Life Cycle Analysis of Carbon Dioxide Emissions from Different Energy Sources

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Optimizing the mitigation of carbon dioxide emissions in Europe

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Content

- Introduction
- Why Life Cycle Assessment?
- LCA-framework
- Examples of comparative assessments of Greenhouse Gas emissions of electricity generation options
- Other environmental burdens and impacts
- Integrated perspective
- Conclusions
Comprehensive Assessment of Energy Systems at PSI

Goals

• Inter-disciplinary assessment of energy technologies and scenarios for Switzerland and other countries

• Communication of results to decision-makers and stakeholders (http://gabe.web.psi.ch/energie-spiegel/)

• Support of rational and sustainable decisions („Honest Broker“)

General Approach

• Development and implementation of „state-of-the-art“ methods and databases

Motivation for Life Cycle Assessment

Comparison of environmental burdens of different (energy) systems

Consideration of one single stage of energy systems may not be proper

Example: „Well to wheel“ comparison of two car types
a) Car with internal combustion engine, Fuel: Gasoline from oil refinery
b) Car with fuel cell engine,
   Fuel: compressed Hydrogen (energy carrier) from natural gas reforming

Environmental burdens (or stressors) are various, which calls for:
aggregation into Categories
Example of Energy System: Natural Gas

Boundary of „Economy System“ for LCA calculations
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Laboratory for Energy Systems Analysis
Technology Assessment

SLC, Brussels, 7 October 2008

Step of energy chain over its lifetime

Product of previous step of chain

Construction  Operation  Decommissioning

Product

Direct

Indirect

Fuels
Electricity
Materials
Transport
Services

Total environmental burdens

> Air emissions
> Liquid Effluents
> Solid wastes
> Land use

Step of energy chain over its lifetime

Requirements
Life Cycle Analysis - LCA (nuclear energy chain)

Chain boundary

Uranium mining & -processing → enrichment & fuel element production → Nuclear power plant, operation

Waste management
- Geologic repository
- Reprocessing
- Interim storage

Consumption:
- fuels
- electricity
- infrastructure
- materials for operation
- transports

Environmental burdens (emissions etc.)

Direct [1 kWh] → electricity
Solar PV Cycle

- Silica sand [kg]
- MG-silicon [kg]
- EG-silicon (Silicon purification) [kg]
- CZ-sc-silicon [kg]
- sc-Si wafer [wafer]
- PV cell, sc-Si [cell]
- Inverse rectifier [unit]
- PV panel, sc-Si [panel]
- 3 kWp slanted-roof installation, sc-Si, panel, mounted, on roof [plant]

*electricity, at 3 kWp slanted-roof, sc-Si, panel, mounted [kWh]*
LCA Database ecoinvent

• Web-based; commercial; version v2.0 available on-line since 2007: [www.ecoinvent.ch](http://www.ecoinvent.ch) (ecoinvent Centre, supported by Institutes of the ETH Domain)

• ~4200 processes; besides energy (nearly 1700, PSI responsible), other sectors: construction materials, metals, chemicals, transport, agriculture → background DB

• Swiss, European, and selected non-European country-specific average conditions and selected best power plant technologies

• About 1000 individual „environmental flows“ accounted for:
  - pollutants to air, water & groundwater, soil
  - energy and non-energy resource uses
  - land uses
Greenhouse gas emissions, Switzerland, direct & indirect (grey)

Total 93.6 Mio. t CO2-eq in the year 2004

- 53.0 Mio. t CO2-eq direct emissions 57%
- 0.9 Mio. t CO2-eq services 0.9%
- 8.3 Mio. t CO2-eq manufactured goods 9%
- 1.2 Mio. t CO2-eq machines and vehicles 1.3%
- 3.0 Mio. t CO2-eq manufactured goods 3.2%
- 4.1 Mio. t CO2-eq food and living animals 4.3%
- 0.9 Mio. t CO2-eq beverages and tobacco 0.9%
- 1.8 Mio. t CO2-eq raw materials 1.9%
- 13.0 Mio. t CO2-eq fuels and electricity 14%
- 7.2 Mio. t CO2-eq chemicals 7.7%
- 0.2 Mio. t CO2-eq oils, fats and waxes 0.3%
- 53.0 Mio. t CO2-eq direct emissions

Source: BAFU 2007
Greenhouse gas emissions of selected energy chains

Source: after Dones et al. 2005

Graph showing greenhouse gas emissions in kg CO2-equivalent per kWh for various energy chains, including Lignite, Hard Coal, Oil, Natural Gas, Natural Gas CC, Diesel, Gas, Wood, Nuclear, Hydro, Wind onshore, Wind offshore, and PV. The graph includes data from countries such as AT, SK, CZ, FI, UK, CH, CN, LU, NL, IT, FR, DE, CN, DK, FI, ES, IT, UK, CH, and China.

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Swiss electricity systems: Greenhouse gases

Bauer at al. 2007 (Axpo Project)
Hard coal chain: GHG emissions, power plant in Europe

Source: Bauer, to be published 2008
Hard coal chain: $\text{NO}_x$ emissions, power plant in Europe

Source: Bauer, to be published 2008
Greenhouse Gas emissions, BWR in CH

Source: Dones 2003
Greenhouse Gas emissions, average BWR in CH

Source: Dones 2003

- N2O
- CH4
- CO2

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Greenhouse Gas emissions, PWR in CH

Source: Dones 2003
Greenhouse Gas emissions, average PWR in CH

Source: Dones 2003
Greenhouse gas emissions: specific PWR in Switzerland

Total 5.8 g(CO₂ eq) / kWh

- Mining
- Processing
- Conversion
- Enrichment
- Fuel element finishing
- PWR power plant
- Electricity from PWR
- Spent fuel reprocessing
- Spent fuel conditioning
- Interim storage
- Final repository

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How and where is the fuel enrichment done?

- **PWR Switzerland**
  - Diffusion EURODIF
  - Diffusion USEC
  - Centrifuge URENCO
  - Centrifuge TENEX

- **BWR Switzerland**
  - Diffusion EURODIF
  - Diffusion USEC
  - Centrifuge URENCO
  - Centrifuge TENEX

- **NPP Germany**
  - Diffusion EURODIF
  - Diffusion USEC
  - Centrifuge URENCO
  - Centrifuge TENEX

- **NPP France**
  - Diffusion EURODIF
  - Diffusion USEC
  - Centrifuge URENCO
  - Centrifuge TENEX

Source: Dones 2003
“Outliers”

ISA (2006)

- Diffusion accounts for a high proportion of total enrichment
- Complete energy chain relies largely on hard coal as the primary fuel source
- Maximum value: Uses a very low uranium concentration in the mined uranium ore

Storm van Leeuwen & Smith (2005)

Much criticism from other experts and the criticism is supported by our own research:

- Methodology & assumptions are questionable and partly not transparent
- Used a lot of very old references
- Energy use in the nuclear cycle is systematically overestimated → exaggerated CO₂-emissions
- Current practice of uranium mining is not analysed correctly, especially for low concentrations in uranium ore – for Switzerland and W.Europe it is not relevant.
- Detailed research must be conducted of low concentration uranium ore mining, taking technological developments into consideration
GHG-emissions: Natural Gas Combined Cycle in Italy

Total 446 g(CO₂ eq) / kWh

- Production
- Transport
- Electricity from power plant

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GHG-emissions: Photovoltaic multi-crystalline Silicon in Switzerland

Total 62 g(CO₂ eq) / kWh
Greenhouse gas emissions, electricity mix

Source: ecoinvent, Mirror on Energy No.11
GHG emissions, US & European electricity production mixes

- hard coal
- nuclear
- natural gas
- photovoltaic
- hydro, pumped storage
- oil
- lignite
- wind power
- hydropower
- industrial gas
- oil
- biogas

US

Germany

France

GB

Italy

Spain

EU-27

kg(CO2eq) / kWh
Composition of European electricity mixes (2004)

- Germany
- France
- GB
- Italy
- Spain

- hard coal
- nuclear
- natural gas
- photovoltaic
- hydro, pumped storage
- hydropower
- oil
- lignite
- industrial gas
- biomass
- wind power
- biogas
Electricity Systems in UCTE (2000)
Life Cycle Impact Assessment LCIA (example)

The aim of LCIA is at simplifying the understanding of the results of the inventory phase (according to ISO 14040 and 14042), by using one single indicator.

Ecoindicator ’99 is a damage oriented LCIA method.

Impact potentials of environmental flows are estimated using factors; The impacts are weighted and assigned to the damage categories:
- Human health
- Ecological quality
- Resources

The weighting of the impact categories is made from 3 cultural perspectives:
- **Hierarchic**: includes environmental damages that are proved.
- **Egalitarian**: considers any effects, even with minimal scientific proof, and takes future generations into account.
- **Individualist**: focuses on the present, only for effects that are proven, and neglects long-term effects.
Environmental Indicators, 2000

Source: Hirschberg et al, 2007
Environmental Indicators, 2000

Source: Hirschberg et al., 2007
Environmental Indicators, 2000

Source: Hirschberg et al., 2007

Metals
Ecotoxicity
Non radioactive waste
Environmental Indicators, 2000

Source: Hirschberg et al., 2007
Environmental Indicators, 2030

Source: Hirschberg et al., 2007
Swiss electricity systems (2030): Eco-indicator 99 (H,A)

Bauer at al. 2008 (Axpo Project)

Carcinogens
Resp. organics
Resp. inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Fossil fuels

EI99(H,A) points / kWh

0.0E+00
1.0E-03
2.0E-03
3.0E-03
4.0E-03
5.0E-03
6.0E-03
7.0E-03
8.0E-03
9.0E-03
1.0E-02
1.5E-02
2.0E-02
2.5E-02
3.0E-02
3.5E-02

Nuclear, EPR
Hard coal IGCC, GER
Nat. gas CC
Nat. gas CHP
Hydro run-of-river
Hydro reservoir
Biogas CHP
SNG CHP
Wind onshore, CH
Wind onshore, GER
Wind offshore DK
PV mc-Si
PV a-Si
Geothermal HDR

Bauer at al. 2008 (Axpo Project)
Eco-Indicator 99 (H,A): US vs. European electricity mixes

The diagram illustrates the Eco-Indicator 99 (H,A) points per kWh for different regions: US, Germany, France, GB, Italy, Spain, and EU-27. Each bar represents the total impact across various environmental categories, including climate change, carcinogens, acidification/eutrophication, land use, ecotoxicity, ozone layer, radiation, minerals, resp. inorganics, and fossil fuels.

- **US**: Shows a relatively balanced impact across all categories, with a slight emphasis on fossil fuels.
- **Germany**: Displays a more pronounced impact in climate change and fossil fuels.
- **France**: Highlights a significant contribution from radiation and minerals.
- **GB**: Reveals a notable impact in climate change and fossil fuels.
- **Italy**: Emphasizes radiation and minerals as significant contributors.
- **Spain**: Shows a balanced impact across most categories with a slight emphasis on climate change and fossil fuels.
- **EU-27**: Demonstrates a composite impact that reflects the aggregated data from all European countries, highlighting climate change and fossil fuels.

The diagram serves as a visual representation of the environmental costs associated with different electricity mixes, aiding in the assessment of sustainability and policy-making.
External costs, new power plants, 2000 (air pollution)

Source: PSI, to be published
External costs, 2030 (air pollution)

Source: PSI, to be published
Total costs of current and future electricity supply systems

Source: Hirschberg et al., 2007
### Overview of Criteria and Indicators for Comparative Sustainability Assessment of Energy Systems

<table>
<thead>
<tr>
<th>Sustainability Area</th>
<th>Impact Area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Economy</strong></td>
<td>Financial Requirements</td>
</tr>
<tr>
<td></td>
<td>Resources</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Global Warming</td>
</tr>
<tr>
<td></td>
<td>Regional Environmental Impact</td>
</tr>
<tr>
<td></td>
<td>Non-Pollutant Effects</td>
</tr>
<tr>
<td></td>
<td>Severe Accidents</td>
</tr>
<tr>
<td></td>
<td>Total Waste</td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Employment</td>
</tr>
<tr>
<td></td>
<td>Proliferation</td>
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<tr>
<td></td>
<td>Human Health Impacts (normal operation)</td>
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<td>Local Disturbances</td>
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<td>Critical Waste Confinement</td>
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<td>Risk Aversion</td>
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</table>

Source: Hirschberg et al., 2004
Multi-criteria Decision Analysis (MCDA), Current Systems, Germany

Equal weighting

Favouring the economy

Favouring the environment and human health

Favouring social criteria

Source: Hirschberg et al., 2004, Current systems, Germany
Kaya Equation Implications

\[ \text{CO}_2 \text{ Emissions} = \text{Carbon content of energy} \times \text{Energy intensity of economy} \times \text{Production per person} \times \text{Population} \]

Goal: Reduction by 50% until 2050

- Needs to be reduced by factor of 3 to reach the goal
- Needs to be reduced by factor of 5 to reach the goal
- Needs to be reduced by factor of 2 to reach the goal

Increase by factor 1.5 (IPCC 2000)
Increase by factor 1.65 (1% growth per year)
Decrease by factor 2.5 (-1.8% per year in alternative scenario of IEA 2004)

Necessitates very strong expansion of all “carbon-free” technologies
Kaya Equation Implications

\[
\text{CO}_2 \text{ Emissions} = \text{Carbon content of energy} \times \text{Energy intensity of economy} \times \text{Production per person} \times \text{Population}
\]

Goal: Reduction by 50% until 2050

- Needs to be reduced by factor of 3 to reach the goal
- Increase by factor 1.5 (IPCC 2000)
- Increase by factor 2.15 (1.6% growth per year)
- Decrease by factor 1.6 (-1% per year)

Necessitates very strong expansion of all “carbon-free” technologies
Concluding remarks

- LCA with LCI as its basis is a fundamental tool for balanced and comprehensive systems comparison, and for a wide variety of environmental studies.
- Detailed and transparent studies demonstrate that most renewables and nuclear have very low total GHG-emissions.
- Both renewables & nuclear are needed to meet future demand & respond to the climate change challenge.
- None of the technological options can fulfill all criteria concerning sustainability and market requirements.
- Trade-offs between environmental, economic and social sustainability components are inevitable and are influenced by value judgements.