PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

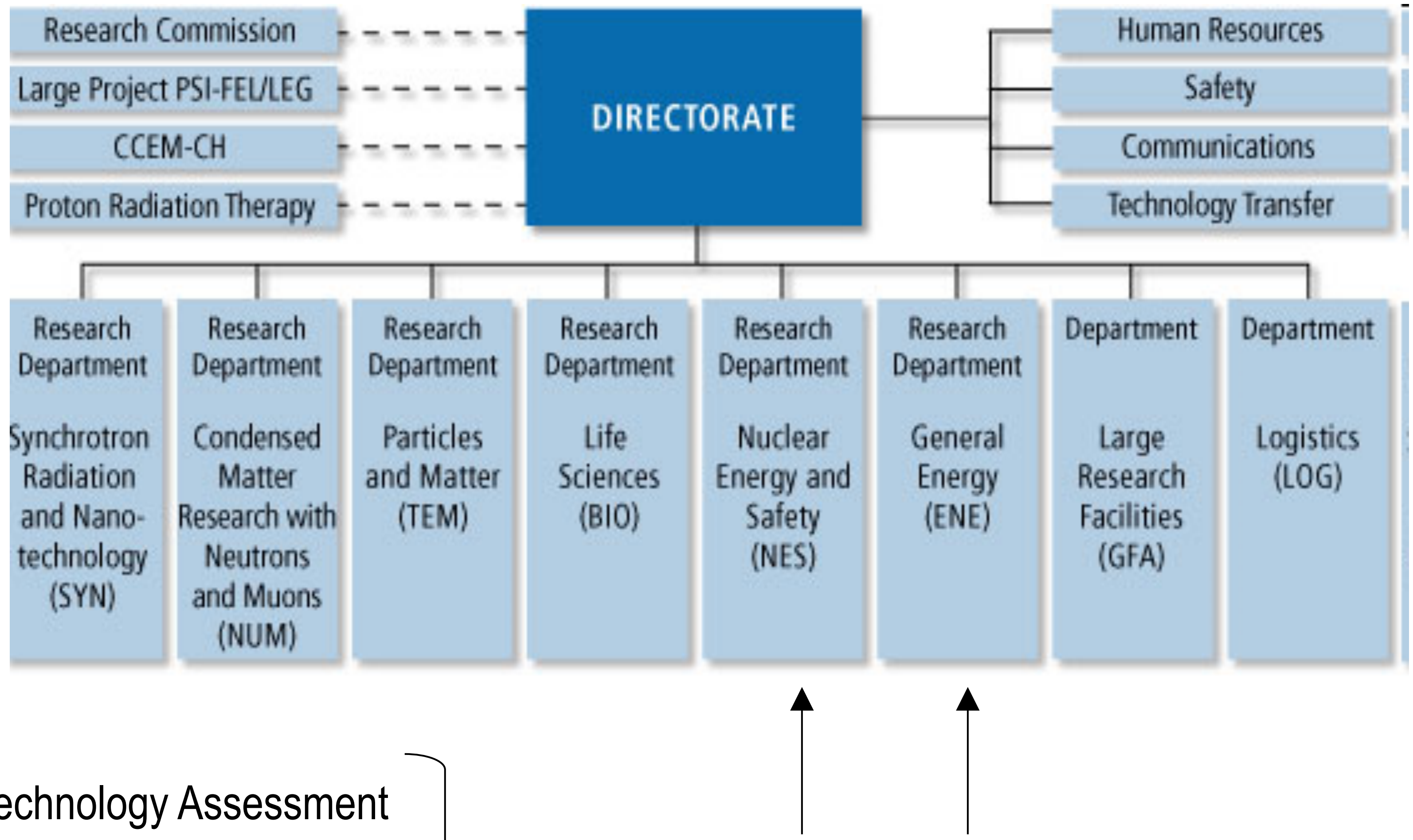
Paul Scherrer Institut

Stefan Hirschberg, Peter Burgherr, Vinh Dang, Hal Turton

Laboratory for Energy Systems Analysis (LEA): Overview, Recent Highlights and Outlook

NES Event, 27 March 2014

Laboratory for Energy Systems Analysis at PSI



Technology Assessment
Energy Economics
Risk and Human Reliability

Laboratory for Energy Systems Analysis (LEA)

Mission and mandate

LEA belongs to both Energy Departments and supports their strategic interests as well as those of PSI.

The Laboratory aims to contribute to effective decision-making on medium- to long-term technology strategies in energy supply and demand, ensuring integration of major environmental, economic and social factors.

LEA also develops methodologies and carries out the associated risk analyses, probabilistic safety assessment (PSA) and human reliability analysis (HRA) for nuclear power plants as well as other domains.

LEA has a mandate to analyze and communicate to decision-makers and stakeholders strengths and weaknesses of energy technologies and broad implications of alternative energy supply strategies.

Communication

Energiespiegel (http://www.psi.ch/info/energie-spiegel):

1. Potential for renewables and energy conservation
2. Scenarios for future electricity and heat supply in Switzerland
3. Criteria and indicators for sustainability
4. Flexible mechanisms for CO_2-reductions
5. Solar technologies
6. Mobility
7. Nuclear energy: fuel reprocessing
8. High-tech materials for sustainability
9. In focus: The Swiss electricity mix
10. CO_2-reduction in Switzerland
11. Order in the Eco-inventory jungle
12. Hopes on hydrogen: No quick fixes
13. Severe accidents in the energy sector
14. Outlook for CO_2-free electricity in Switzerland - new renewable energy sources
15. CO_2-free electricity for Switzerland - new nuclear technologies
16. Wood – A versatile, renewable energy resource
17. Clean energy for China
18. The 2000 W Society: Standard or Guidepost?
19. Caution – Particulates!
20. Sustainable Electricity: Wishful thinking or near-term reality?
21. The new Swiss energy policy: How will electricity be produced?
22. A Glimpse into the Future

Media Presence

NZZ am Sonntag

56 | Wissen

Die wahren Kosten der Stromerzeugung

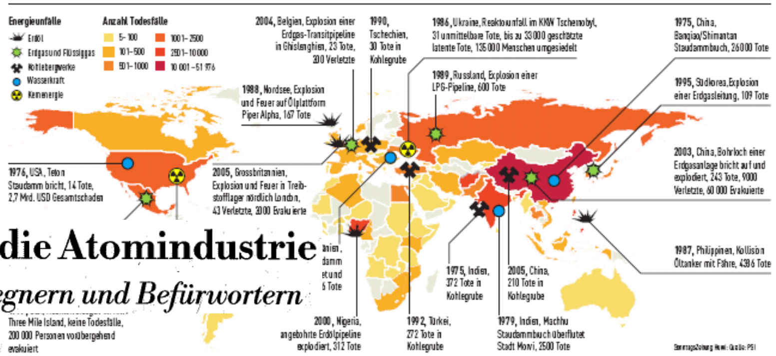
Umwelt- und Gesundheitsschäden sind im Strompreis nicht enthalten. Wie hoch diese externen Kosten sind, haben Wissenschafter des Paul-Scherrer-Instituts berechnet. Ihre Resultate helfen beim Entscheid für eine nachhaltige zukünftige Energieversorgung. *Von Stefan Hirschberg*

SonntagsZeitung

Die Schattenseite des Energiebedarfs

Eine Studie des PSI prognostiziert die Unfallgefahren verschiedener Technologien

Beispiele von schweren Unfällen in verschiedenen Energieketten



NZZ

Zukunftsszenarien für die Atomindustrie

Verhärtete Fronten zwischen Gegnern und Befürwortern

An einer Fachtagung der kernenergie-kritischen Schweizerischen Energie-Stiftung (SES) zeigten sich die enormen Hürden, die dem Bau eines neuen Kernkraftwerks in der Schweiz im Weg stehen.

...

Entsprechend erfrischend waren Aussagen, wie die des Leiters des Labors für Energiesystem-Analysen am Paul-Scherrer-Institut, der abseits von Ideologien versuchte, die Vor- und Nachteile der verschiedenen Produktionsarten gegeneinander abzuwägen. Sein Fazit, dass eine klimafreund-

...

SCIENTIFIC AMERICAN™

Dangerous Energy

Fossil power imposes a great human toll

Deadly accidents involving nuclear reactors, oil rigs and coal mines in recent months have reminded us that all forms of energy generation carry risks. In developed countries, coal is the most hazardous (*bottom left*), according to the Paul Scherrer Institute in Switzerland, which studied more than 1,800 accidents worldwide over nearly 30 years. Some stages of the supply chain are more deadly than others, however, and they differ in whether they pose greater risks to workers or the public (*top*).

Accidental deaths that occur in developing nations are higher, although reporting is inconsistent (thus, numbers are not shown). "Regulations are less strict," explains Peter Burgherr, head of technology assessment at the energy systems analysis laboratory at the institute. "Working conditions are also poorer," and less mechanization means more people are doing manual labor in harm's way.

The Washington Post

According to a database compiled by the Paul Scherrer Institut, from 1970 to 2008 there were 1,686 accidents in the coal industry, 531 in the oil industry and 186 involving natural gas in which five or more people died. There was just one such nuclear accident — at Chernobyl 25 years ago this month.

The New York Times

At U.S. Nuclear Sites, Preparing for the Unlikely

"One million people a year die prematurely in China fro[m]

industrial sectors," said Stefan Hirschberg, head of safety analysis at the Paul Scherrer Institute, an engineering research center in Switzerland. More than 10,000 Americans a

Laboratory for Energy Systems Analysis (LEA)
S. Hirschberg

Technology Assessment (TA)
P. Burgherr

- Interdisciplinary assessment of energy and mobility technologies to support rational and sustainable decisions
- Life Cycle Assessment, risk assessment, environmental impact and external cost assessment, technology costs, electric sector simulation, multi-criteria decision analysis

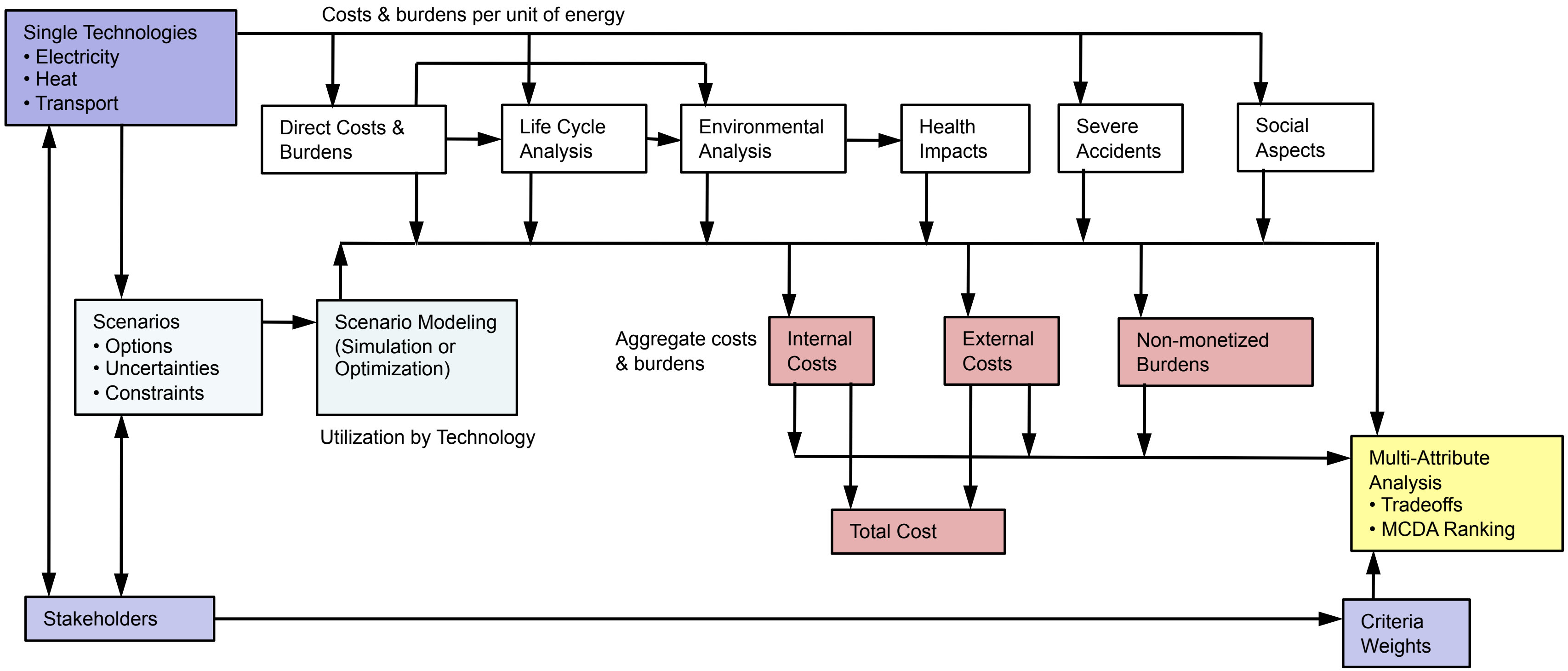
Energy Economics (EE)
H. Turton

- Quantitative scenario analysis of energy systems in the context of global climate change and sustainable development
- Interactions between energy, economics, environment and technology

Risk and Human Reliability (RHR)
V. N. Dang

- The human factor in Probabilistic Safety Assessments (PSAs)
- Errors of commission, HRA quantification, operator-plant simulation for dynamic safety assessment
- Innovative applications of PSA methods, e.g. patient safety for PSI's Proton Therapy Facilities

PSI's General Analysis Framework



For electric vehicle analysis

Vehicle (technology) characterization requires

- Drivetrain simulation

Scenario analysis requires

- Traffic forecasting/simulation
- Grid modeling (demand/generation/transmission)

Laboratory for Energy Systems Analysis

THREE GROUPS = THREE PROJECTS

Technology Assessment (TA)
P. Burgherr
- 7 staff scientists
- 1 guest scientist
- 1 Ph.D. student
- 1 vacancy (staff)

Energy Economics (EE)
H. Turton
- 3 staff scientists
- 1 post-doc
- 1 guest scientist
- 3 Ph.D. students

Risk & Human Reliability (RHR)
V. N. Dang
- 5 staff scientists
- 1 post-doc
- 1 Ph.D. student
- 1 vacancy (Ph.D. student)

Personnel

- Currently 16 staff scientists (including Lab-head); thereof 6 PSI positions
- 2 guest scientists
- 2 post-docs, 5 Ph.D. students
- During 2013: 1 Ph.D. Thesis, 5 M.Sc Thesis and 2 Bachelor Thesis completed; 9 internships

Scope

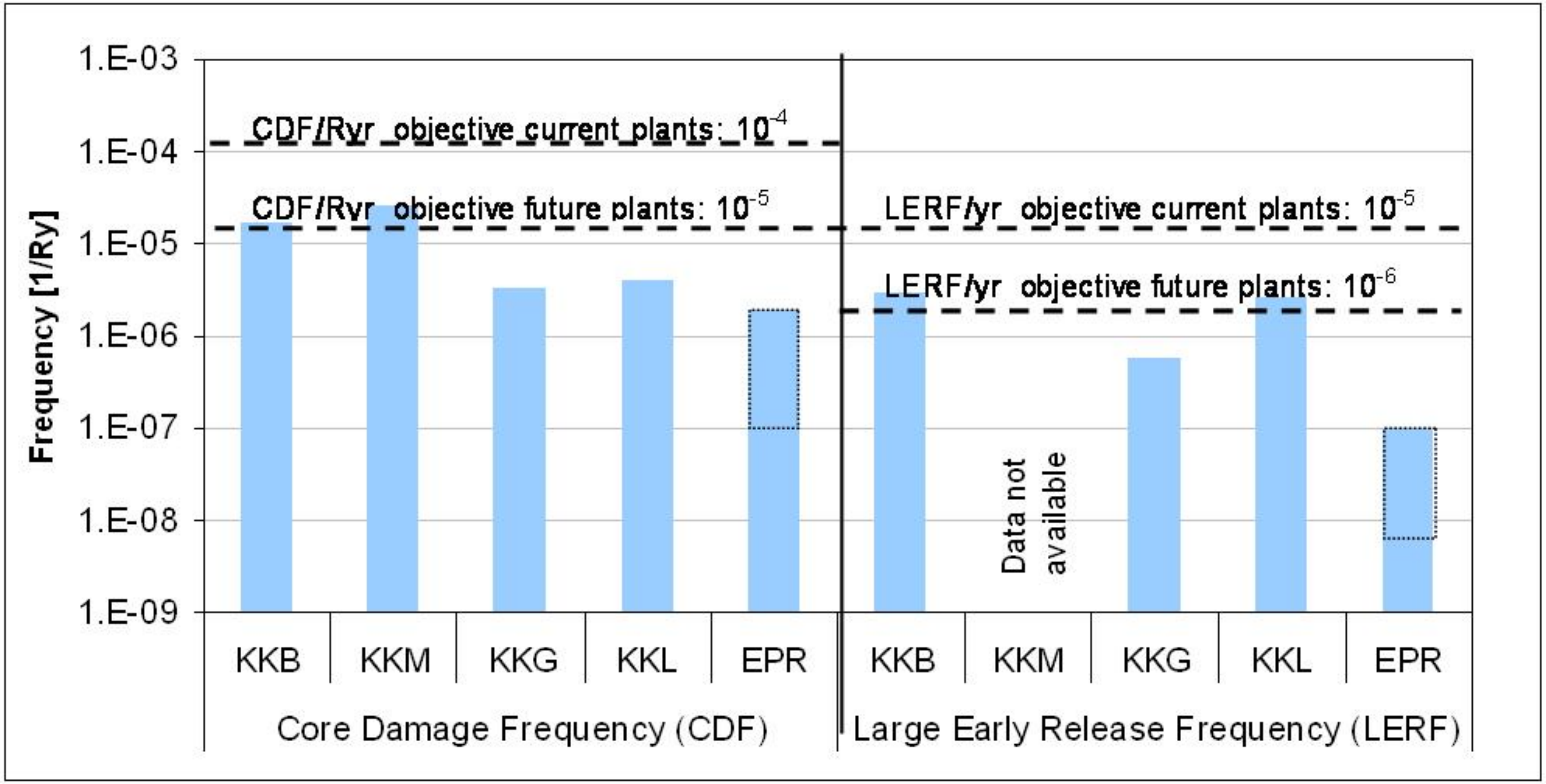
- Current and future fossil, nuclear and renewable technologies
- National, regional and global energy issues
- Risk-based perspective on human-related safety issues and innovative PSA applications

Contribution to SFOE Energy Perspectives 2050

Bewertung aktueller und zukünftiger Kernenergietechnologien
Erweiterte Zusammenfassung des Berichts „Current and Future Nuclear Technologies“

Stefan Hirschberg[1], Petrissa Eckle[1], Christian Bauer[1], Warren Schenler[1], Andrew Simons[1]
Oliver Köberl[2], Jörg Dreier[3],Horst-Michael Prasser[4] und Martin Zimmermann[2]

Risks indicators for current Swiss NPPs and EPR



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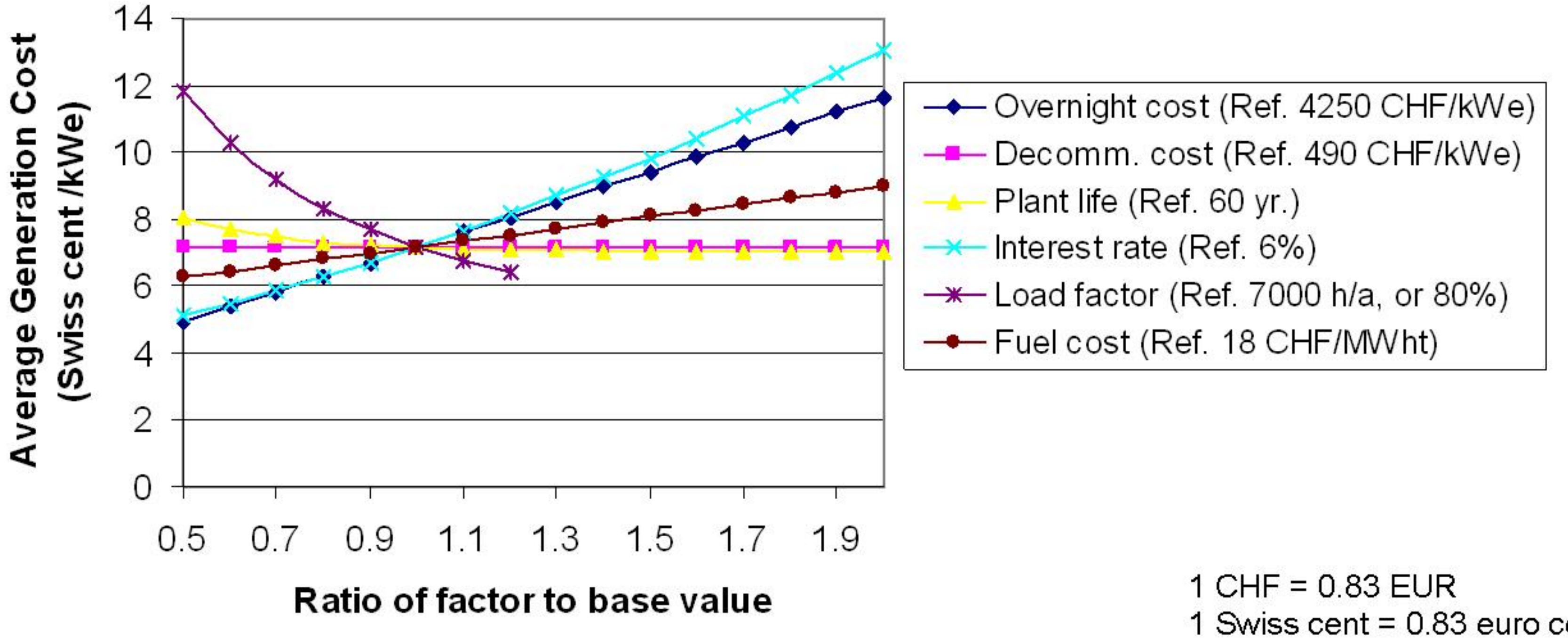
Cost sensitivity for EPR



1 CHF = 0.83 EUR
1 Swiss cent = 0.83 euro cent

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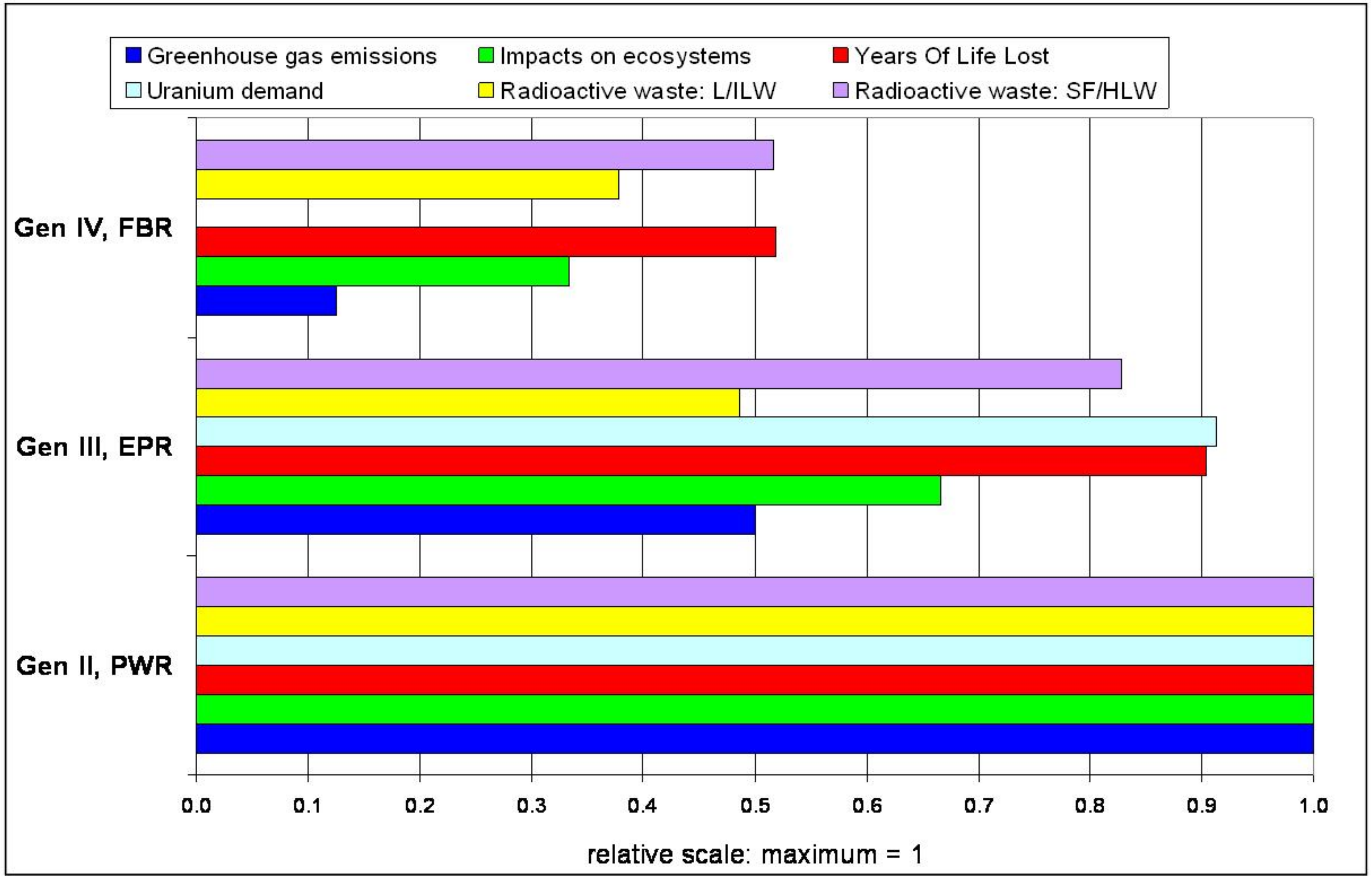
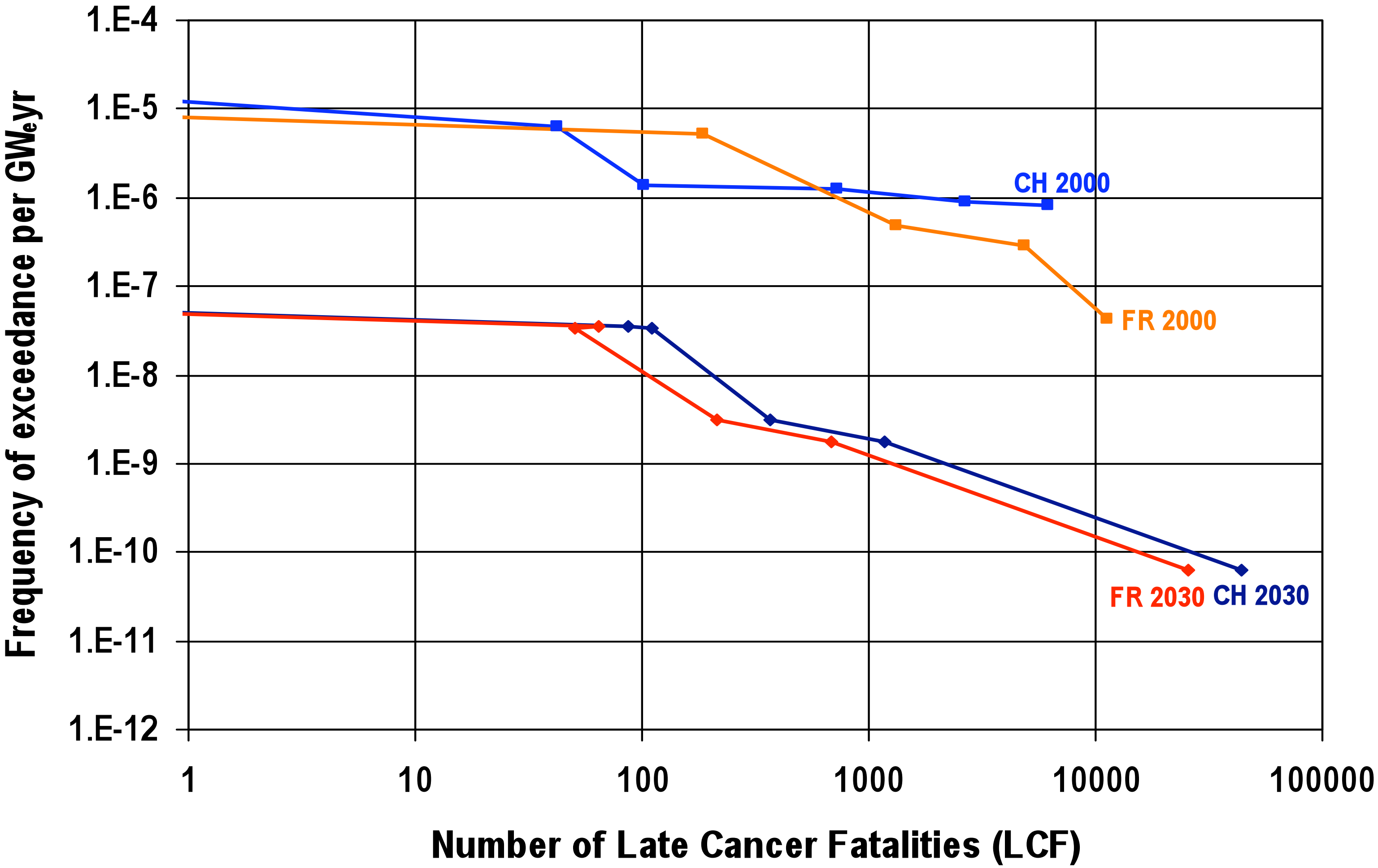
Relative environmental indicators per kWh generated at Gen II, III, and IV reactors



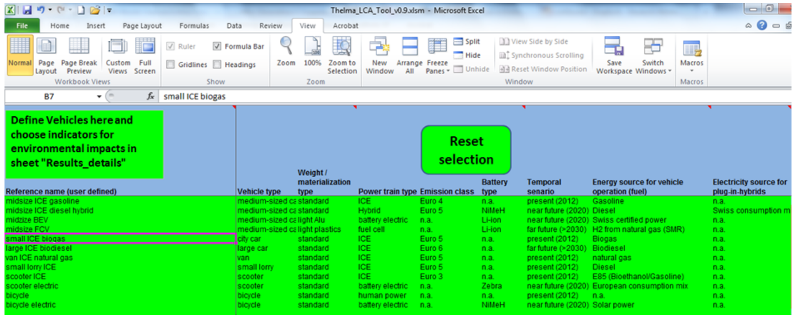
F-N Curves: Latent Cancer Fatalities (LCF) - current plants & EPR

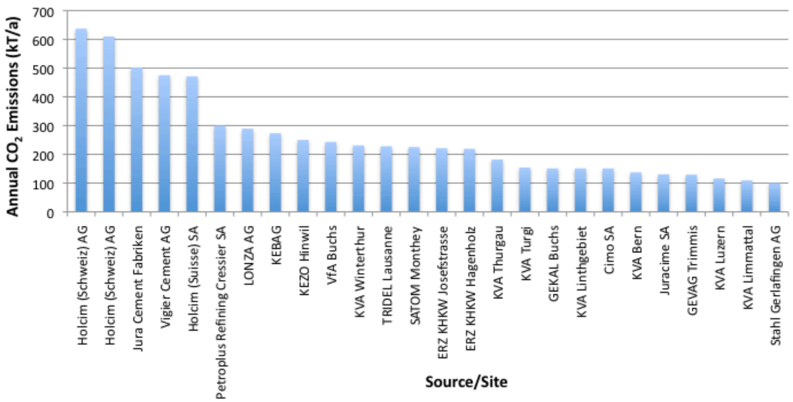


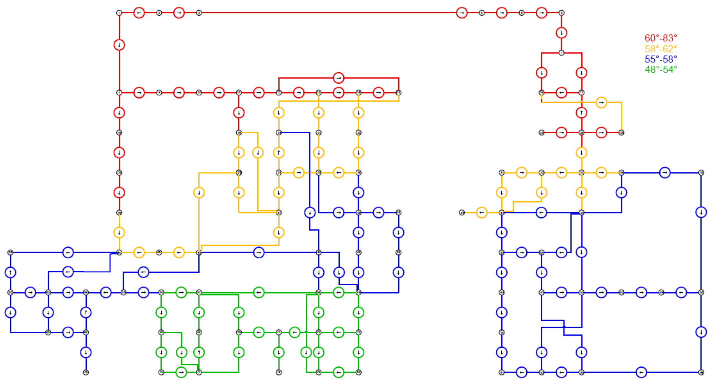
Source: Hirschberg et al., 2008

TA Project Activities 2013: Selected Examples

- **<u>THELMA</u>**: Technology-centered Electric Mobility Assessment (2010-2014; CCEM, SER, EV)
- **<u>CARMA:</u>** Carbon Dioxide Management in Power Generation (2009-2013; CCEM/CCES, SER, Alstom, BFE)
- **Rad-W-LCA**: LCA of nuclear waste disposal (2012-2014; Nagra)
- **ecoinvent v3**: new features (e.g. new properties, more system models, new global supply chains) and datasets (release May 2013; ecoinvent centre)
- **<u>TA Swiss DGE</u>**: Comprehensive evaluation of deep geothermal systems (TA: LCA, costs, risks, integration) (2013-2014; TA Swiss)
- **<u>Alkammonia</u>**: Ammonia fuelled alkaline fuel cells for remote power applications (TA: LCA, cost assessment, MCDA) (2013-2016; EC FCH-JU; AFC Energy)
- **Optiwares**: Optimization of the use of wood as a renewable energy source (TA: external costs) (2012-2016; CCES, CCEM)
- **R-Spill**: Oil spill risk assessment for different regions and facility types (2013-2014; BP Int. Ltd.)
- **MODCAT-CH**: Modelling consequences of Swiss hazard scenarios based on historical observations (2013-2014; FOCP)
- **<u>SoSCI</u>**: Impacts of solar storm events on power grid infrastructure (2013-2014; Swiss Re)





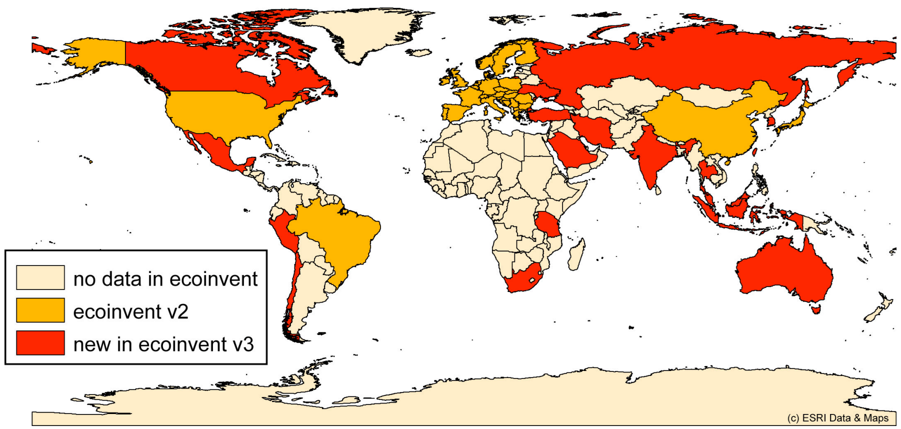


The ecoinvent V3 LCA database

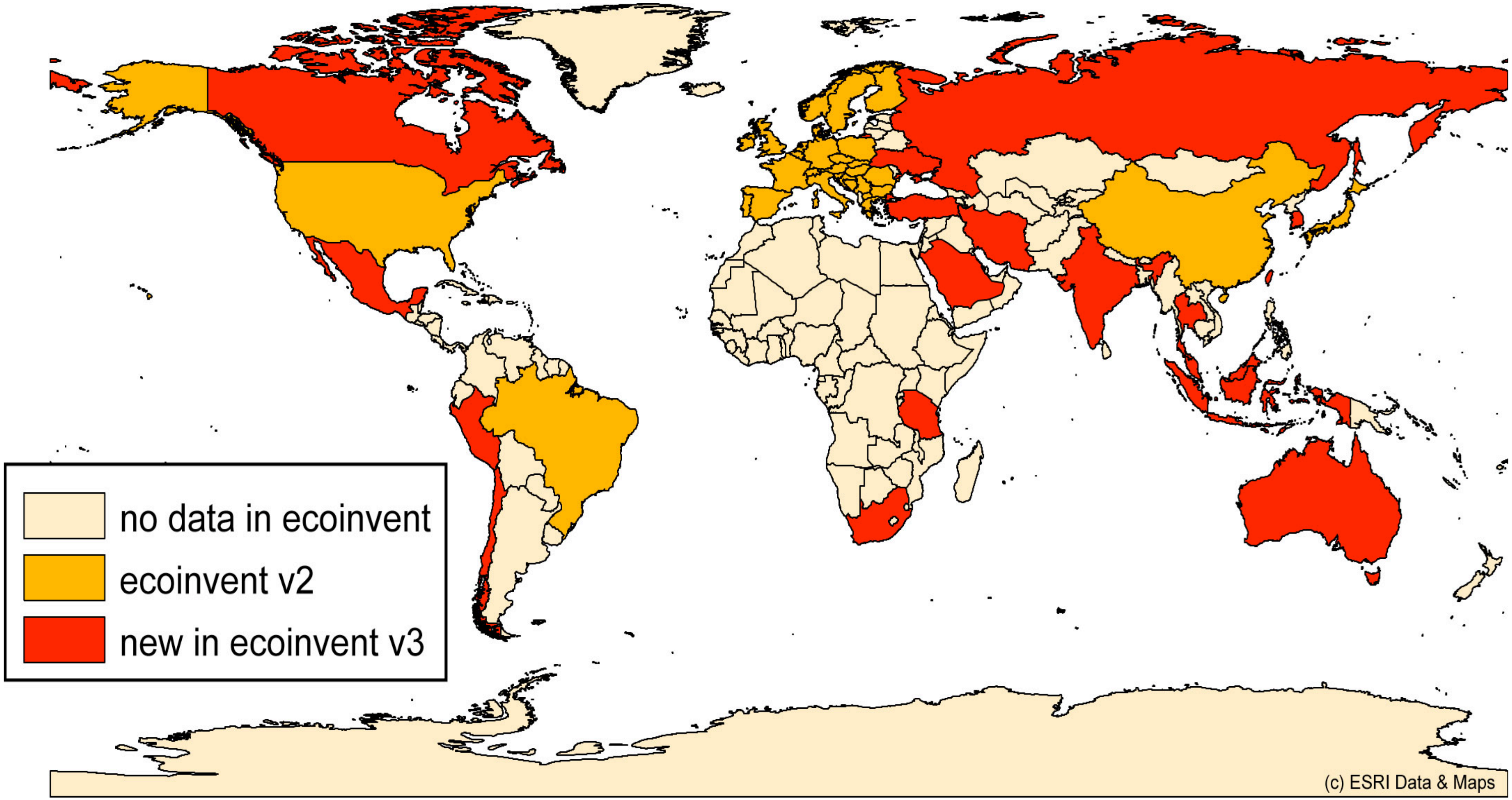
Web-based Life Cycle Assessment database

www.ecoinvent.org

- World's leading supplier of consistent and transparent life cycle inventory (LCI) data
- About 10'000 LCI datasets in total of which PSI contributes ca. one third
- Competence center of: ART PSI EPFL ETH EMPA
- Covers global economy: energy supply, transport, building sector, basic materials, chemicals, agriculture, waste treatment
- Used by more than 4000 members in more than 50 countries
- Included in the leading LCA software and eco-design tools worldwide
- Main recent LEA contribution: electricity supply



Electricity supply in the ecoinvent v3 LCA database



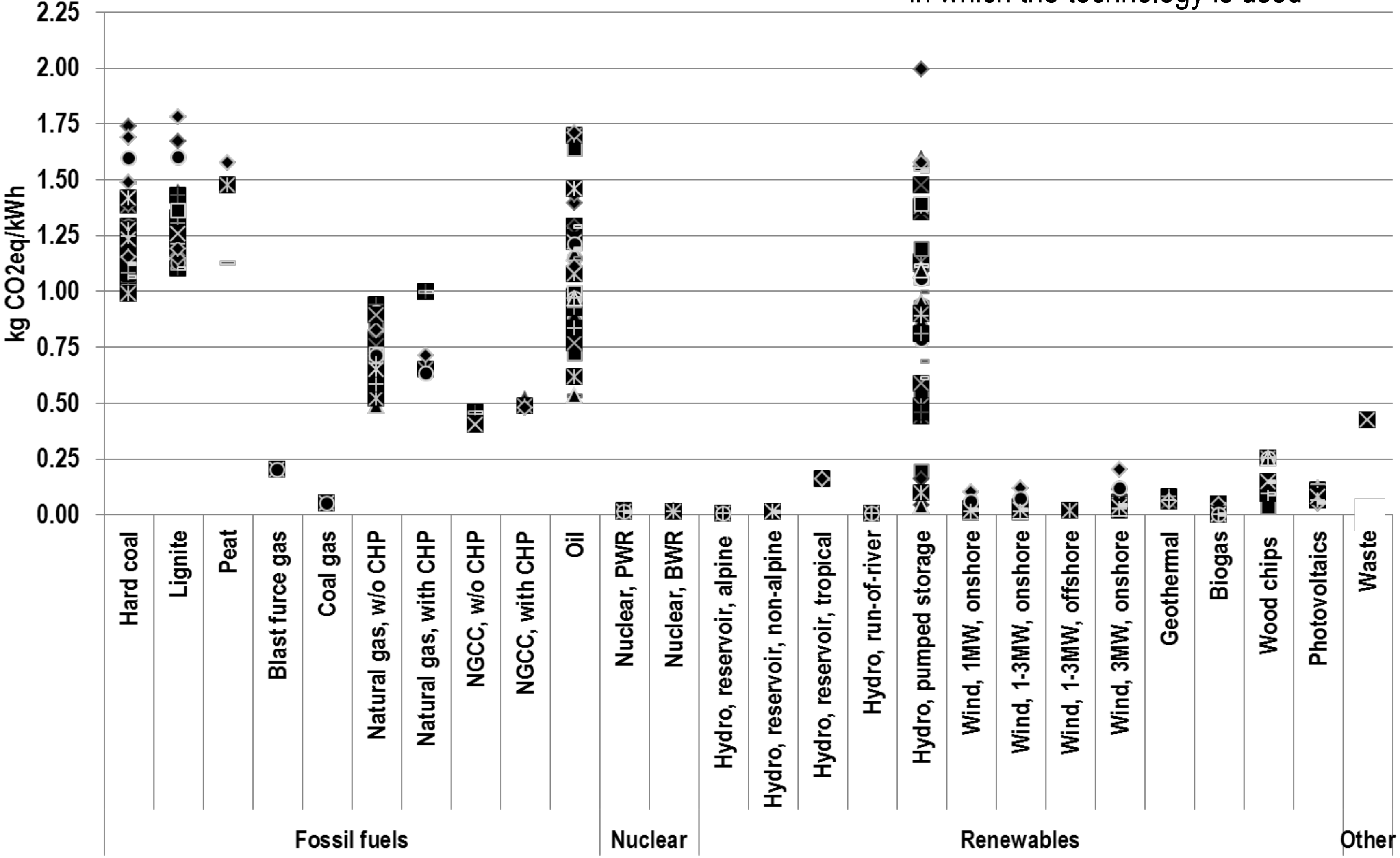
v2: 32 countries – ca. 65% of 2004 worldwide electricity production

v3: 50 countries – ca. 83% of 2008 **worldwide electricity production**

Source: Treyer and Bauer (2013)

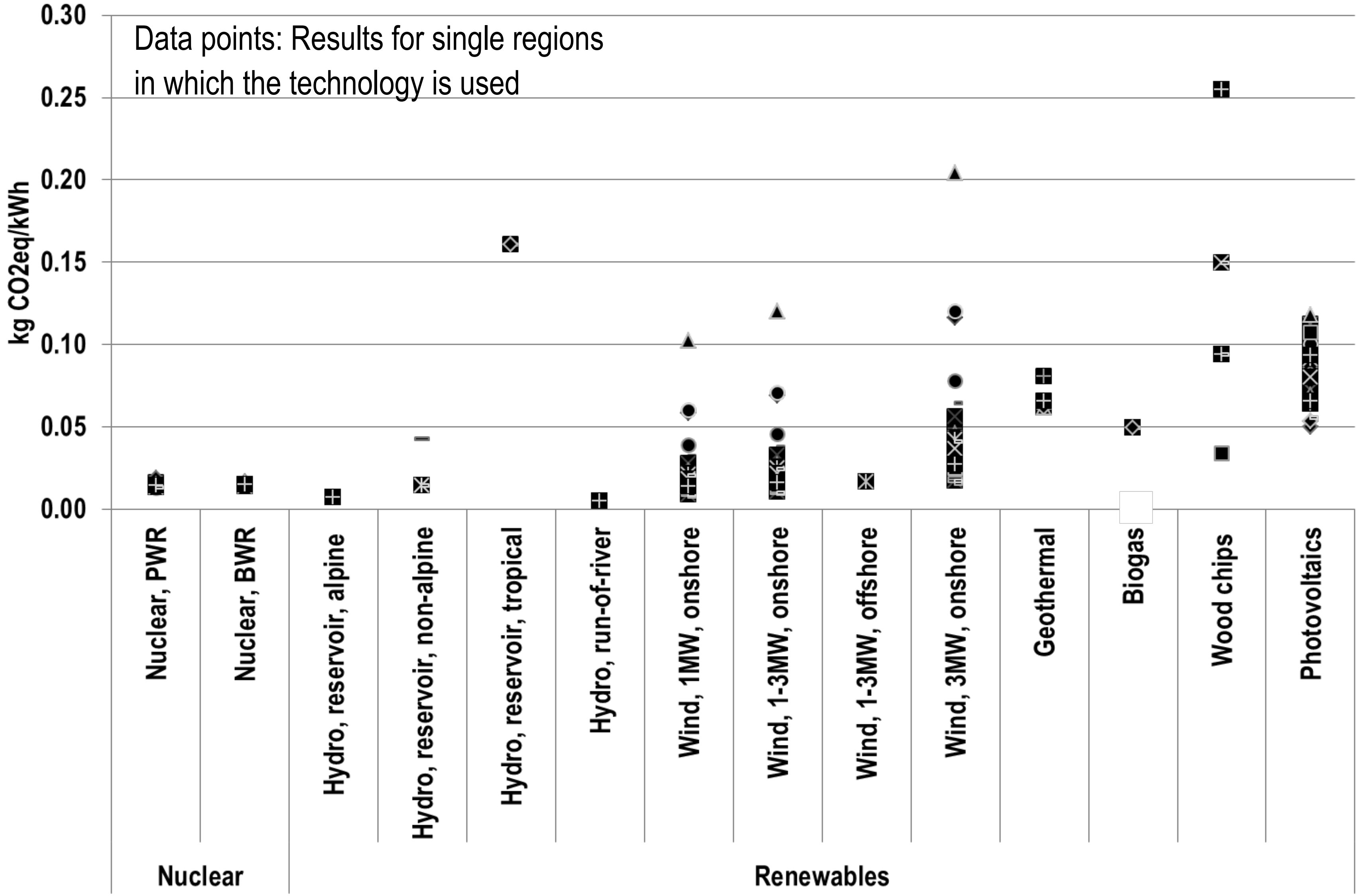
New results: GHG emissions per kWh

Data points: Results for single regions in which the technology is used



Source: Treyer and Bauer (2013)

New results: GHG emissions per kWh – nuclear & renewables

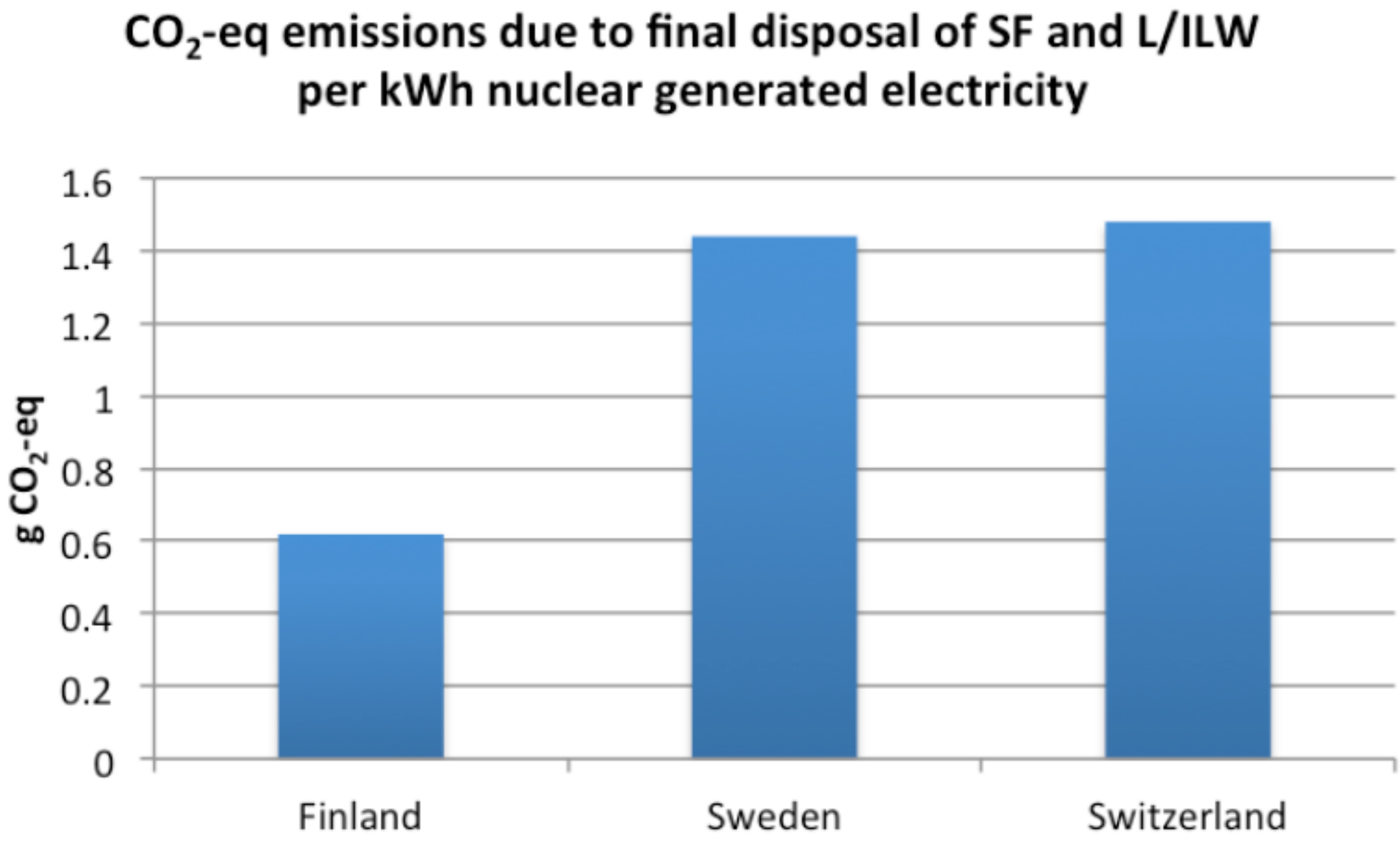


Source: Treyer and Bauer (2013)

LCA of nuclear waste disposal: CH – SE – FI

- Study comissioned and supervised by Nagra (2011 – 2014)
- 2 parts:
  - LCA for rad. waste disposal in CH based on KS11 (latest «Kostenstudie»)
  - LCA for rad. waste disposal in FI & SE based on public info and direct contacts with FI & SE organisations
- **Goal and scope**:
  complete accounting for environmental burdens due to final disposal of high-, intermediate-, and low-level radioactive waste (2 repositories)
  → covering construction and operation until final sealing
- Underlying scenario:
  50 years of NPP operation of CH reactors, 50/60 years in FI and SE

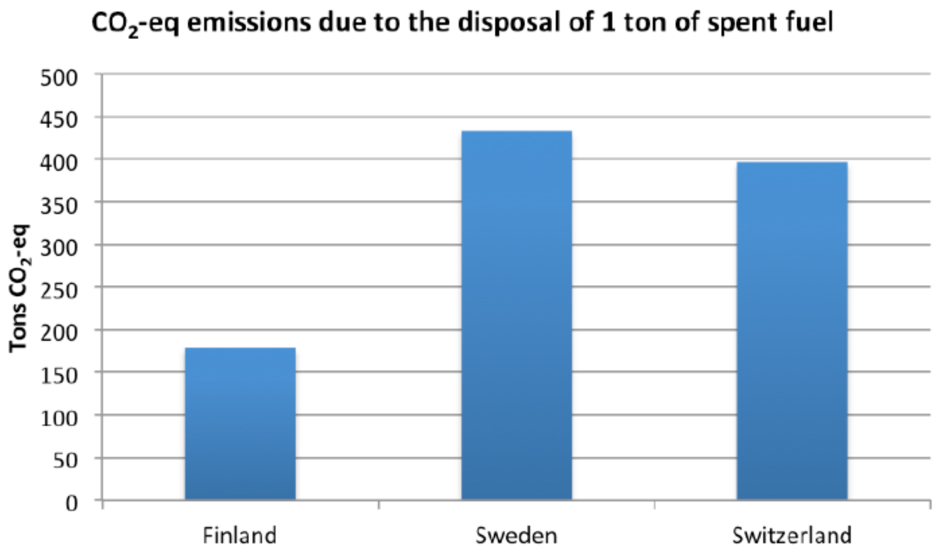
LCA of nuclear waste disposal: CH – SE – FI



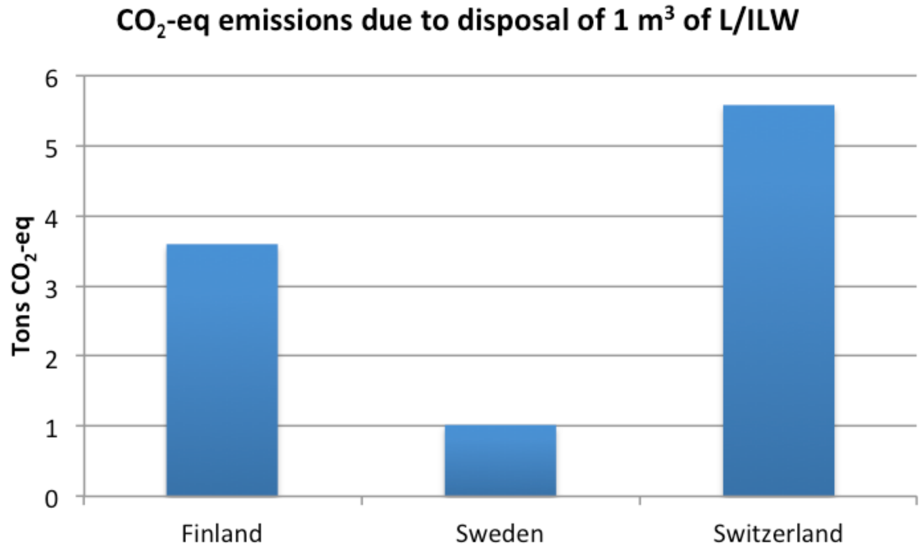
Overall GHG emissions from nuclear power: ~ 15-20 g/kWh

LCA of nuclear waste disposal: CH – SE – FI

Spent fuel

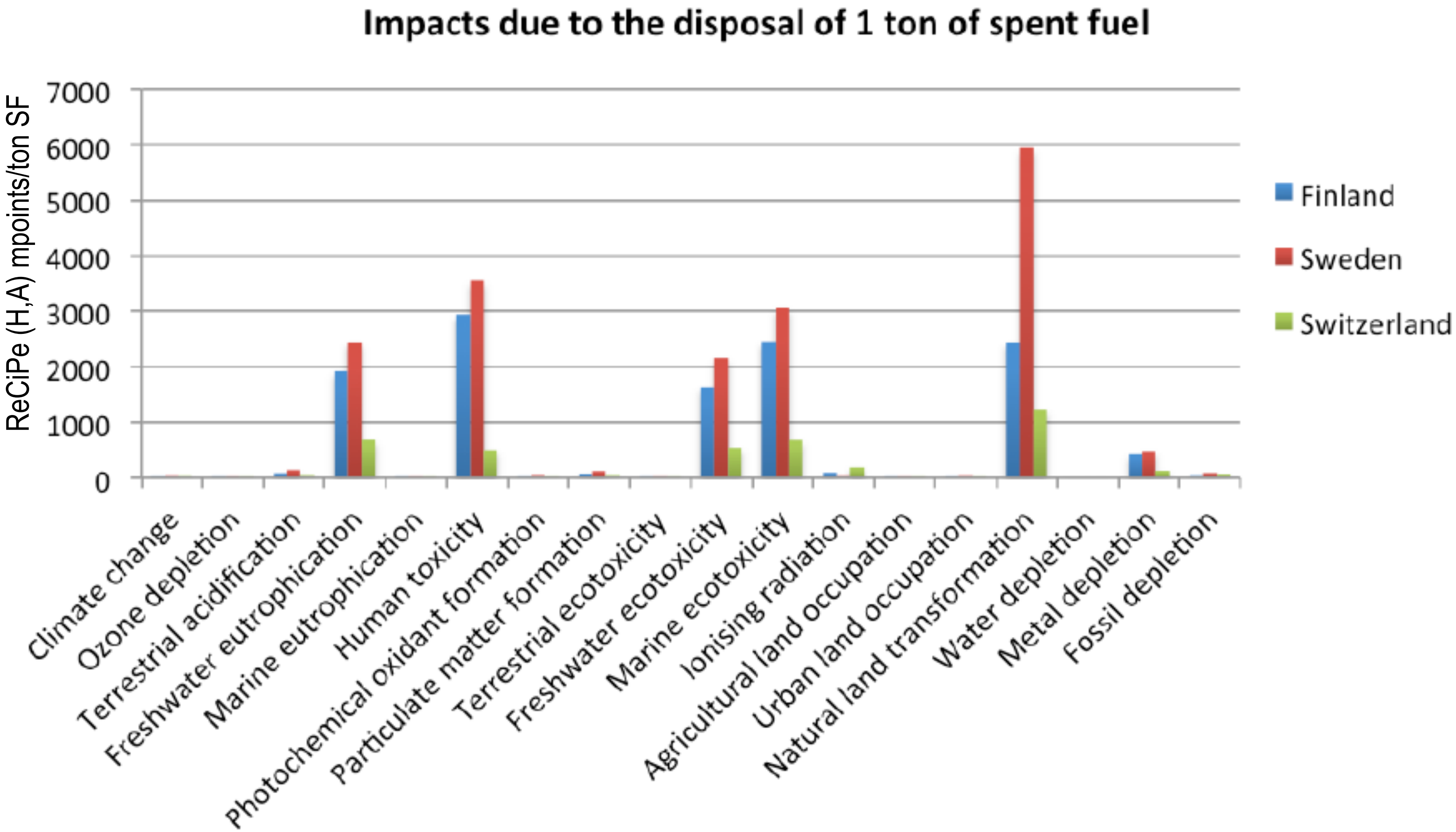


L/IL waste



- Main origin of env. burdens: construction and backfilling materials, waste canisters
- Overall GHG emissions in CH due to geological disposal of radioactive waste: 1.9 Mio. tons (compared to 54 Mt in CH in 2010)
- Similar GHG emissions for SF disposal in CH & SE; lower in FI, different backfill material
- Highest GHG emissions for L/ILW disposal in CH due to cement use (backfill material)

LCA of nuclear waste disposal: CH – SE – FI



Main reason for higher impacts in SE & FI: use of copper for waste canisters

Scenario analysis

- There are significant ***uncertainties*** affecting the Swiss energy system

- These uncertainties can have influences ***throughout the energy system***.

Future

Swiss energy system

Technology development ?

Climate policy ?

Today

Swiss energy system

Future role of geothermal, CCS,… ?

Development of energy prices ?

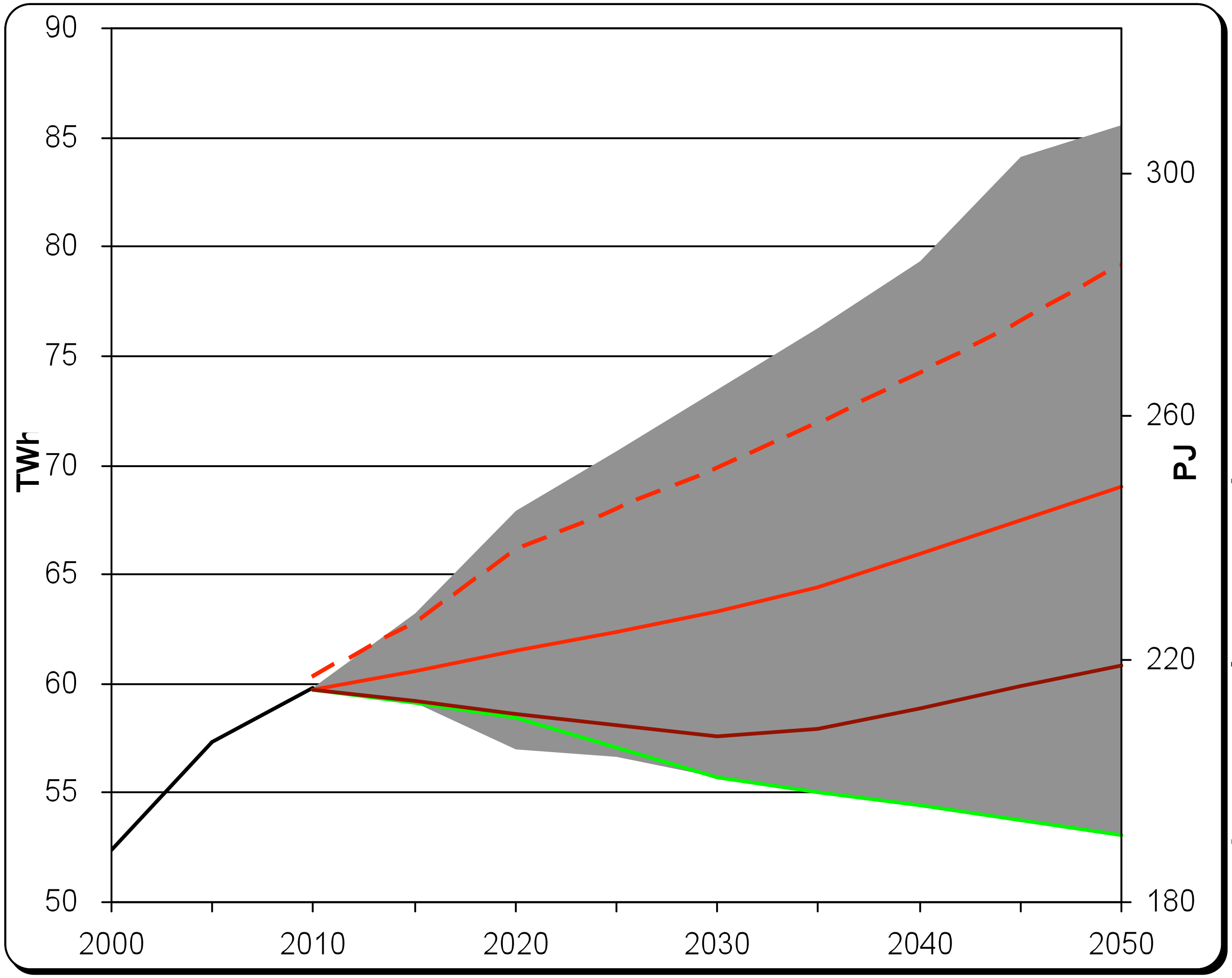
Role of nuclear ?

Objective:

- Analyze how these uncertainties may affect the possible future role of specific technologies.
- Under which conditions specific technologies are robust?

LEA's new electricity supply scenarios for CH

Electricity demand uncertainties



Demands in BFE energy strategy 2050 (Sept. 2012)

→ ***BFE: Business as usual (May 2011)***

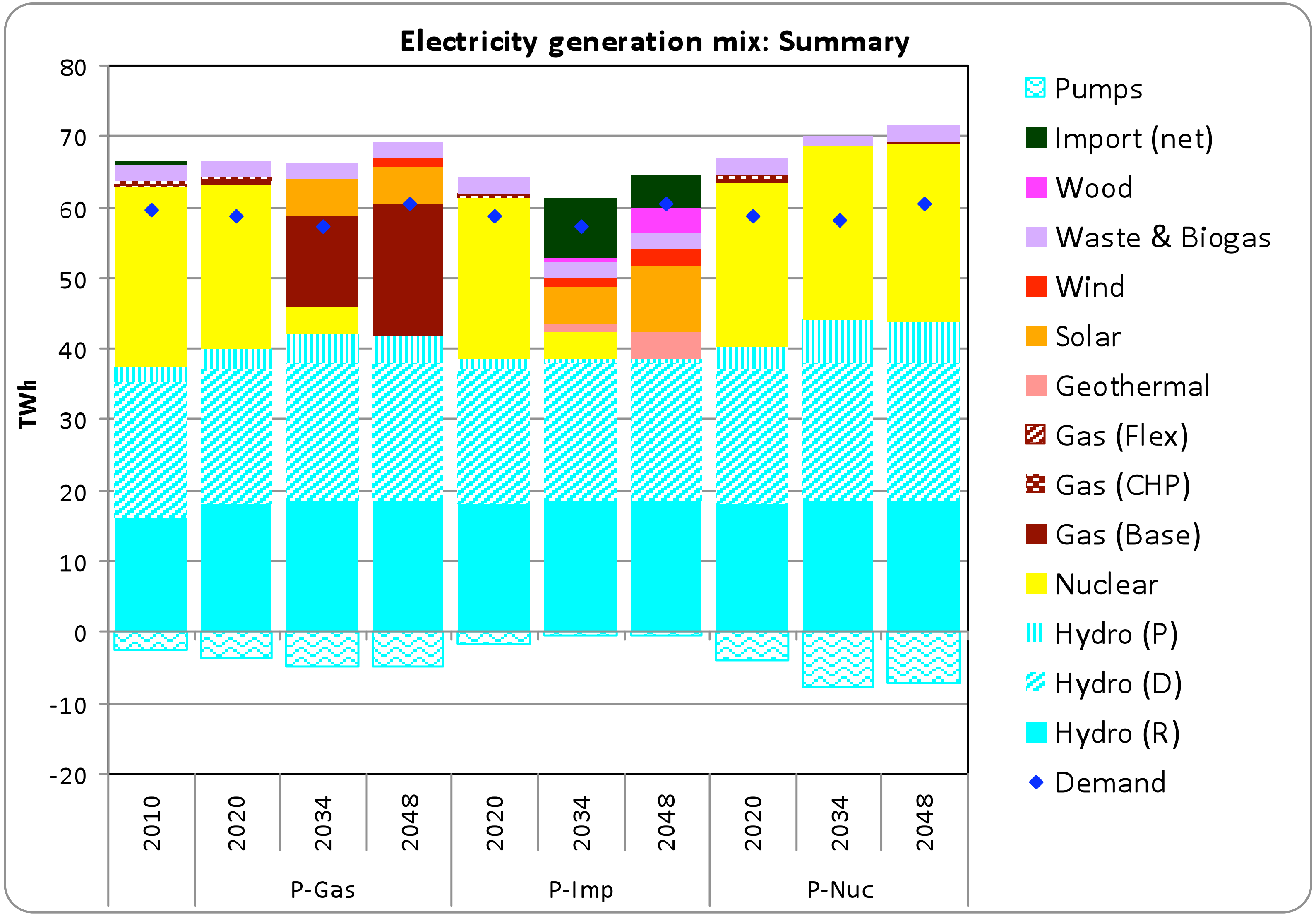
→ **BFE: Business as usual**

→ **BFE: POM - Measures**

→ **BFE: New Energy Policy**

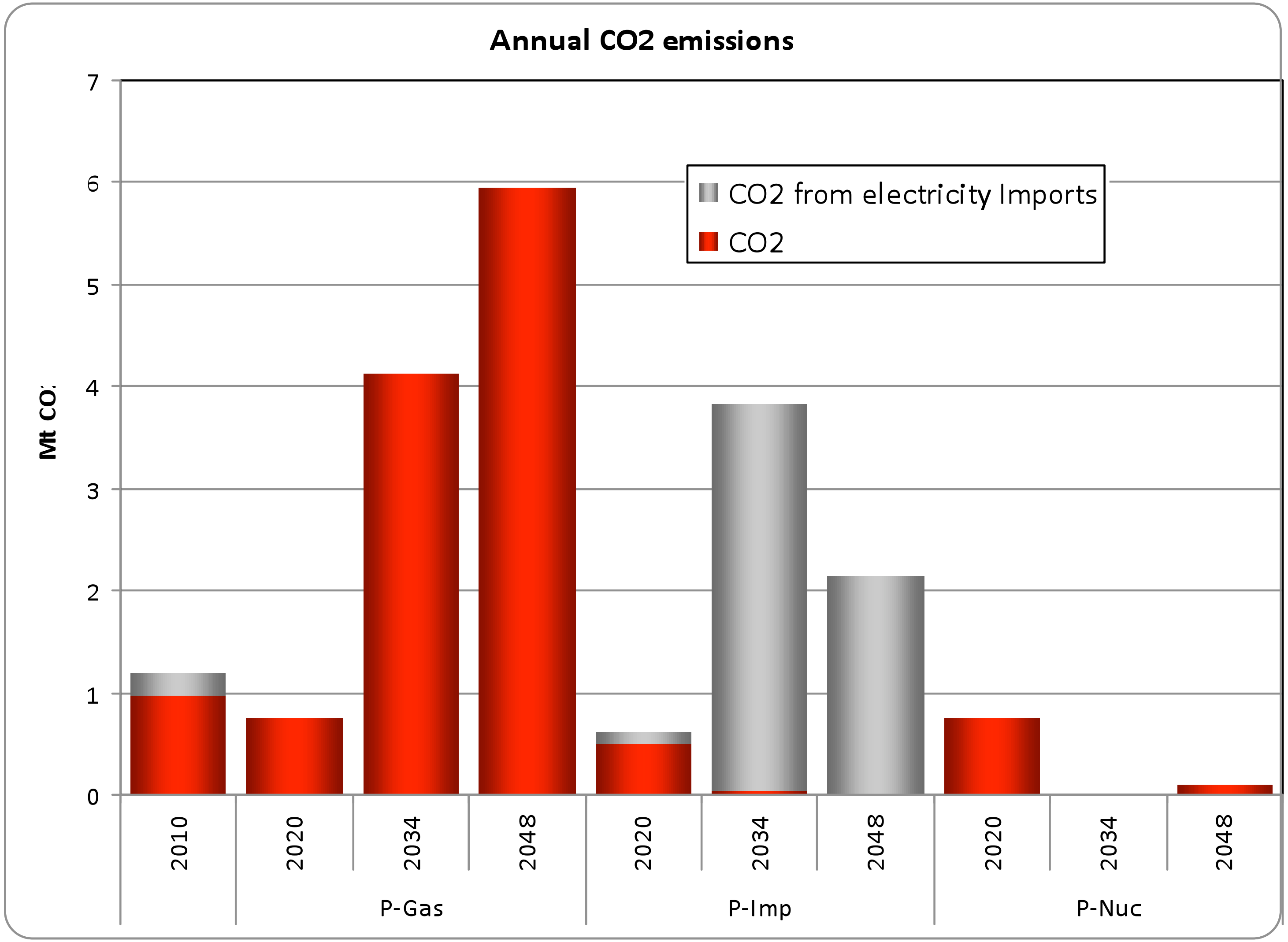
Source: Ramachandran et al., 2012

Electricity generation mix for POM demand



Source: Ramachandran et al., 2012

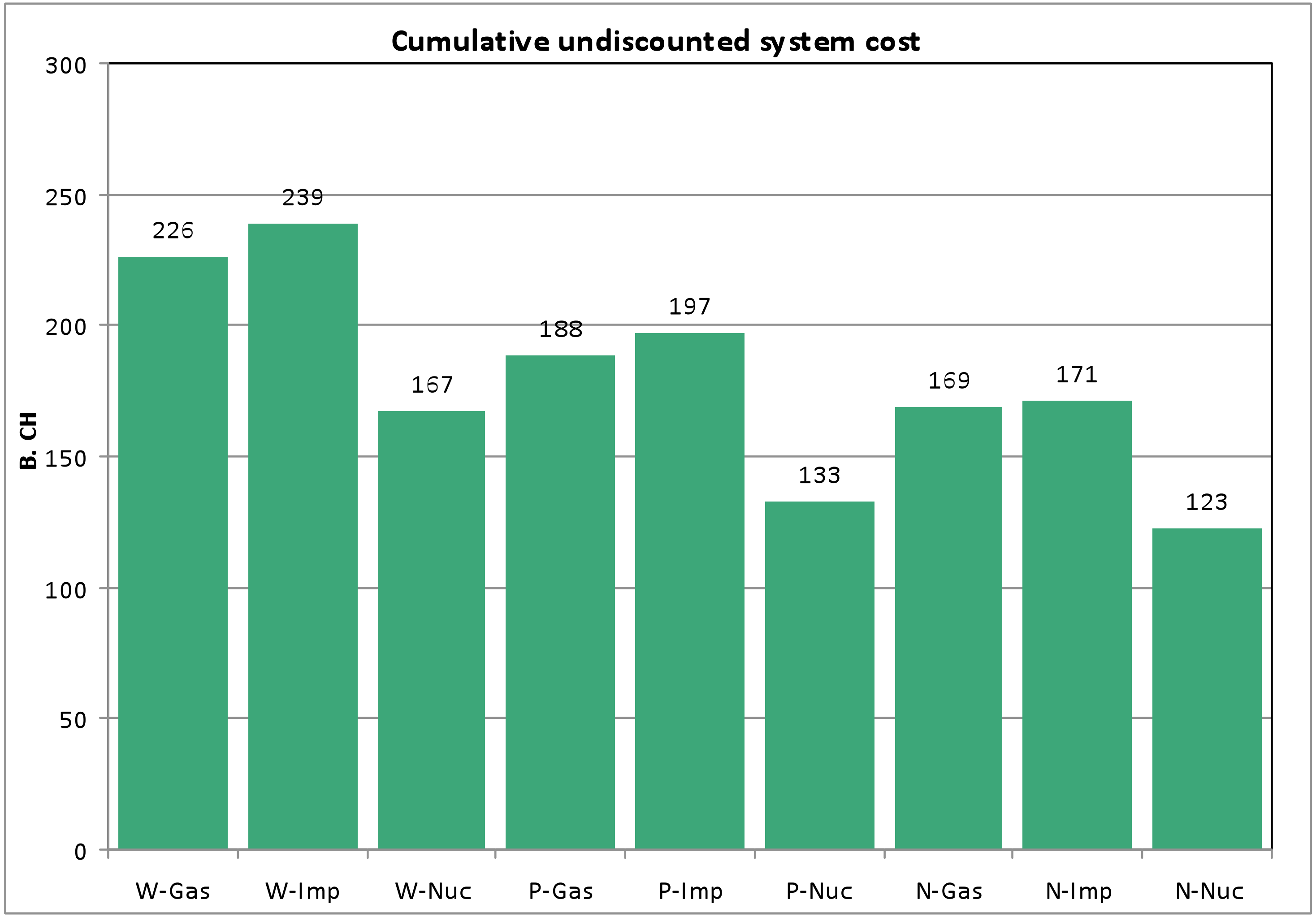
Annual CO2 emissions



Source: Ramachandran et al., 2012

➢ **'Estimated' emission from imported electricity @ 462 g/kWh**

Cumulative (2013 – 2055) undiscounted system costs in Billion CHF_{2010}



Source: Ramachandran et al., 2012

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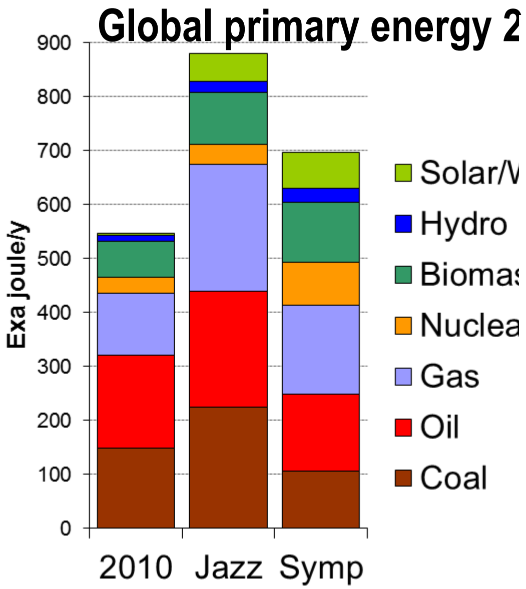
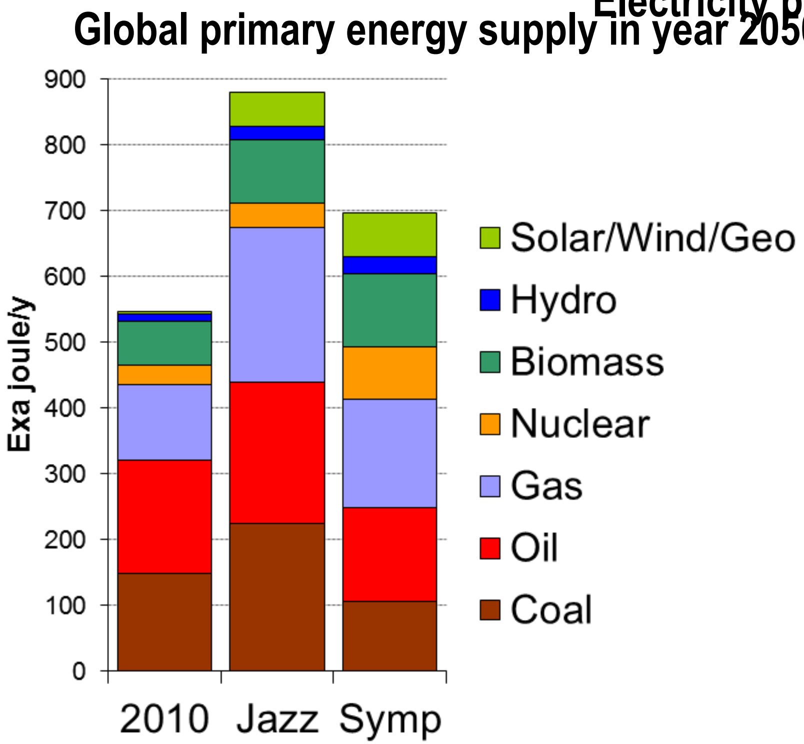
World Energy Scenarios 2050 (LEA-EEG & World Energy Council)

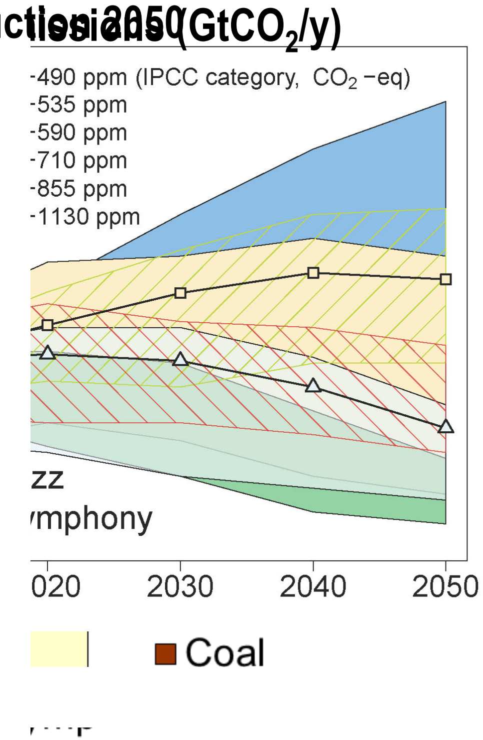
- Highlight at World Energy Congress (7'560 participants); Energie-Spiegel
- **2 scenarios of the energy system** with regional socio-economic factors:

Jazz (market oriented)	Symphony (regulation oriented)
•focus on energy access	• secure & environ. sustainable energy
•«market» chooses technologies	• targeted support for technologies

- **Analytical tool: PSI's energy system model GMM**
- Micro-economic equilibrium model with resources, energy flows, energy technologies and demand sectors in 15 world regions





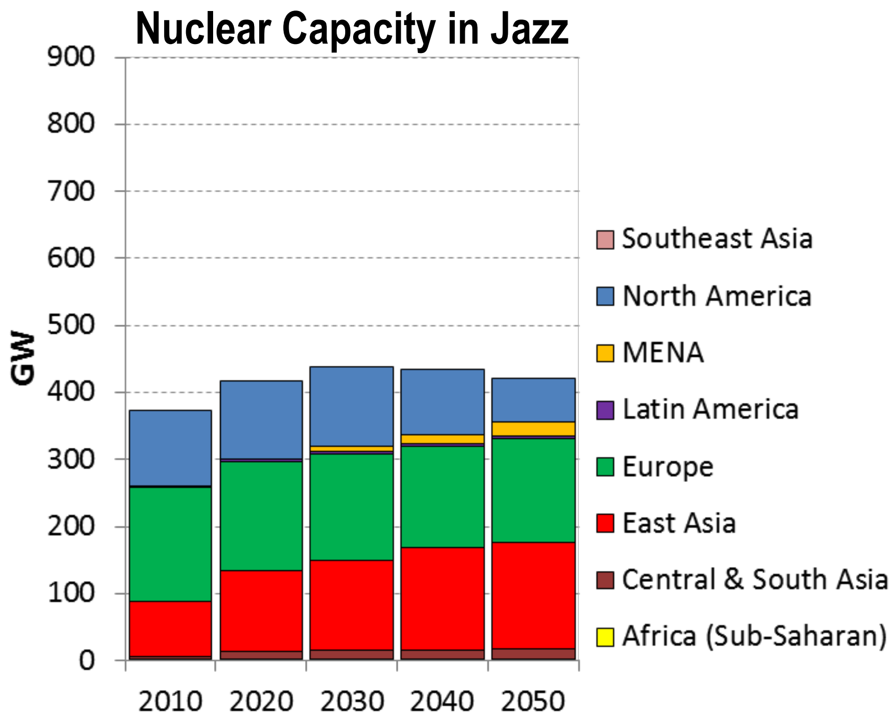


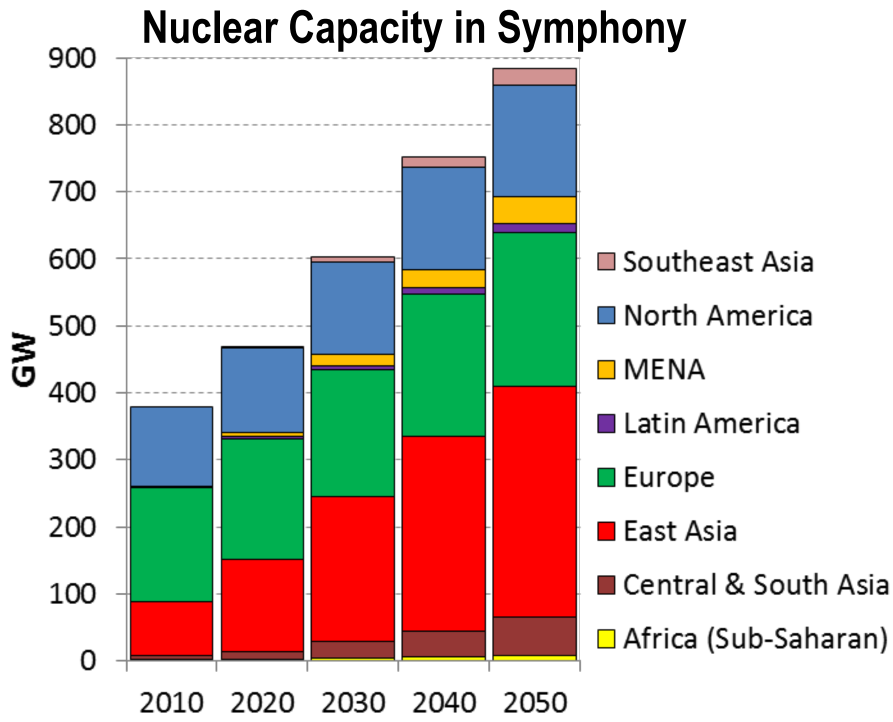
- Fossil primary energy stays
- Increase of electricity enable

PAUL SCHERRER INSTITUT PSI

Nuclear Energy

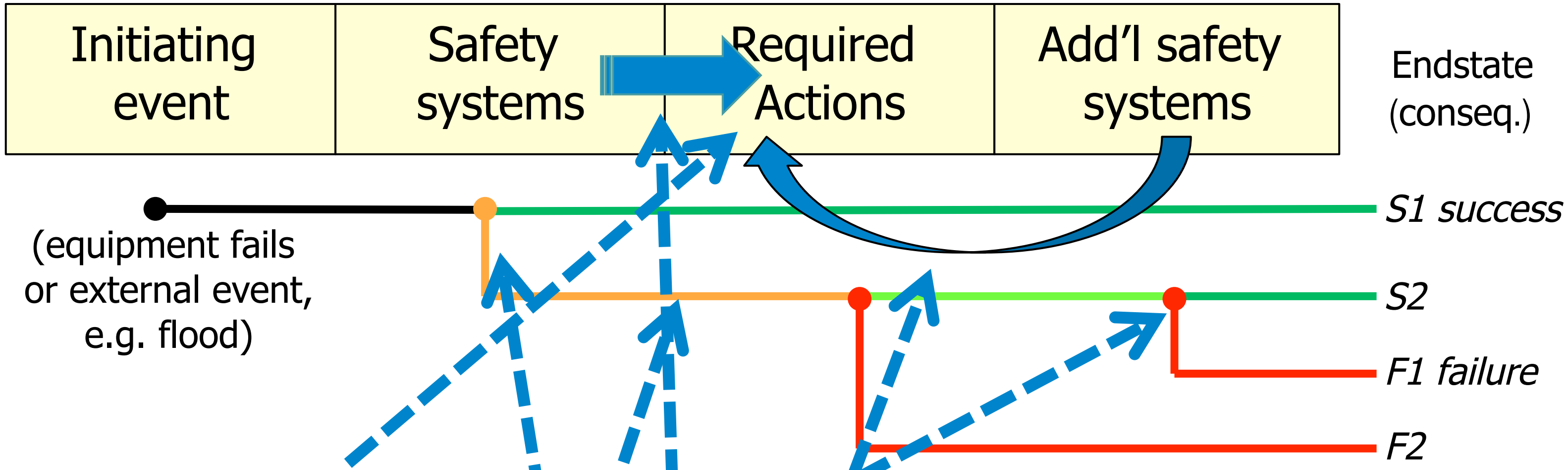
Jazz (market oriented)	Symphony (regulation oriented)
•limited market for long-term projects •slowly emerging, regional CO_2 markets •some nuclear plants under construction are not commissioned	•nuclear growth is enabled by states because of security of supply (quasi-domestic) •internationally convergent ,more stringent CO_2 price





- China: +220 GW in Symphony, +63 GW in Jazz
- Generation 3+/4: 88 GW in 2050 in Symphony (none in Jazz)
- H_2 with nuclear power (high temperature / high pressure electrolysis, sulphur-iodine cycle) after 2050+

Risk and Human Reliability



A. Basic, classical HRA: Identify, Characterize, Quantify

- Situation assessment (decision) + implementation

B. “2nd order” issues: *“Errors of commission”.* Undesired, aggravating actions, not foreseen in design, emergency procedures, training.

- Can be postulated almost anywhere – need efficient screening

- Predicting these decision failures and estimating their probabilities even more difficult

C. Dynamic PSA: Simulation-based risk assessment

- Eliminate (some) simplifications made in order to handle numerous combinations of initiating events and failures, e.g.. quasi-static model above
- Dynamic event trees – simulation model combined with failure model generates order of headers, considers variability of timing. Also allows propagation of physical uncertainties.

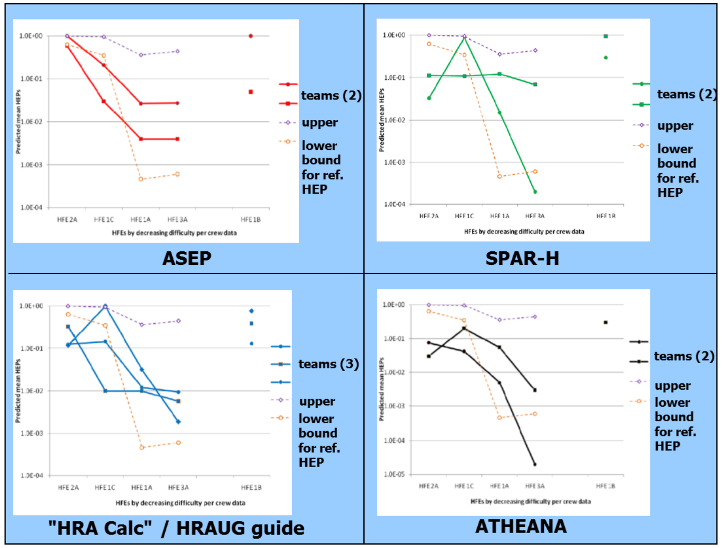
Using dedicated simulator studies to assess HRA methods

Int'l HRA Empirical Study (NUREG-2127, HPR-373, NUREG/IA-0216)

- SGTR (2 scenarios), LOFW (2 scenarios)
- 13 actions (HFEs)
- 14 licensed crews
- method vs. reference data. Could not address inter-analyst method reliability (consistency)

U.S. HRA Empirical Study (NUREG-2156)

- 3 scenarios: SGTR, LOFW+induc. SGTR, Loss of CCW and Seal LOCA
- 4 (+1) actions (HFEs)
- 4 licensed crews
- 2-3 analysis teams per method * 4 methods



Probabilities are the output of interest but analyzing the consistency of rationale/ findings underlying them is essential.

- **Int'l study data collected in Halden**
- **U.S. data collected at US NPP by plant & Halden staff**
- **Data analysis from operational, human factors, PRA, and HRA perspectives a major part of the effort**

Study steering/assessment group
- **USNRC +Sandia+INEL**
- **OECD Halden**
- **PSI** (participation supported by ENSI)
- **EPRI**
- **EDF** (steering only)

An effort to set up an international study on quantitative uses of simulator data in support of HRA (analyses) is under way.

LEA Risk and Human Reliability – 2013

HRA-IV Completed

EOC analyses for Swiss plants
- Pilot III study report issued following plant review
- Pilot II (KKL) published in RESS journal article

EOC quantification
- CESA-Q revision – model-based quantification using Bayesian Belief Network framework: basic approach published in RESS 2013; new postdoc

Simulator data / HRA Empirical Studies
- Int'l HRA Empir. Study: Halden Project Report with overall findings (HPR-373), forthcoming as NUREG-2127
- Interm. results for intra-method (user) variability, U.S. study, 2012; final results report *(2014)*

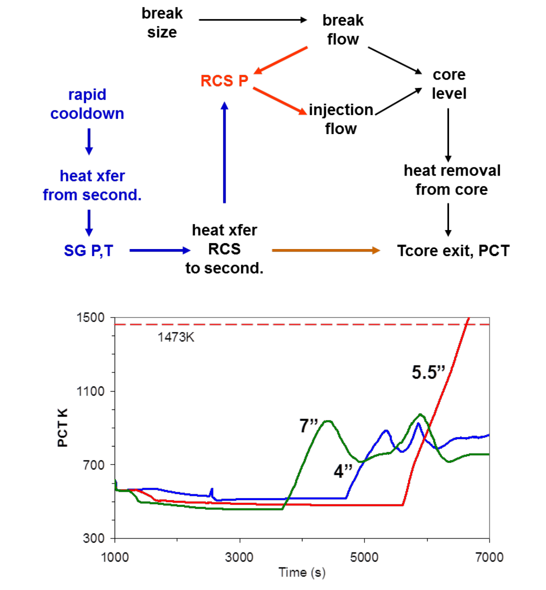
Seismic HRA
- Review of seismic events at NPPs (technical basis for seismic HRA)

Proton Therapy safety analyses

- Risk analysis of Gantry 2 safety systems and functions: qualitative assessment of coverage

Probabilistic-deterministic analysis: Uncertainty propagation in dynamic event tree analyses

- **swissnuclear project relaunched** w/ LRS postdoc (12.2013)
- **Nuclear M.S. thesis, starting 2.2014**



Interacting, dynamic, competing processes make identifying limiting cases challenging

Errors of Commission Pilot Studies

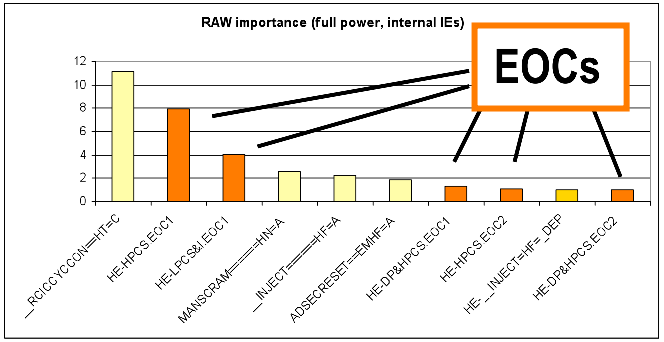
PSI's CESA method

"Commission Errors Search and Assessment"

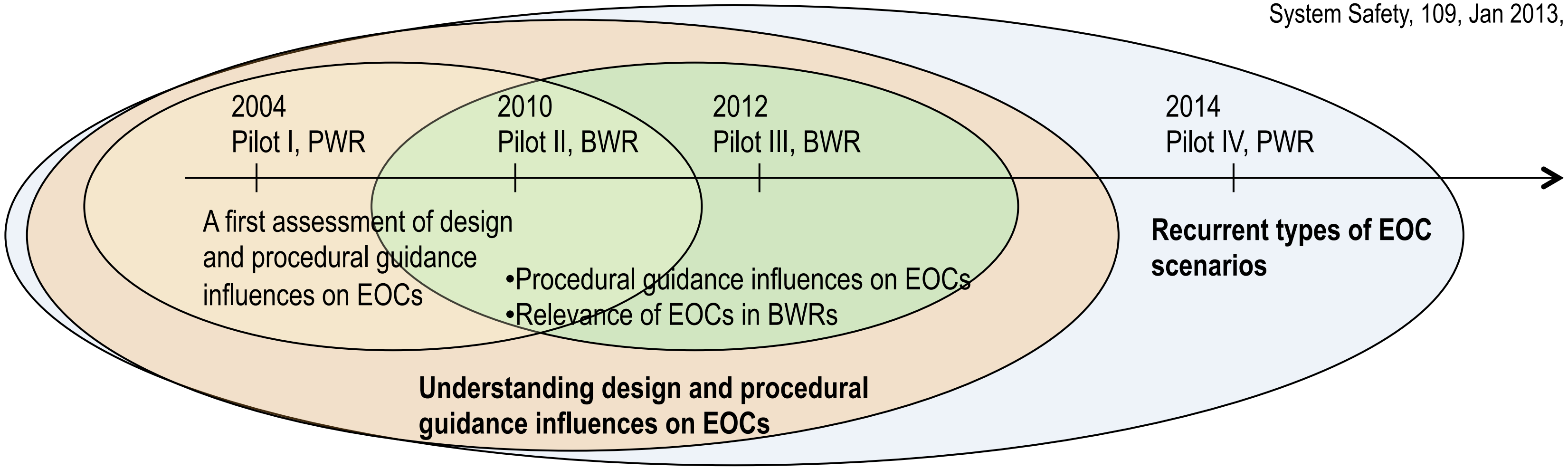
- **start with key actions required** in accident scenarios
- **then search for situations** where action criteria
  - are satisfied but action is inappropriate
  - erroneously appear to be satisfied

- ❑ **One of 1st EOC studies for Boiling Water Reactor**
- ❑ **6 scenario-specific EOCs added to PSA**
- ❑ **Contribution of top EOCs comparable to EOOs**

~ 5% increase in CDF (internal, at-power)



L. Podofillini, V.N. Dang, O. Nusbaumer, D. Dres, "A pilot study for errors of commission for a boiling water reactor using the CESA method" Reliability Engineering & System Safety, 109, Jan 2013, 86-98



LEA strategic goals

- Developing, implementing and applying integrated framework for inter-disciplinary technology assessment.
- Developing, maintaining and extending comprehensive and consistent databases relevant for inter-disciplinary systems analysis.
- Developing analytical models and tools to improve understanding of energy technology development and policy strategies for realizing sustainable energy systems at the Swiss, European and global levels.
- Addressing current and emerging safety issues, through the development, evaluation and application of risk analysis and human reliability analysis methods, and the collection and analysis of data and operating experience.

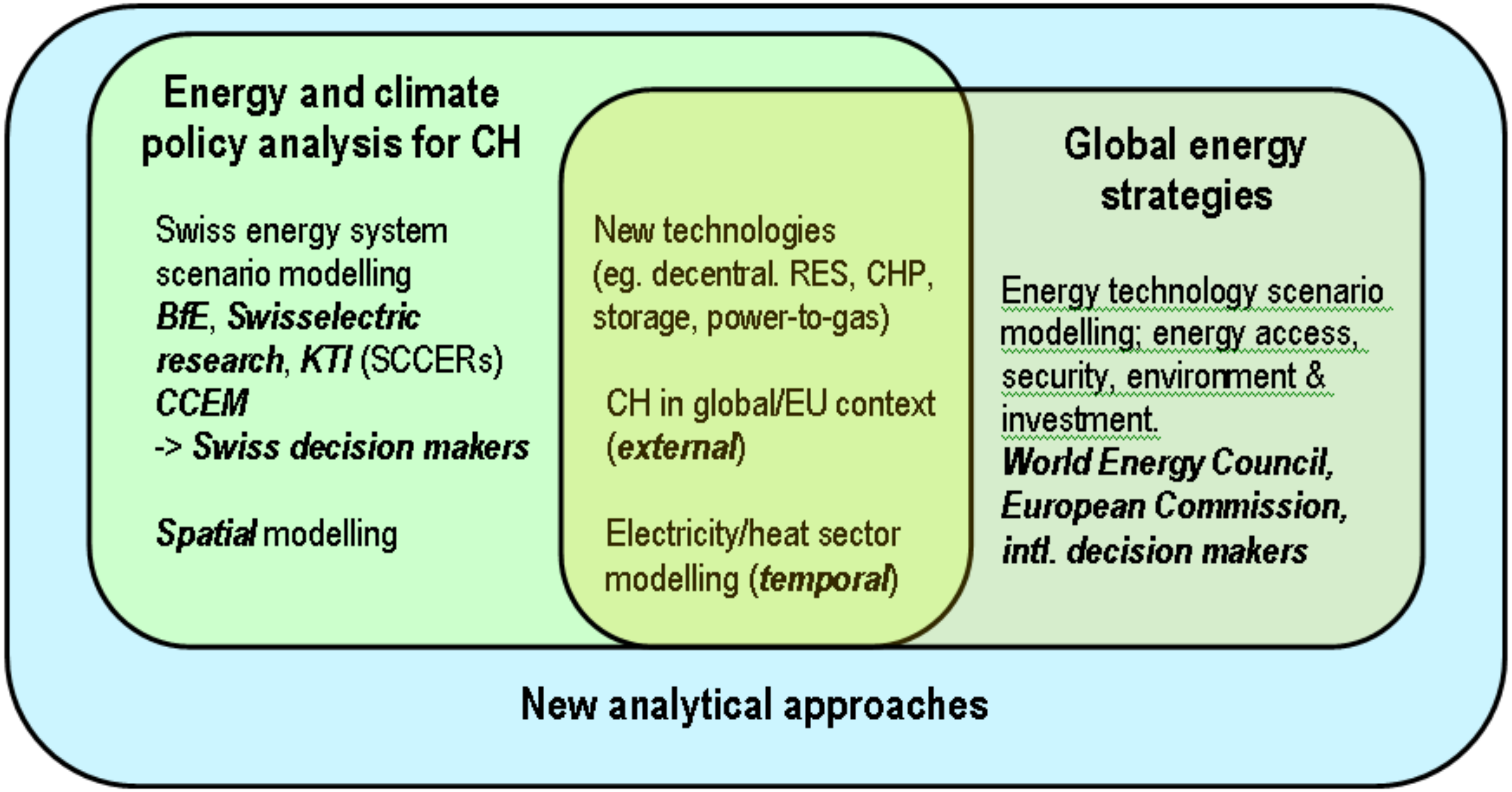
LEA Technology Assessment Project Portfolio

LCA, EIA&EC:
- Ecoinvent v3 updates and extensions
- LCA of nucelar
- Optiwares (biomass)
- Nagra (finishing 2014)
- Pilot project Basel

Integrated Assessment:
- SCCERs
- NRP70
- ALKAMMONIA, POWER UP, TOWER POWER
- Integration of stochastic renewables
- Migthy MCDA
- THELMA (finishing 2014)
- TA Swiss DGE (finishing 2014)

CRA:
- Future resilient systems
- Geotherm-2
- Critical infrastructures
- Risk of innovative reactor concepts
- Oil spill benchmarking
- ENSAD updates and extensions

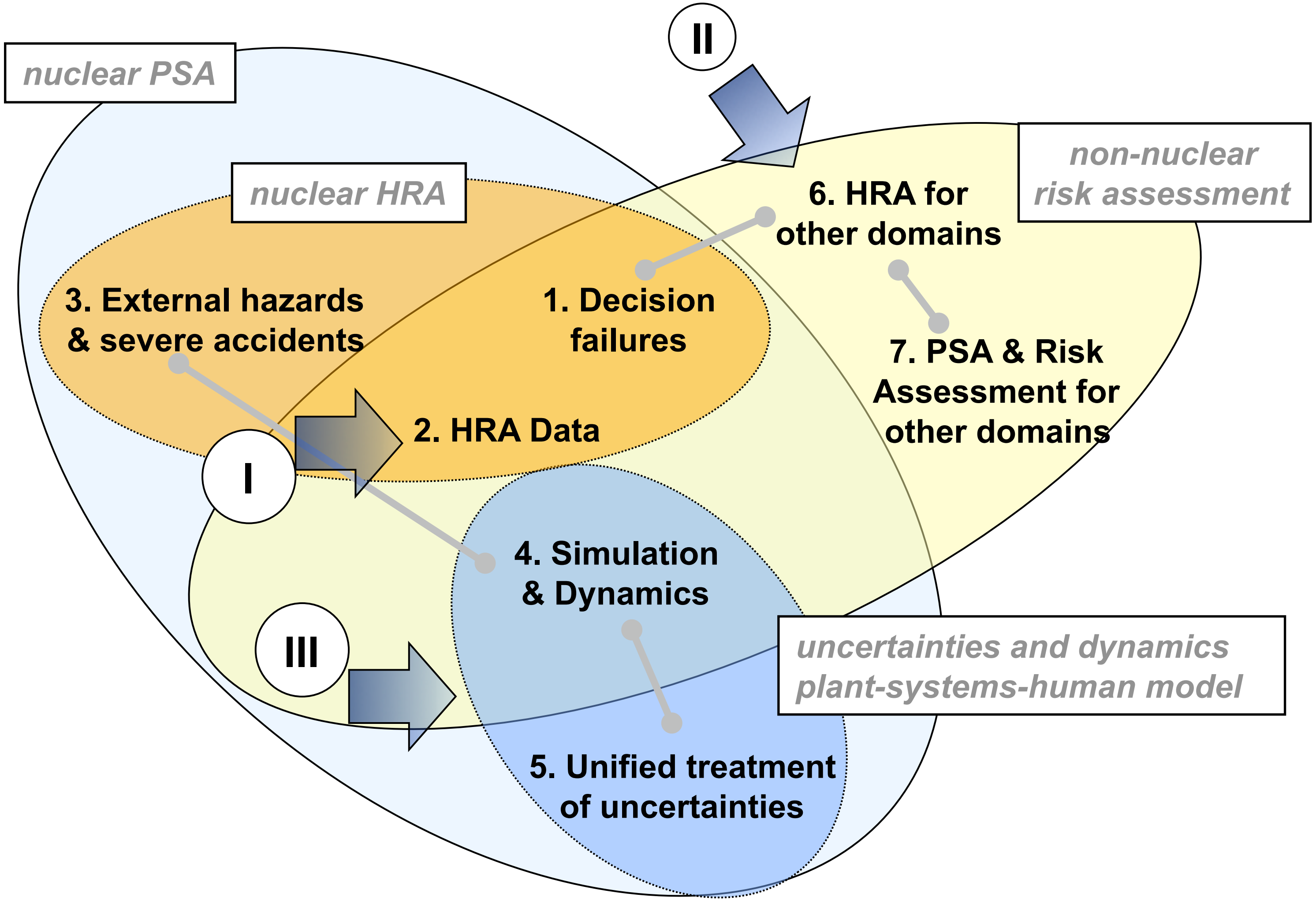
LEA Energy Economics Project Portfolio



LEA RHR: Strategic areas and new projects

Core Competencies and Strategic Areas	New activities and projects to 2017
Human Reliability Analysis – nuclear HRA	❑ ***Reliability of Operators in Emergency Situations*** (ROES, 2014-2017) ▪ HRA data collection in simulators, pilot, to be scaled up in follow-on ▪ HRA, decision-making in external hazard scenarios
Dynamic PSA: Analysis of accident dynamics and uncertainties	❑ **Dynamic PSA for advanced reactor designs** – could provide an element of NES (multidisciplinary, multi-lab) *Zukunftsprojekt*
PSA and System Safety: PSA / HRA in other domains	❑ ***People & Operations in Resilient Systems*** (for Singapore NRF, “Future Resilient Systems”) – proposed 2014-2018 ▪ HRA and risk analysis for other domains, societal risks ▪ Other more moderately scaled proposals being prepared: industrial safety, healthcare

LEA Risk and Human Reliability



- **Building on core disciplines, activities, and topics**
- **HRA ... PSA and Risk ... Dynamic risk assessment**

Final remarks

- New modelling challenges posed by planned increased decentralization of the Swiss energy system (e.g. expansion of stochastic renewables, need of storage options, security of supply issues and other old and new risks)
- Nuclear remains to be an important option particularly from international perspective
- Critical importance of integrated systems analysis
- LEA is well prepared for the new challenges thanks to its diversification, successful project acquisitions, variety of available competences, balanced and fact-based approaches, and excellent reputation
- Very high increase of second party funds
- Timely focus on critical risk topics for NPPs: human factors, seismic and flooding risks
- Strong enhancement of synergies between LEA-groups and co-operation with other PSI departments

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Thank you for your attention!

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