. Maximum attention for potential of energy efficiency and renewables (and ‘clean’ fossil fuel technologies).

2. Development of a nuclear technology that is: safer, cleaner, more proliferation resistant, economic, and efficiently dealing with scarce resources.

3. Regain of trust in nuclear experts, decision makers and decision-making processes.
Standard in the Netherlands for ‘acceptable personal risk’.

(Probability per year of acute death due to an activity – e.g. power production in a nuclear plant - assuming that a person would live the whole year at a fixed distance from the plant).

Note: An NPP in NL is much safer, but …….
Inherently safe reactors:
they’d work if we’d let them

Although they shut down automatically and cannot melt or explode, advanced designs are limited to demonstrations because of economics and institutional inertia
Implications of ‘inherent safety’

- Energy production per unit of fissile material should be restricted.
- Power density of the reactor core should be small enough.
- Heat capacity of reactor core should be large enough.
- Surface/volume ratio of core should be large enough.
- Rate of increase of reactivity should be limited.
- Reactivity coefficient, power coefficient and void coefficient should be negative.
- Restrictions to the chemical and physical properties of the materials used in the reactor.

PM: vulnerability with respect to attacks from terrorists.
Fig. 4. Het elektrisch vermogen en de thermische vermogensdichtheid van verschillende reactorontwerpen (gemodificeerd ontleend aan ref. [1]). PWR = drukwaterreactor, KCB = kerncentrale Borssele, KCD = kerncentrale Dodewaard, DOEL = kerncentrale Doel (België), BWR = kokendwaterreactor, ABWR = Advanced BWR, SBWR = Simplified BWR, PIUS = Process Inherent Ultimate Safety (een nieuw Zweeds ontwerp met grote mate van passieve veiligheid), CANDU = Canadese zwaarwaterreactor, AGR = Advanced Gascooled Reactor, HTGR = hoge-temperatuur gasgekoelde reactor.

Source: H. van Dam, 1990
Inherently safe reactors

Potential candidates a.o.:

- **HTGR**, e.g. 50-100 MWe Pebble Bed Modular Reactor that was developed in South Africa and the HTR-PM that is developed in China. 10 MW demonstration plant in operation in China since 2000: ‘loss of coolant’ test and ‘reactivity increase’ test in 2004. First commercial plants (190 MWe) scheduled for about 2015.

- **Generation IV reactors**, e.g. VHTR.

- **ADS - Accelerator Driven Systems**, e.g. Energy Amplifier as proposed by Rubia: till now paper studies only. However: see ADS-plan in Belgium (research reactor MYRRHA, scheduled for 2020).
In an HTGR, the fuel is located inside triso-coated particles (graphite layers, including a silicon carbide layer). The graphite layers should moderate the energy of the neutrons and maintain the fission products. The particles don’t des-integrate up to a temperature of 1600-1800 degrees Celsius.

Source: D.D. Lanning et al, 1991
Radioactivity in High Level Waste from LWR’s

Through *partitioning* and *transmutation* the life time of long lived radioactive waste can be reduced from more than 100,000 years to less than 2,000 years, maybe even close to 500 years.

This technology might come available commercially within a few decades, depending on investments in the development of this technology.

Cost: 0.5-1.5 ct/kWh.

Figure 6.1. Radioactivity of individual radionuclides in high-level waste from the light-water reactor uranium fuel cycle. (Reprocessing, 150 days after discharge from reactor; enrichment, 3% uranium-235; burn-up, 30,000 megawatt-days per ton of heavy metal; residence time, 1,100 days; 0.5% uranium and 0.5% plutonium remaining in the high-level waste.) (Adapted from Benedict et al. 1981.)
Projections from the OMEGA Program for a cleaner fuel cycle by partitioning and transmutation of waste
Partitioning and Transmutation: some problems and questions

| • Reprocessing required (risk of proliferation and accidental releases). |
| • Not (yet) applicable in a Pebble Bed Reactor approach. |
| • Not all radioactive nuclides are treated: |
  1. plutonium, americium, curium; |
  2. technetium, iodine, cesium. |
| • Some radionuclides still have a long lifetime. |
| • Increase of radioactivity on shorter term. |
| • Slow process (many decades required). |
| • Increase of electr. production costs (0.5-1.5 ct/kWh). |
Risk of nuclear weapons proliferation posed by nuclear energy technologies

Nuclear explosives can be made from:
- highly enriched uranium
- plutonium

World Energy Assessment (2000):

“Reactor-grade plutonium can be used to construct devastating nuclear weapons at all levels of technical sophistication (DoE-US, 1997). (..) However, using reactor grade rather than weapon grade plutonium would present some complications. But even with relatively simple designs (..) nuclear explosives could be constructed (..)”.
The risk of atomic weapon proliferation

- "A 1000 MWe light-water reactor (LWR), the dominant type in most of the world, discharges approximately 200 kg of plutonium annually in its spent fuel - enough for more than 20 nuclear weapons".

- "A global installed nuclear capacity of 3000 GWe would produce over 500,000 kg of plutonium per year. With plutonium-breeder reactors approximately 5,000,000 kg of separated plutonium would be placed into global commerce each year".

- "Because of the high diversion risk inherent in a 'plutonium economy', an alternative nuclear system that is diversion-resistant as well as safe and cost-effective would have to be developed before nuclear power could play a major role in the energy future of the world".

From: R.H. Williams et al.  
Energy Policy, 1990
How to reduce the risk of misuse of nuclear materials and technologies

Nuclear power systems should be designed to satisfy the following criteria:

1. Reactors shall be designed to reduce to very low levels the production of weapons-usable materials in spent fuel (of the order of a critical mass or less per year per GW of capacity).

2. As far as possible, fissionable weapons-usable material (plutonium) should be contained in spent fuel.

3. Spent fuel shall be stored in international (multi-national) centers.

4. Fissionable weapons-usable material that is not contained in spent fuel and facilities to enrich uranium or to separate plutonium shall not exist outside international (at least multi-national) centers.

5. The new technology and approach should be ‘culture proof’ and applicable without discriminatory conditions among nations.

Source: Modified from Williams and Feiveson, Energy Policy, 1990
Accumulation of radionuclides in the biosphere

- Accumulation of radio-nuclides (like Kr-85) in the atmosphere can significantly influence its electrical properties.
- Also, the chemistry of the atmosphere can be influenced (increased free radicals).
- This could have an impact on e.g. formation of clouds, and therefore on weather and climate.

Source: D. de Jager, October 1992
## Levelized costs in 2030 of different electricity generation technologies

*(in US$2005/MWh, using a 5% discount rate)*

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital ($/kWe)</th>
<th>O&amp;M ($/kWe)</th>
<th>Fuel ($/GJ)</th>
<th>Waste ($/MWh)</th>
<th>Generating costs ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>900-2800</td>
<td>6-18</td>
<td>0</td>
<td>0</td>
<td>27-151</td>
</tr>
<tr>
<td>Wind (onshore)</td>
<td>900-1300</td>
<td>9-30</td>
<td>0</td>
<td>0</td>
<td>21-131</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4000-6200 a</td>
<td>118-180</td>
<td>0.7-0.9</td>
<td>1-2</td>
<td>53-100</td>
</tr>
<tr>
<td>Advanced Coal</td>
<td>1100-1600</td>
<td>46-65</td>
<td>1.3-2.8</td>
<td>0</td>
<td>27-46</td>
</tr>
<tr>
<td>Adv. Coal with CCS</td>
<td>1700-2400</td>
<td>69-96</td>
<td>1.3-2.8</td>
<td>6</td>
<td>44-69</td>
</tr>
<tr>
<td>Gas CC</td>
<td>400-500</td>
<td>16-20</td>
<td>2.6-6.5</td>
<td>0</td>
<td>24-49</td>
</tr>
</tbody>
</table>

a) In East Asia at present 1800-2500 $/kWe; the GEA pathways assume these costs will increase with rising affluence.

Thanks!

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## Contribution ‘modern renewables’ in 2009 using different calculation methods

<table>
<thead>
<tr>
<th>Technology</th>
<th>Primary Supply using the substitution method</th>
<th>Primary Supply using the physical content method</th>
<th>Primary Supply using the direct equivalent method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower</td>
<td>32</td>
<td>11.2</td>
<td>11.2</td>
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<td>3.7</td>
<td>1.3</td>
<td>1.3</td>
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<td>Geothermal energy</td>
<td>1.2</td>
<td>3.3</td>
<td>0.67</td>
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<tr>
<td>Low temp. solar thermal energy</td>
<td>0.5</td>
<td>0.43</td>
<td>0.43</td>
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<tr>
<td>Solar PV electricity</td>
<td>0.33</td>
<td>0.12</td>
<td>0.12</td>
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<tr>
<td>Solar thermal electricity (CSP)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.007</td>
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<tr>
<td>Ocean energy</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total supply</strong></td>
<td><strong>49.9 EJ</strong></td>
<td><strong>28.5 EJ</strong></td>
<td><strong>25.9 EJ</strong></td>
</tr>
</tbody>
</table>

Nuclear power plants in Europe, in operation and under construction, as of Jan. 19, 2011

<table>
<thead>
<tr>
<th>Country</th>
<th>in operation</th>
<th>under construction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>net capacity [MWe]</td>
</tr>
<tr>
<td>Belgium</td>
<td>7</td>
<td>5,926</td>
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<tr>
<td>Bulgaria</td>
<td>2</td>
<td>1,906</td>
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<tr>
<td>Czech Republic</td>
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<td>3,722</td>
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<td>Finland</td>
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<td>France</td>
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<td>Germany</td>
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<td>Ukraine</td>
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<tr>
<td>United Kingdom</td>
<td>19</td>
<td>10,137</td>
</tr>
<tr>
<td>total</td>
<td>195</td>
<td>170,016</td>
</tr>
</tbody>
</table>

Source: http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm