Can the nuclear sources contribute to the solution of climate change and energy issues?

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Outline

• Introduction
• World energy needs and issues
• Nuclear Fission
• Nuclear Fusion
• Conclusions
Dipartimento di Energetica @ Politecnico di Torino

• ~ 100 staff
• ~ 4 MEuro budget
• Activities in nuclear fission, nuclear fusion, energy policy, building physics, hydrogen/fuel cells, renewable sources, internal combustion engines, …
• Collaborations with major universities, research centres around the world
• Funding from private sector, local and national public administrations, EU
The history of human civilisation can be written as the history of the development of the mankind ability to control always growing energy fluxes.

Yearly per capita needs range today over two orders of magnitude (IEA 2005)
The fossil fuel era (world)

[IEA, 2004]
CO2 production for different sources

Villahermosa, Mexico, 13 Mar 2008
Climate change: CO₂ and global warming

**CO₂ concentration in the atmosphere: Mauna Loa curve**

![Graph showing CO₂ concentration from 1959 to 1998.](image)

Source: Scripps Institution of Oceanography (SIO), University of California, 1998.

**Trend in global average surface temperature**

![Graph showing temperature trend from 1880 to 2000.](image)

Source: School of environmental sciences, climatic research unit, University of East Anglia, Norwich, United Kingdom, 1999.
Climate change: Simulation of the anthropic effect

Natural forcing including the effects of human activity

Temperature change °C

-0.5 0 0.5 1.0

Observed
Model simulation

Stott et al 2000
Evolution of energy consumption yesterday → today
Oil peak is approaching…

OIL AND GAS LIQUIDS
2004 Scenario

Villahermosa, Mexico, 13 Mar 2008
Evolution of energy consumption today → tomorrow

Forecasting of world TPES needs in Gtoe/y
from IEA, World Energy Outlook 2004

[IEA, 2004]
The risks of forecasting (I)

Villahermosa, Mexico, 13 Mar 2008

[V. Smil, 1996]
The risks of forecasting (II)

Figure 3.8
Forecasts of the global TPES in the year 2000 made by the participants in the 1983 International Energy Workshop. The predicted extremes were about 45% lower and 60% higher than the actual rate. Plotted from a table in Manne and Schrattenholzer (1983).
The energy crisis

- Fossil Fuels depletion
- Supply security
- The ENERGY crisis
- Environmental impacts
- Greenhouse effect
The different natures of the problem

Economic
Geopolitic
Social
Technologic

Emphasis here: Technology/Fuel availability

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Three possible solutions

- Increase efficiency ➔ Reduce energy use?
- Use abundant fossil fuels (coal) with CO$_2$ sequestration
- Use non CO$_2$ emitting energy sources (renewable, nuclear)
CO$_2$ emissions in 2050

CCS = Carbon Capture & Storage (sequestration)
Cost of saved energy
Carbon sequestration
Cost of renewable vs. fossil

[E. Uherek, based on data extracted from IEA publications and from "Renewable Energies" (2004), German Ministry of Environment]  Villahermosa, Mexico, 13 Mar 2008
Nuclear fission

• Present
• Challenges
• Next generation fission plants
Villahermosa, Mexico, 13 Mar 2008

Status of Nuclear Energy (world)

- 439 nuclear power plants in operation with a total net installed capacity of ~372 GWe
- 33 nuclear power plants under construction (~27 GWe)
- On order or planned 94 units (~102 GWe)

Nuclear Electricity Generation %
(World 16%)

Countries: Lithuania, France, Slovakia, Belgium, Sweden, Ukraine, South Korea, Slovenia, Switzerland, Bulgaria, Armenia, Czech Republic, Germany, Japan, Spain, UK, Finland, USA, Russia, Canada, Hungary, Romania, Argentina, South Africa, Mexico, Netherlands, India, Brazil, Pakistan, China

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Status of Nuclear Energy (EU)

Electricity production

Nuclear 31.0%
Gas 19.9%
Oil 4.5%
Solids 29.5%
Hydro 10.6%
Geothermal + solar 0.2%
Wind 1.8%
Biomass 2.1%

RES* 14.8%

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Public Perception

"Overall, do you strongly favor, somewhat favor, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States?"

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Price stability and supply security

- Relative price stability of kWh is assured regardless of uranium price fluctuations, because of low relative cost of fuel.
- Because nuclear fuel supplies are highly energy-intensive (and thus small in volume), they can readily be stockpiled, affording a major buffer for energy security.

Fuel (I)

• **Worldwide Uranium known resources**
  Present economic resources about 5 Mt
  Estimated conventional resources more than 11 Mt U* (22 Mt recoverable as by-product of unconventional resources as phosphate; up to 4000 Mt in seawater)

• **Present consumption 0.068 Mt/y**
  It is enough to last 80-100 years at today’s rate of consumption (it will depend also on the increasing burnup and efficiency of the NPPs)

• **Reprocessing** of spent fuel from conventional light water reactors also utilises present resources more efficiently, by a factor of about 1.3 overall

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*Uranium 2003 – Resources, Production and Demand, NEA No. 5291, OECD, Paris (2004)*
Fast breeder reactor (U\textsubscript{238} → Pu\textsubscript{239}) will increase 50-fold or more the utilisation of natural Uranium (as well as the 1.2 million tonnes of depleted Uranium now stockpiled as a result of enrichment activities) Such technology is of fundamental importance for the future of nuclear fission energy.

Some advanced reactor designs are likely to be able to make use of Th\textsubscript{232} → U\textsubscript{233} on a substantial scale.

Thorium is reported to be about three times as abundant in the earth's crust as Uranium.
TPES → Carriers → Final uses

(Villahermosa, Mexico, 13 Mar 2008)

[IEA]
Electric Energy Needs

Electricity Needs and Prospects

<table>
<thead>
<tr>
<th>Country</th>
<th>Electricity Consumption (MWh per capita in 2002)</th>
<th>Projected Increase to 2020 in Electric Power Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>0.42</td>
<td>11</td>
</tr>
<tr>
<td>Pakistan</td>
<td>0.38</td>
<td>10</td>
</tr>
<tr>
<td>China</td>
<td>1.2</td>
<td>6-7</td>
</tr>
<tr>
<td>Russia</td>
<td>2</td>
<td>5.4</td>
</tr>
<tr>
<td>Africa</td>
<td>0.51</td>
<td>1-2.3</td>
</tr>
<tr>
<td>USA</td>
<td>1.11</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Source: IAEA

To meet rising demands, countries and regions are projected to increase their installed electric power capacity by factors ranging from just over one in the US to eleven in India by 2020.

[IAEA, 2007]
Challenges

- **Costs**: nuclear power has higher capital costs compared to natural gas with combined cycle turbine technology (CCGT) and coal.

- **Safety**: nuclear power has perceived adverse safety, environmental, and health effects, heightened by the 1979 Three Mile Island and 1986 Chernobyl reactor accidents.

- **Proliferation**: nuclear power entails potential security risks, notably the possible misuse of commercial or associated nuclear facilities.

- **Waste**: nuclear power has serious challenges in long-term management of radioactive wastes. Most countries have yet to implement final disposition of spent fuel or high level radioactive waste streams.
Generation III+

ESBWR (GE)

IRIS
(21 partners, 10 countries)

AP1000 (Westinghouse)

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Accelerator Driven System - ADS

- Sub-critical systems used in accelerator driven systems need an external source of neutrons to sustain the chain reaction.

- These “extra” neutrons are provided by the accelerator via a spallation source.

- ADS has great potential for waste transmutation reducing the burden to underground repositories.

- The use of the thorium cycle offers challenging options for nuclear waste reduction, both at the back end and the front end.
Generation IV (principles)

Technological goals:
- sustainability
- safety and reliability
- economics
- physical protection
- proliferation resistance

• GIF = Generation IV International Forum
  (Argentina, Brazil, Canada, China, Euratom, France, Japan, Republic of Korea, the Russian Federation, Republic of South Africa, Switzerland, the United Kingdom, and the United States)

• Define concepts for use beyond 2025
Generation IV (solutions)
**Generation IV → Electricity, Heat, Hydrogen**

<table>
<thead>
<tr>
<th>Generation IV System ($T_{outlet}$)</th>
<th>Hydrogen Production</th>
<th>Heat Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I-S Process</td>
<td>Ca-Br Process</td>
</tr>
<tr>
<td>GFR (850°C)</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>MSR (700-850°C)</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>SFR (550°C)</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>LFR (550°C)</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCWR (550°C)</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>VHTR (1000°C)</td>
<td>P</td>
<td>S</td>
</tr>
</tbody>
</table>

P: Primary option
S: Secondary option
O: Option for all systems

1 Bottoming cycle using heat at temperature heat has been used

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Projected nuclear fission capacity growth

Notes: Tentative scenario, assuming potential inexpensive uranium reserves of approximately 10 Mt.

Source: IAEA 2007

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Nuclear fusion

• Principle and potential
• ITER
• Path to a commercial reactor
What happens in a fusion reactor (tokamak)

- **Conditions:** confine magnetically a mixture (*plasma* = fully ionized gas) of Dueterium and Tritium, with density $\sim 10^{20}-10^{21} \text{ m}^{-3}$ and temperature $\sim 10-20 $ keV ($\sim 10^8 ^\circ \text{C}$), in a torus-shaped volume ($\sim 10^2-10^3 \text{ m}^3$), for a sufficiently long time.

- **Target:** sufficient amount of D-T nuclear fusion reactions

**Potential:** (almost) unlimited and (almost) clean energy!!
A rough comparison of reserves for different resources

<table>
<thead>
<tr>
<th>RESOURCE</th>
<th>IF TOTAL (y)</th>
<th>@ 2001 RATE (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Natural gas</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>U235</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Coal</td>
<td>200</td>
<td>900</td>
</tr>
<tr>
<td>U238, Th232</td>
<td>2,000</td>
<td>-</td>
</tr>
<tr>
<td>Fusion (D-T)</td>
<td>20,000</td>
<td>-</td>
</tr>
<tr>
<td>Fusion (D-D)</td>
<td>2,000,000,000</td>
<td>-</td>
</tr>
</tbody>
</table>

Total/actual 2001 usage rate assumed in 2nd/3rd column [Freidberg, 2007]
Why fusion reactions are difficult to obtain

• Compared to fission reactions between neutron and charged nucleus, fusion reactions between two positively charged nuclei, are much more difficult to obtain because of Coulomb repulsion ($\sigma_{\text{fus}} / \sigma_{\text{fiss}} \sim 10^{-2} – 10^{-3}$)

• Although studies in the two fields started in similar period, kWh are being produced since more than 50 years from fission reactors, while no electricity has been produced so far from fusion
What does NOT happen in a fusion reactor

- CO₂ production? NO
- Chain reaction? NO + +
- Spontaneous divergence of produced power? NO
- Radioactive reaction products? NO + +
- Long-lived radioactive waste? NO
- Open fuel cycle? NO +

+, ++, … additional assets with respect to fission
Components in a tokamak fusion reactor

- V = vacuum chamber,
- PI = pellet injector, NBI = neutral beam injector,
- FW = first wall, DP = divertor plate,
- A = antenna for auxiliary plasma heating,
- B = blanket,
- Magnet system: CS = central solenoid, TF = toroidal field coil, PF = poloidal field coil,
- C = cryostat,
- SG = steam generator, T = turbine.

Vertical cross section of the torus
ITER

- Construction of ITER tokamak approved 2005

- Cost ~ 10 GEuro: ~ 50 % EU, ~ 50 % (JA + RF + US + CN + KO + IN)

- Site Cadarache, France

- ~ 10 y construction (start 2007) + ~ 20 y operation
ITER targets

- $500 \text{ MW}_{\text{th}}$ with energy amplification $Q = \frac{\text{power out}}{\text{power in}} \geq 5-10$;
- Integration of key technologies for fusion reactors (e.g., superconducting coils, remote maintenance);
- Test of components for future reactors (e.g., divertor, vacuum pumps);
- Test of tritium breeding modules in the blanket for DEMO.

Radioactivity below natural in ~100 y after shutdown!
ITER location

Broader approach (JT60SA, IFMIF)
Research on fusion @ Politecnico di Torino

- RF plasma heating and antennas
- Burning plasma physics
- Materials
- Safety
- Plasma-wall interactions, Superconducting coils
Strategy for achieving commercial fusion power -- The Fast Track

[ ITER-relevant technology ]

[ Concept improvements, Stellarator ]

[ Tokamak physics (JET, AUG, JT60SA) ]

[ Fusion power technology – DEMO-relevant ]

[ ITER ]

[ IFMIF ]

[ DEMO and PROTO combined ]

[ DEMO ]

[ PROTO ]

Decision

Experiment al electrical power production

Commercial fusion power

[G. Janeschitz, FED, 2006]
Conclusions (I)

• Increasing fossil fuel costs, reduced availability and environment-related effects will make more and more competitive all non-fossil sources, included energy efficiency/savings

• Renewable energy sources are still expensive, especially if we don’t take into account “externalities”, and require a completely different energy structure (local vs. centralized, low vs high intensity energy production)

• Coal coupled to CO2 sequestration appears as the only viable fossil source on medium-long term
Conclusions (II)

- *Can the nuclear sources contribute to the solution of climate change and energy issues? YES*
  - Nuclear fission is already a source of electricity with about zero greenhouse gases
  - **Next generation fission reactors** have been designed as safer, more economically viable, less proliferant, with less waste and potential hydrogen production. Most of them will be (fast) breeder reactors, multiplying fuel resources up to 100 times
  - **Nuclear fusion** has huge additional potential in terms of fuel availability, intrinsic safety, environment, provided complex physics&technology issues can be properly solved starting from ITER
Thank-you for your kind invitation and attention!