PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

**Paul Scherrer Institut**

Stefan Hirschberg

# Laboratory for Energy Systems Analysis (LEA): Competences and Highlights

**NES Event 18 March 2015**

# 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.

# Inter-departmental Laboratory for Energy Systems Analysis

**Technology Assessment (TA)**
**P. Burgherr**

- 9 staff scientists
- 1 Ph.D. student
- 1 vacancy (Ph.D. student))

**Energy Economics (EE)**
**Vacancy**

- 2 staff scientists
- 2 post-docs
- 3 Ph.D. students
- 2 vacancies (GL + Ph.D. st.)

**Risk & Human Reliability (RHR)**
**V. N. Dang**

- 5 staff scientists
- 1 post-doc
- 1 Ph.D. student
- 1 vacancy (Ph.D. student)

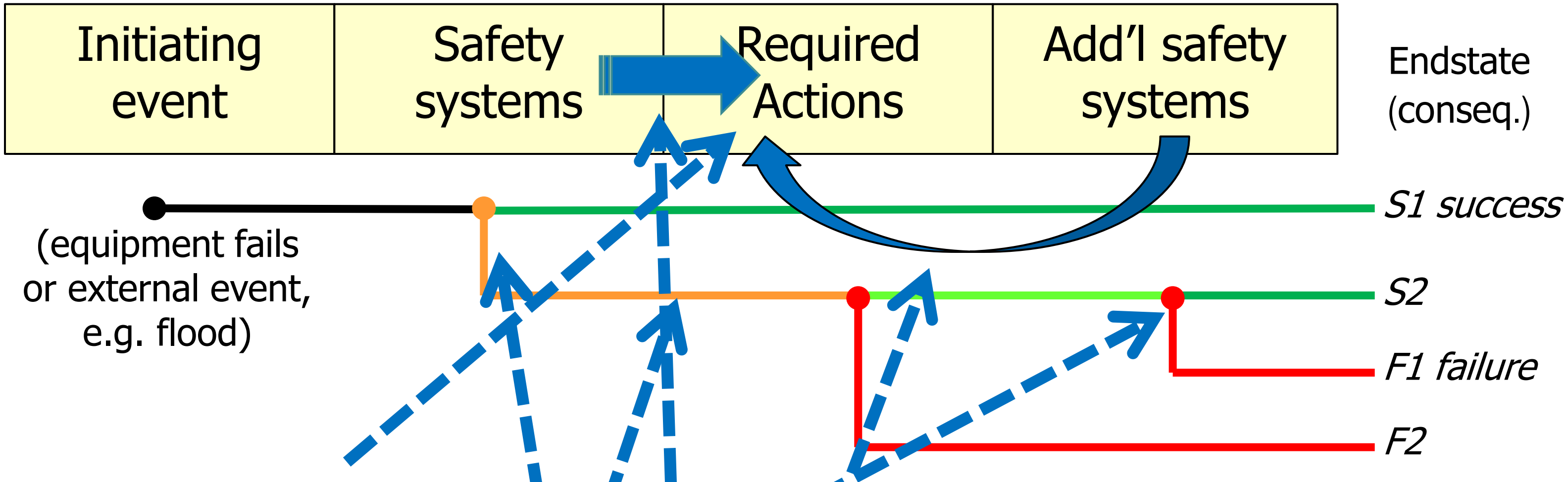
## Personnel

- Currently 17 staff scientists (including Lab-head); thereof 5.8 PSI positions
- 3 Post-docs, 5 Ph.D. students
- 4 vacancies (+ 9 Future Resilient Systems Singapore)
- High number of Master/Bachelor students and internships
- Inter-disciplinary and multi-national (15 countries)
- Personnel with German as mother tongue (6), Swiss (4) and women (7)

## Scope

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

# Risk and Human Reliability



Initiating event

Safety systems

Required Actions

Add’l safety systems

Endstate (conseq.)

(equipment fails or external event, e.g. flood)

*S1 success*

*S2*

*F1 failure*

*F2*

**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

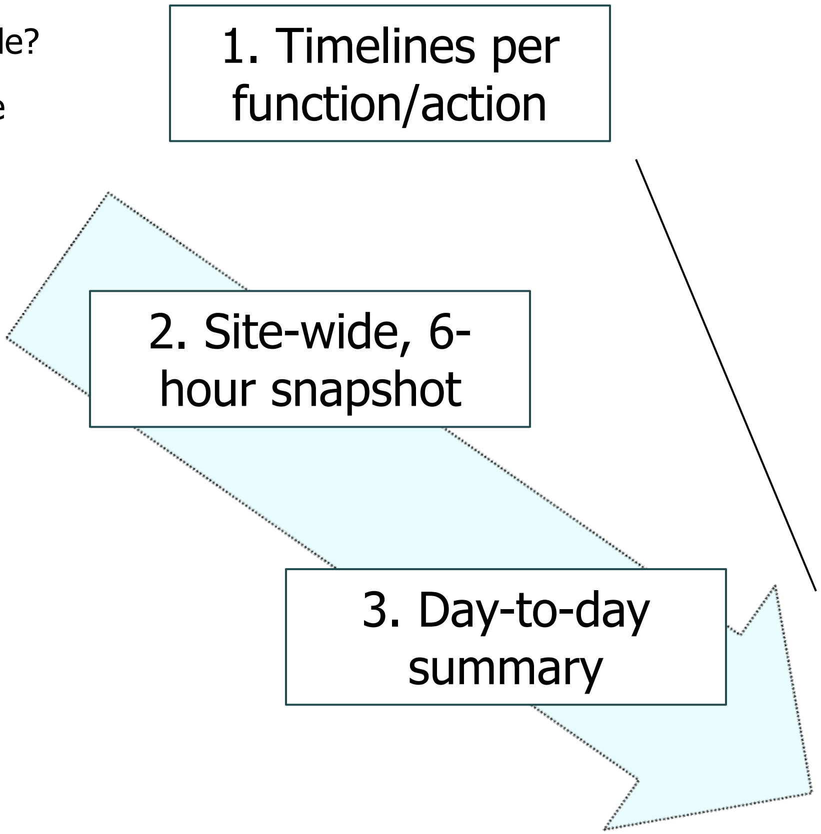
**C. Dynamic PSA: Simulation-based risk assessment**

- 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.

# Fukushima – analysis from an HRA view

Questions

- What did decision-makers know about state of the units, over time?
- When were decisions made?
- What procedural guidance (EOPs, SAMG, AM) was available?
- How long did implementation require?
- Was implementation successful? (why not?)
- Personnel and equipment resources?



1. Timelines per function/action

2. Site-wide, 6-hour snapshot

3. Day-to-day summary

| **“Action” phases** | |
|---|---|
| Decision / cognition | *Pre-decision (evaluate/develop options)* |
| | Strategy (set or change goal) |
| | *Plan (develop/adapt implementation plan or procedure)* |
| | Decision - initiate |
| Implem-entation | *Pre-implementation (collect and stage equipment)* |
| | Implementation - start |
| | Implementation – completion of actions |
| | *Implementation – outcome (effective, failed, etc)* |

- ➢ Decisions, outcomes of actions, contributors to delays
- ➢ Shortcomings of procedures and guidance
- ➢ Performance issues

# Site-wide, 6-hour snapshot (excerpt)

| Day | Time | Events | Goals |
|---|---|---|---|
| **03-11** | 1800-0000 | 1830 U1 freshwater inj. ready but reactor pressure is too high<br>2007 U1 reactor pressure read locally<br>2049, 2158 U1&U2 CR temporary lighting; U3&U4 temporary lighting<br>2350 U1 containment pressure read, near design pressure | From afternoon, batteries collected from buses etc. to power instrumentation; small generators collected (for temporary lighting, and for instruments). |
| **03-12** | 0000-0600 | 0000-0400 aftershocks delay actions<br>0400 U1 – fire engine connected (higher discharge head than D/D fire pump)<br>0430 Tsunami warning and suspension of field work (duration unclear)<br>Arrival of power supply trucks from offsite. | 0006 U1 decision to prepare venting plan<br>0130, U1 venting strategy decided, pending (offsite) evacuations<br>0245 U1 decision to use fire engine for inj. |
| | 0600-1200 | 0546-1430 U1 freshwater inj. at low rates<br>0720 Low voltage for U1 provided | Cabling of power for U1 & U2<br>0905 U1 venting decision (alignments begin 0915) |
| | 1200-1800 | 1430 U1 venting succeeds (rupture disk ruptures)<br>1453 U1 freshwater runs out<br>1530 High voltage for U2 provided<br>***1536 U1 explosion*** | 1454 U1 switchover to seawater |
| | 1800-0000 | 1904 U1 successfully inj. seawater<br>2036 loss of U3 reactor level indication due to instrumentation batteries. | [Note: 2045 end of main U1 timeline from INPO] |
| 03-13 | 0000-0600 | 0242 U3 HPCI manually tripped. Communicated to ERC at 0355. | 0355 U3 depress (SRVs), batteries, seawater injection decisions<br>0515 U3 venting decision<br>0700 U3 freshwater prioritized |

# Day-by-day summary

| Day | Goals | Key events (completion, setbacks) |
|---|---|---|
| 3-11 (Day 1) | U1 injection, depressurization | 1830 U1 freshwater inj ready but RV press too high |
| 3-12 (Day 2) | U1 injection, venting<br>Air supply for operation of valves for U1 containment venting | 0000-0400 21 aftershocks<br>0546 U1 injection but low flowrate due to press<br>1430 U1 venting, allowing injection (freshwater) by fire engine, *success*<br>1536 U1 explosion (damage to fire engine used for U1 freshwater injection; suspension of field work until 1720)<br>1904 U1 injection (seawater) by restaging to use fire engine connected to FPS |
| 3-13 (Day 3) | U3 venting, injection<br>U2 venting, RV depress., injection<br>Scavenging batteries for U3 (a.m.) | 0920 U3 venting successfully started, *noted by ERC*<br>0925 U3 injection (freshwater)<br>1100 U2 venting failed<br>12—aftershocks with evacuation<br>1313 U3 injection (switchover to seawater)<br>2100 U2 venting (2$^{nd}$ attempt) failed |
| 3-14 (Day 4) | Seawater level in U3 condenser pit<br>U3 restore/maintain injection<br>U2 venting, RV depress., injection | 0110 low seawater level<br>0900 condenser pit seawater level restored, *success*<br>1101 U3 explosion<br>1443-1630 aftershocks [p. 253-254 Hatamura interim]<br>1630 U3 restoration of seawater injection<br>1800 U2 SRV opened, decrease of RV level<br>1954 U2 injection (seawater) at low rate<br>2130 U2 2$^{nd}$ SRV opened |
| 3-15 (Day 5) | Spent Fuel Pool | 0600 U4 explosion<br>*(0600 U2 containment breach suspected)* |

# Actions: Outcomes, durations, delays

| Function/action | Decision | Outcome/operation | Time to achieve | Additional details |
|---|---|---|---|---|
| U2 freshwater and seawater inj (preparation) | 03-12/early hours ~0255 (staging only) | The seawater equipment is damaged by the U1 explosion at 03-12/1536. | | **U1 venting had priority from 03-12/0255**. In parallel, workers at U2 worked to stage injection, planning to use fire pumps for fresh water and seawater. |
| U2 containment venting (strategy and preparation) | 03-12/1730 (prioritized) | 03-13/0810 first alignment took place, with opening of MO containment vent valve. | | U2 containment venting was prioritized. |
| U2 venting (1) | 03-13/1015 | **03-13/1100 (venting not successful)** | 45’ | 03-13/1015 is the actual order to vent, presumably the opening of the AO drywell and/or suppression chamber vent valve.<br>**Containment pressure below rupture disk setpoint and inability to keep vent valves open.** |
| U2 seawater inj (1) | 03-13/1205 | Ready by 03-13 late afternoon. | | **03-13 evacuation orders due to aftershocks**<br>Lack of seawater 03-14/0110-0900 with priority for U3,<br>U3 explosion damage at 03-14/1101. |
| U2 venting (2) | 03-14/1230 | 03-14/2100 (not successful) | 8.5h | **U3 explosion at 03-14/1101 and aftershocks, both leading to suspensions of field work until 1600.** |
| U2 RPV depress | 03-14/1230 | 03-14/1800 (1st SRV) and 2120 (2nd SRV) | 5.5h then 3+h | **Evacuation order in force until 03-14/1600** |
| U2 seawater inj (3) | 03-14/1230 or 1325 | 03-14/1954 (actual start but no injection due to reactor pressure)<br>03-14/2120 (limited success after 2nd SRV opened) | 7h | **U3 explosion at 03-14/1101 damaged equipment staged for U2, and evacuation order** in force until 1600.<br><br>03-14/1630-1800 attempt to open an SRV and to align seawater injection.<br>No seawater available (prioritized for U1 and U3 until 03-14/1957) |

# Fukushima analysis

Background

- Shortcomings of emergency preparedness were identified by many organizations relatively quickly
  - Inadequacy of protections against tsunamis exceeding the design basis
  - Design basis for Loss of Offsite Power: assumed short-term AC power only
  - Severe Accident Management assumed AC power available within 30 minutes, including credit for AC power from neighboring unit
- Not analyzed
  - Design basis exceedance curve for tsunami (and, correspondingly, no PSA treatment of tsunami as consequence of earthquake)
  - SAMG based on internal events PSA only (no seismic, no tsunami, no area events affecting multiple units)

Became assumptions underlying Accident Management guidelines and procedures

# Fukushima analysis - Findings

- Critical assumptions of AM guidance and procedures were not satisfied in event
    - AC available within 30 min
    - DC available 8 hours
    - Operability from control room
    - Instrumentation available in control room
    - Loss of most on-site communications

Major delays

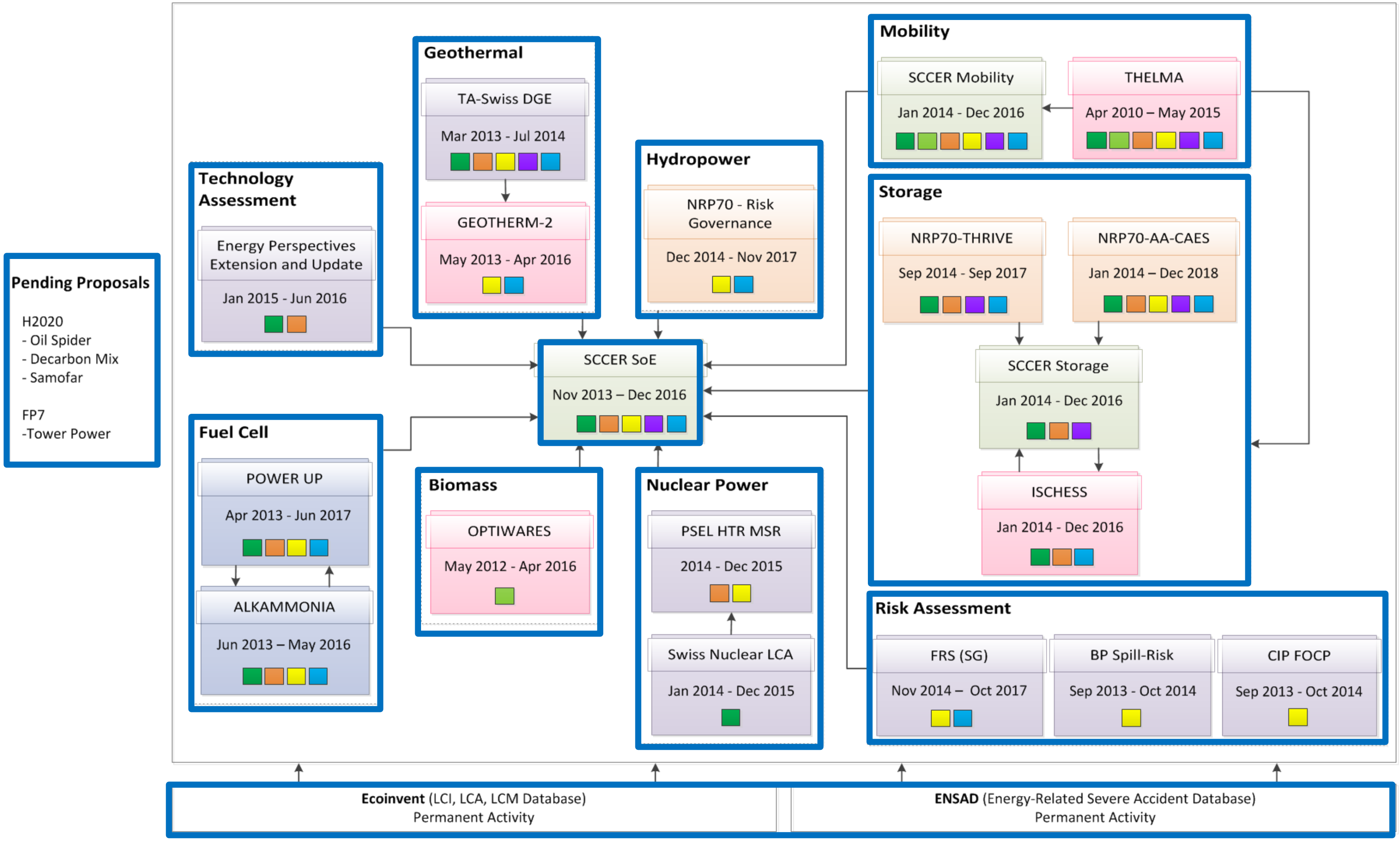
- Suspensions of field work due to tsunami warnings and earthquake aftershocks
- Unit 1 and Unit 3 reactor building explosions, scattering radioactive debris
    - led to suspensions of work
    - damaged staged equipment, e.g. U2 injection

- Power for instrumentation and actuation of equipment had to be improvised.
    - Scavenged batteries shared between instrumentation and actuation *(10 car batteries = 120 V DC)*
    - Compressors for actuation power
- "Foreseen" AM measures included no contingency for loss of all power, so plans needed to be developed ad hoc
    - Reactor depressurization (opening of SRVs)
    - Containment venting
- Essential AM measures that were needed in event were not foreseen, also had to be developed ad hoc
    - Water injection using fire engine
    - Injection of seawater
- Not foreseen => no procedure, no training, documentation not readily available (P&IDs), no equipment (hoses, connectors, etc.)

- Lack of resources (people, batteries) to pursue additional strategies in parallel, e.g. U2 and U3 venting / depressurization
    - Reports confirm that RCIC (U2) and HPCI (U3) operation explicitly used by ERC to prioritize implementation
- Strategies selected early (containment venting as well as seawater injection) but massively hindered by loss of all AC and DC and no anticipation of this condition

# Technology Assessment Projects

## Projects Relationship Diagram



**Pending Proposals**

H2020
- Oil Spider
- Decarbon Mix
- Samofar

FP7
-Tower Power

**Technology Assessment**

Energy Perspectives Extension and Update
Jan 2015 - Jun 2016
🟩🟧

**Geothermal**

TA-Swiss DGE
Mar 2013 - Jul 2014
🟩🟧🟨🟪🟦

GEOTHERM-2
May 2013 - Apr 2016
🟨🟦

**Hydropower**

NRP70 - Risk Governance
Dec 2014 - Nov 2017
🟨🟦

**Mobility**

SCCER Mobility
Jan 2014 - Dec 2016
🟩🟢🟧🟨🟪🟦

THELMA
Apr 2010 – May 2015
🟩🟢🟧🟨🟪🟦

SCCER SoE
Nov 2013 – Dec 2016
🟩🟧🟨🟪🟦

**Storage**

NRP70-THRIVE
Sep 2014 - Sep 2017
🟩🟧🟪🟦

NRP70-AA-CAES
Jan 2014 – Dec 2018
🟩🟧🟨🟪🟦

SCCER Storage
Jan 2014 - Dec 2016
🟩🟧🟪

ISCHESS
Jan 2014 - Dec 2016
🟩🟧🟦

**Fuel Cell**

POWER UP
Apr 2013 - Jun 2017
🟩🟧🟨🟦

ALKAMMONIA
Jun 2013 – May 2016
🟩🟧🟨🟦

**Biomass**

OPTIWARES
May 2012 - Apr 2016
🟢

**Nuclear Power**

PSEL HTR MSR
2014 - Dec 2015
🟧🟨

Swiss Nuclear LCA
Jan 2014 - Dec 2015
🟩

**Risk Assessment**

FRS (SG)
Nov 2014 – Oct 2017
🟨🟦

BP Spill-Risk
Sep 2013 - Oct 2014
🟨

CIP FOCP
Sep 2013 - Oct 2014
🟨

**Ecoinvent** (LCI, LCA, LCM Database)
Permanent Activity

**ENSAD** (Energy-Related Severe Accident Database)
Permanent Activity

**Project Customers:**

- ETH Competence Centers (CCEM/CCES)
- Swiss Competence Centers for Energy Research (SCCERs)
- NRP70 – Energy Turnaround
- EU Projects
- Authorities, Organizations, Industry

**Research Disciplines:**

| | | | | | |
|---|---|---|---|---|---|
| 🟩 | Life Cycle Assessment | 🟧 | Cost Assessment | 🟢 | Environmental Impact Assessment / External Costs |
| 🟪 | Integrated Assessment | 🟨 | Risk Assessment | 🟦 | Multi-Criteria Decision Analysis (MCDA) |

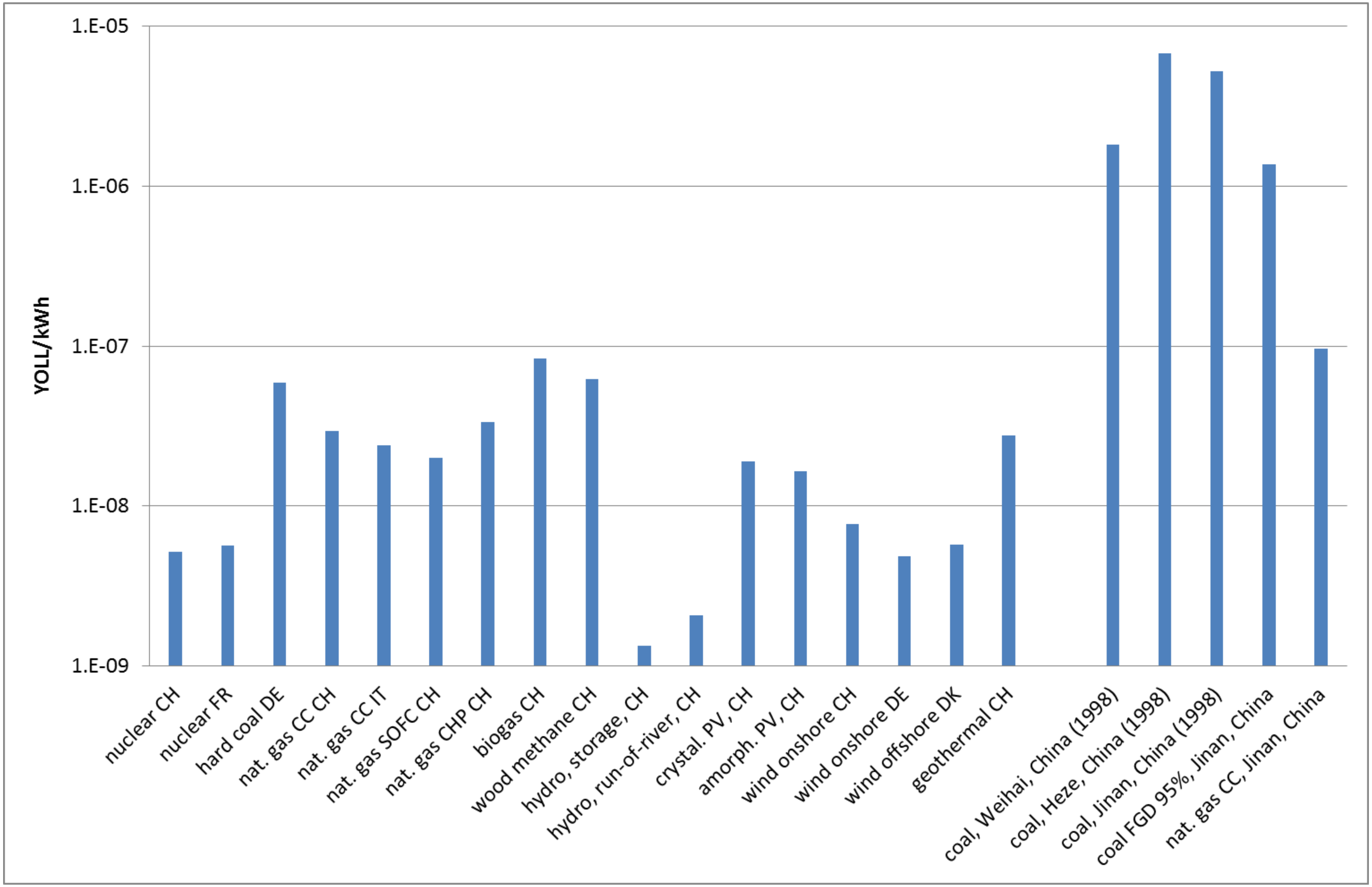
S. Hirschberg, Laboratory for Energy Systems Analysis, Energy Departments

# Health impacts of electricity generation: Normal operation, accidents, terrorism

- Minimization of health impacts is one of the goals of sustainable energy policies.
- High public interest but serious misunderstandings and deficiencies of available analyses.
- Questions addressed:
  - How large are health effects associated with various electricity generation technologies and fuel cycles?
  - How do health risks from normal operation compare with those resulting from accidents and hypothetical terrorist attacks?
  - Which are the major limitations of the current estimates?

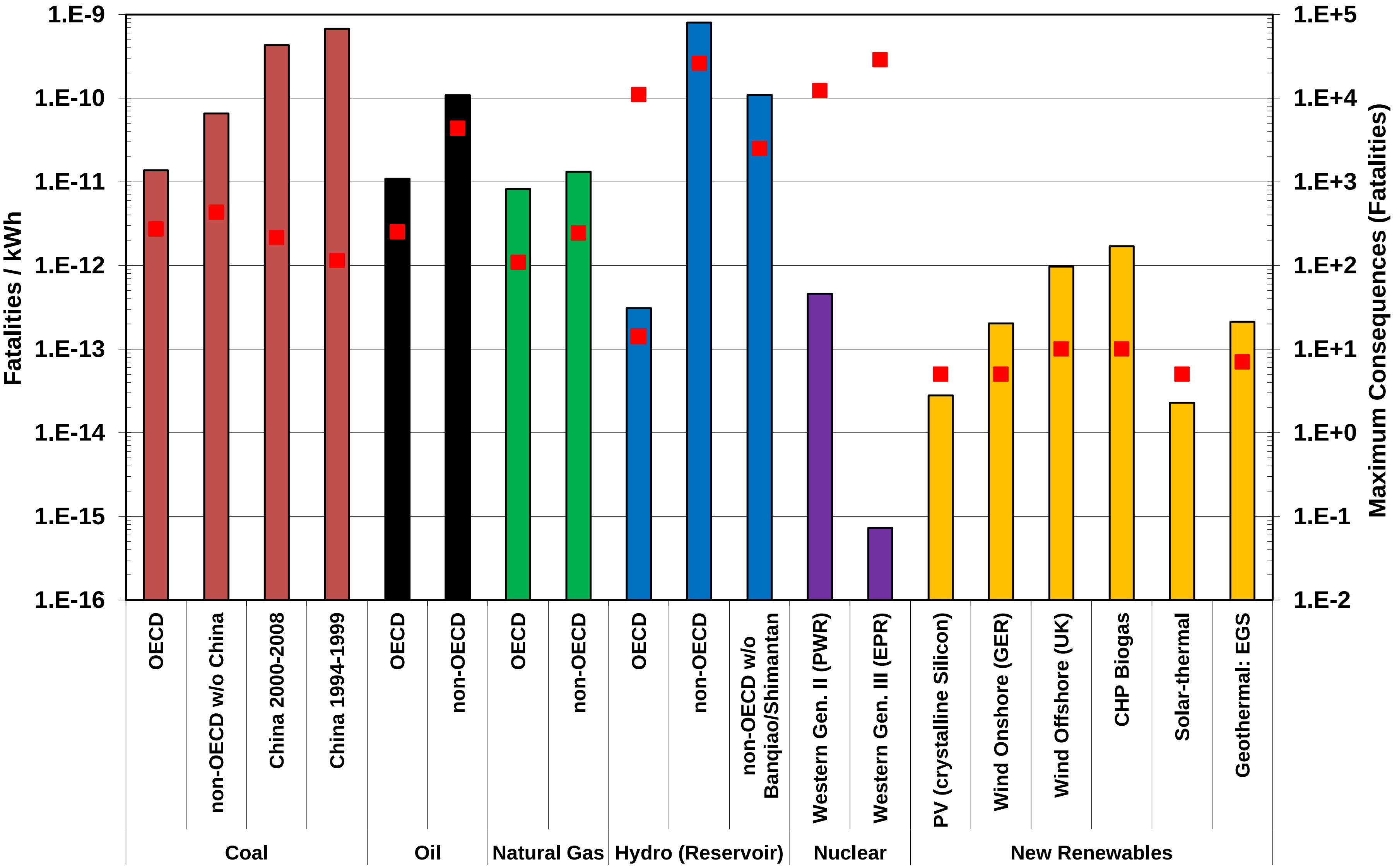
# Normal Operation: Mortality based on Impact Pathway Approach

## YOLL = Years of Life Lost



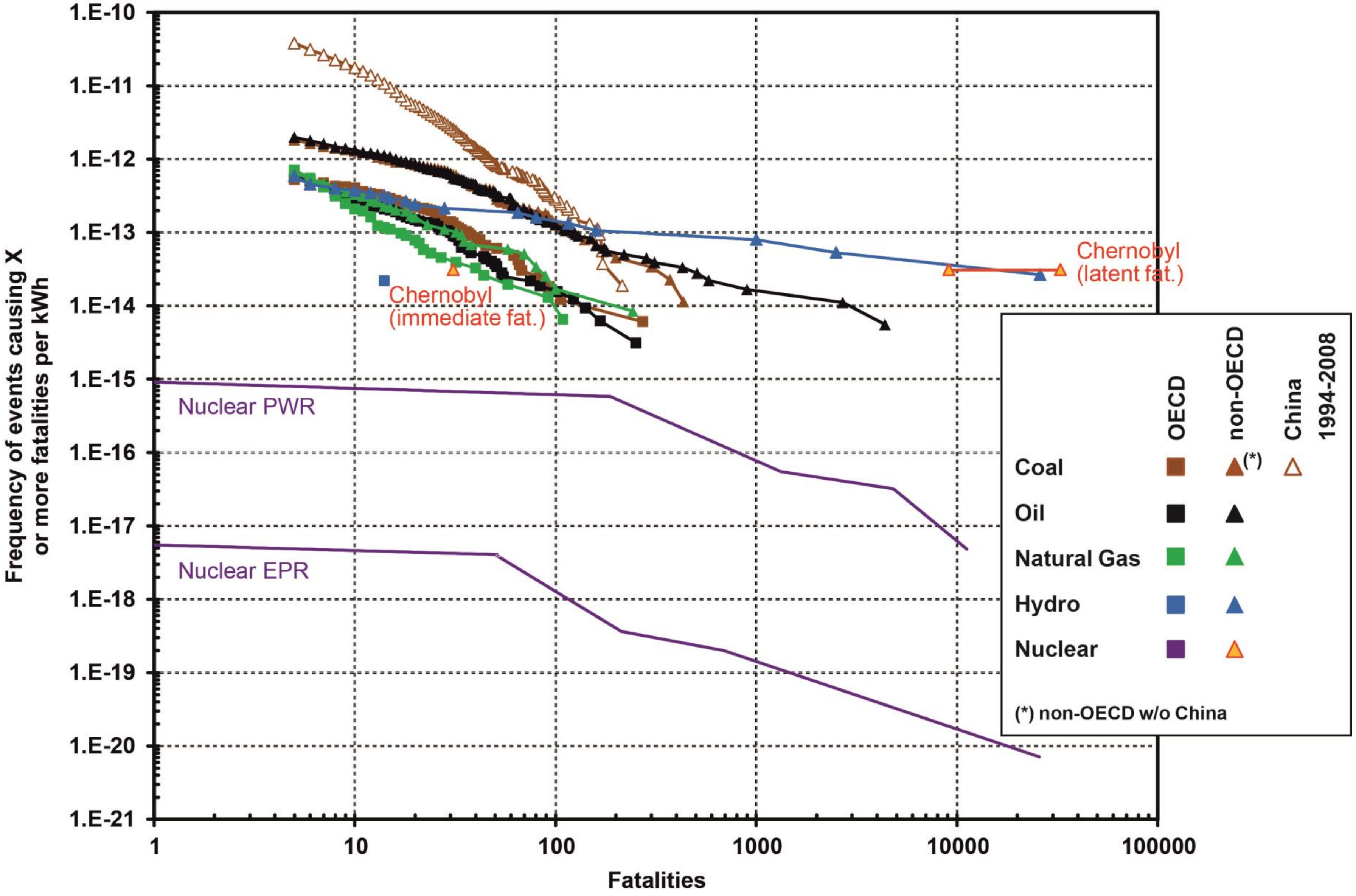
Sources: after Hirschberg et al., 2003; Heck & Hirschberg, 2011; Roth et al., 2009; Hirschberg et al., 2014

# Severe accident fatality rates and maximum consequences



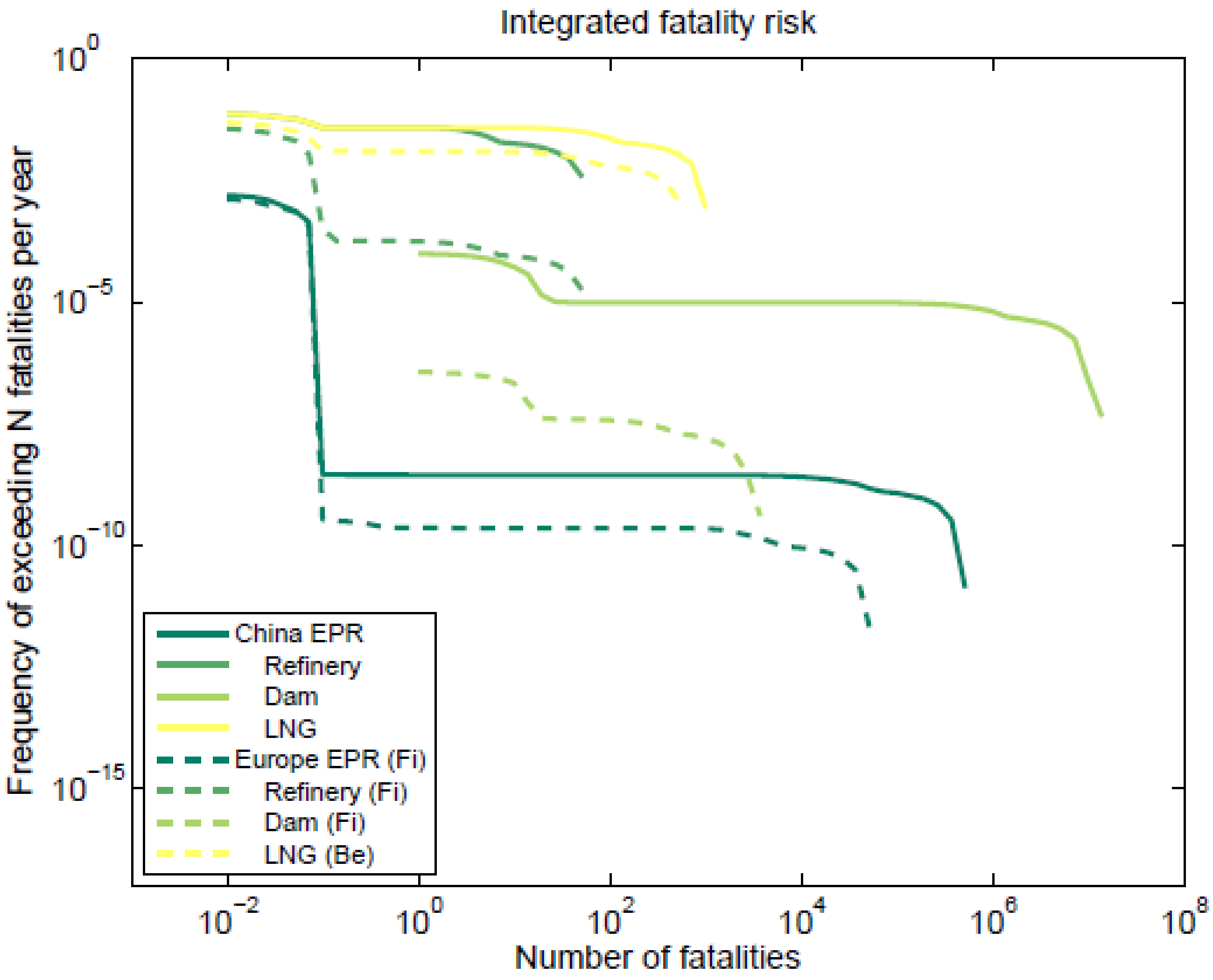
Sources: after Burgherr, 2011; Burgherr et al., 2013; Burgherr et al., 2014; Burgherr & Hirschberg, 2014

# Frequency-Consequence Curves: OECD & non-OECD (1970-2008)



Sources: after Burgherr et al., 2013; Burgherr & Hirschberg, 2014; Hirschberg et al., 2014

# Frequency-consequence curves for hypothetical terrorist attacks



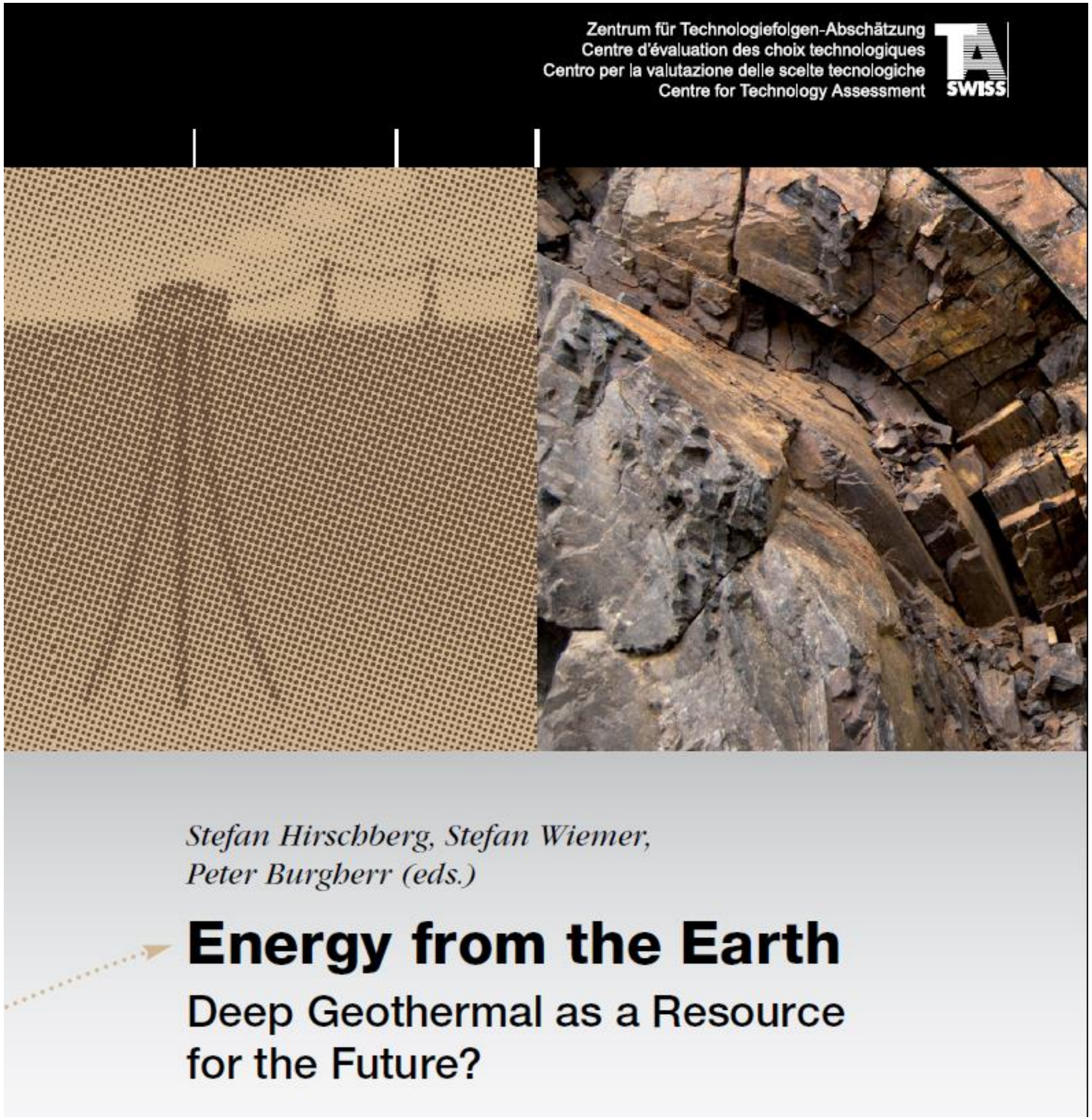
Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

# Conclusions: Health effects

- **General:**
  - State-of-the art approaches to comprehensive comparative assessment of the various contributions to health risks of energy systems established and applied
  - Importance of covering full energy chains
  - Strong dependence on technologies, location and operational environment
  - Dominance of health impacts from normal operation
- **Normal operation risks:** Renewables and nuclear mostly exhibit very good performance with hydro being the best option; coal ranks mostly worst while performance of natural gas is mixed.
- **Severe accidents risks:** Lowest fatality rates apply to hydro and nuclear in OECD countries though in both cases events with very low frequency can lead to quite extreme consequences.
- **Terrorist threat risks:** Frequency of a successful terrorist attack with very large consequences is of the same order of magnitude as can be expected for a disastrous accident in the respective energy chain.
- **Limitations:** Choice of reference technologies, geographical coverage, treatment of health impacts of climate change, solar PV accident risks, cyber risks and implementation of terrorist risk assessment.

Source: Hirschberg et al., 2014

# TA-SWISS project on deep geothermal energy



Zentrum für Technologiefolgen-Abschätzung
Centre d'évaluation des choix technologiques
Centro per la valutazione delle scelte tecnologiche
Centre for Technology Assessment

TA SWISS

*Stefan Hirschberg, Stefan Wiemer,*
*Peter Burgherr (eds.)*

**Energy from the Earth**

Deep Geothermal as a Resource
for the Future?

- Research consortium:
  4 organizations
  32 scientists
- Highly inter-disciplinary competences
- Effort: ~ 5 person-years
- Duration: ~18 months
- Report: ~500 pages
- Very high media echo
- Recognition (BFE etc.)

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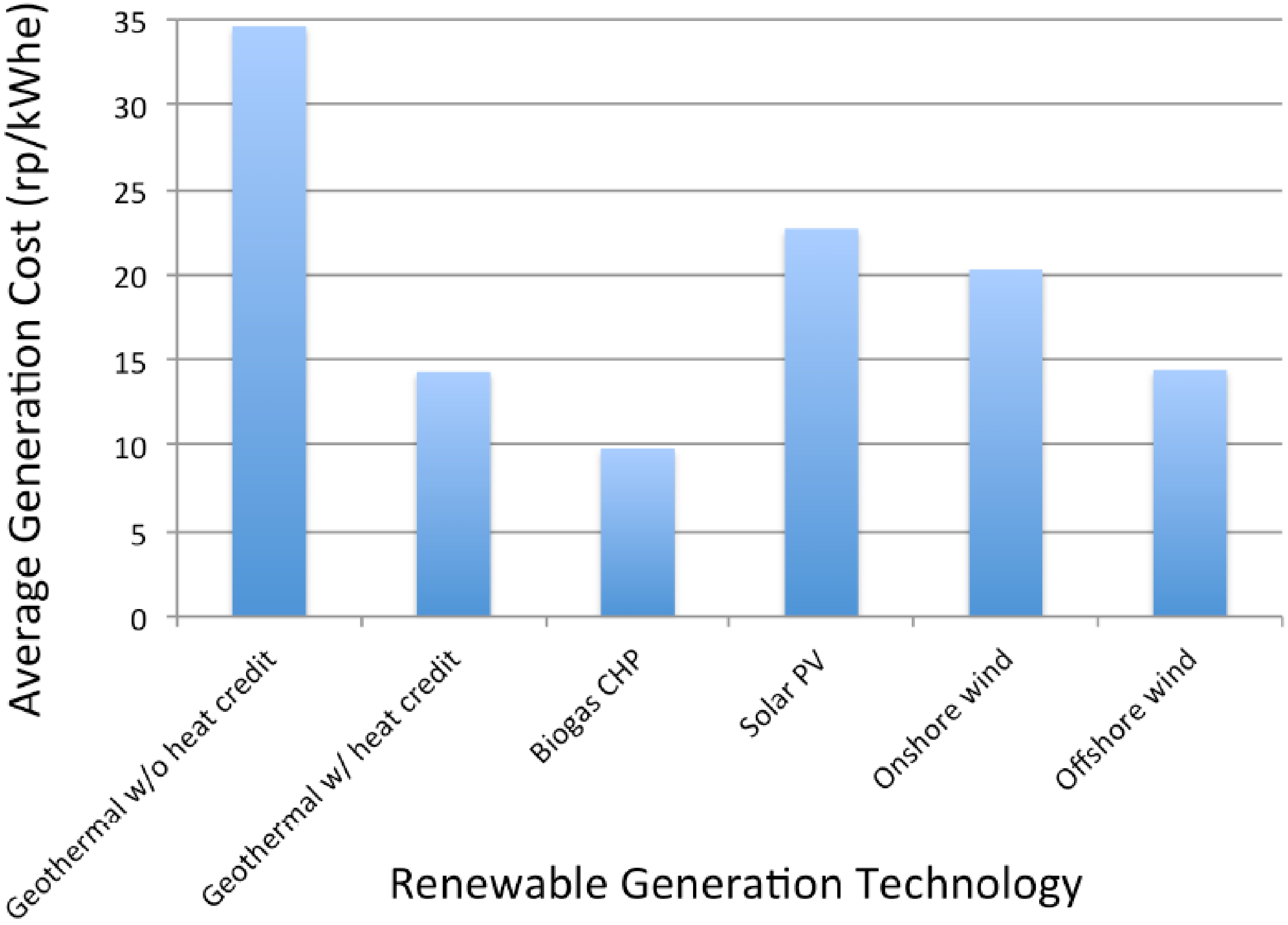
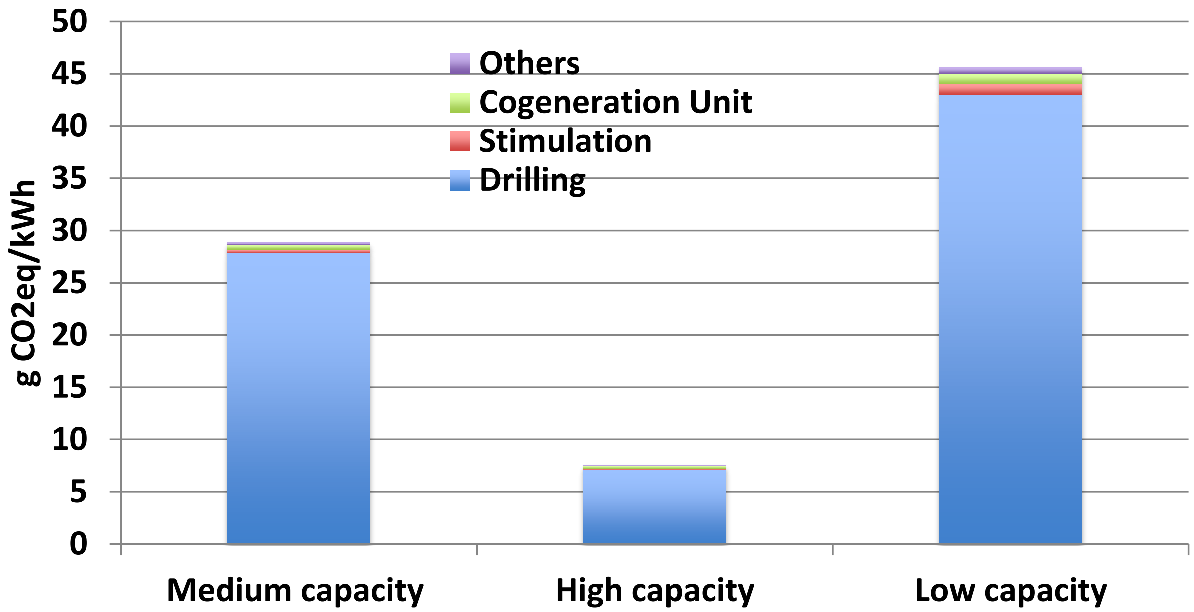
# Costs of deep geothermal power vs. other technologies



Source: Schenler, 2014

# Impact assessment results – Climate change



«Others»: Refrigerant loss during operation, pump material, land use

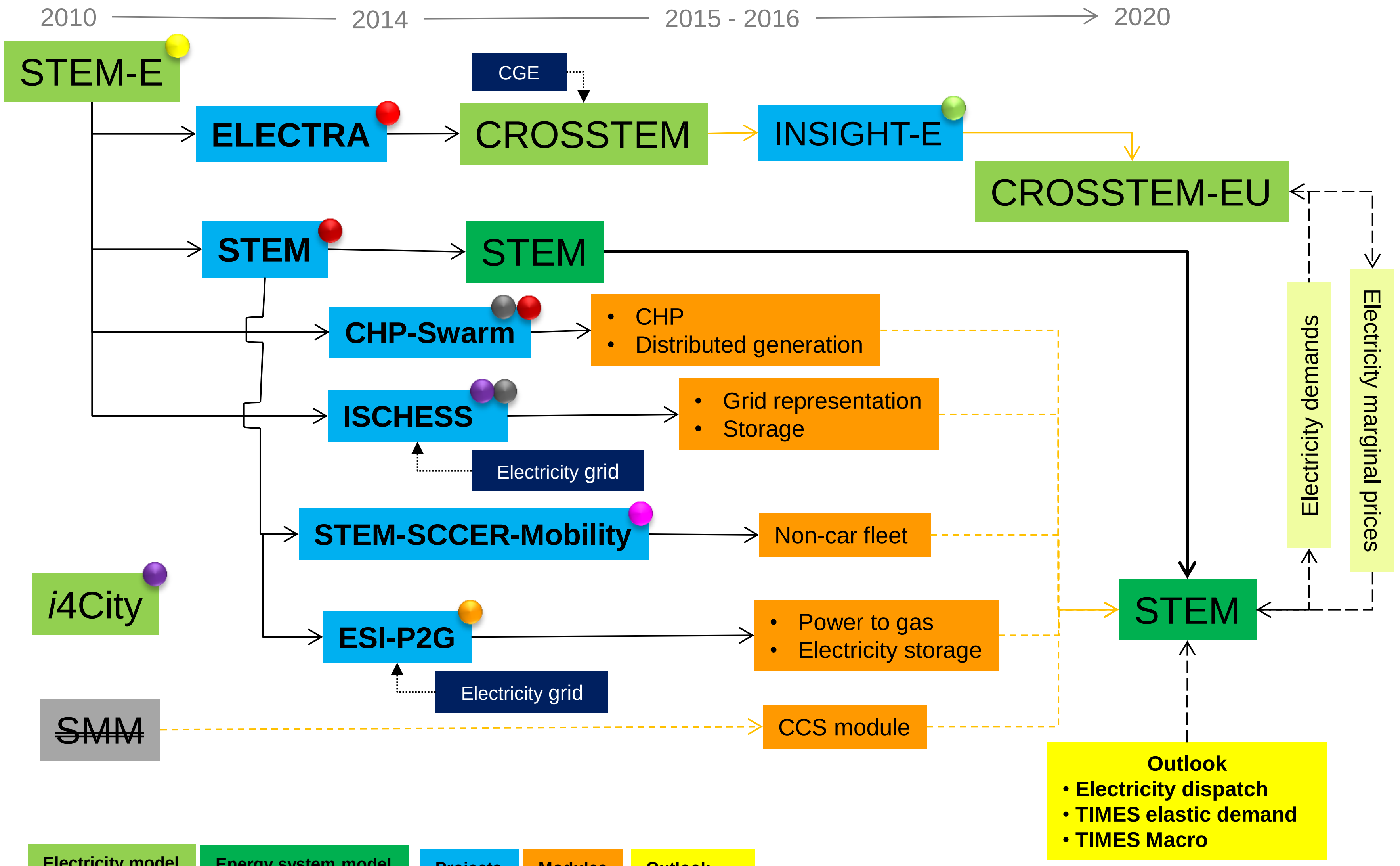
Source: Treyer et al., 2014

| | | | |
|---|---|---|---|
| Plant net capacity | **5.5 MWel** | **14.6 MWel** | **2.9 MWel** |
| Gradient | 35°C/km | 40°C/km | 30°C/km |
| Depth of wells | 5 km | 6 km | 5 km |
| Number of wells | 6 (2 well triplets) | 3 (1 well triplet) | 3 (1 well triplet) |
| Surface plant life time | 30 a | 30 a | 20 a |
| Well life time | 20 a | 30 a | 20 a |
| Production flow rate | 147 l/s (2*73.5) | | |
| Surface system | Organic rankine cycle (ORC) | | |
| Cooling system | Air cooling | | |
| Rig power source | Electricity | | |

# Selected conclusions on Enhanced Geothermal Systems

- **The EGS potential** is large provided a combination of **cost reductions, heat sales and efficient use of the resource.**
- It has so far proved **difficult to create a petrothermal reservoir to allow commercial flow rates**, without the benefit of pre-existing, highly-permeable fracture zones and faults.
- **EGS technology is not mature and requires a program of basic research** before it is ready for large-scale deployment.
- **Environmental burdens of EGS** are lower or of the same order as those of other electricity generation technologies in Switzerland.
- The contribution of **geothermal** to the **security of energy supply** should be more strongly emphasized.
- **Earthquake risks** can be controlled, but **not eliminated**. The success and economy of geothermal energy will depend on the level of **socially acceptable risk**.

# TIMES model developments



2010 — 2014 — 2015 - 2016 → 2020

STEM-E

ELECTRA

CGE

CROSSTEM

INSIGHT-E

CROSSTEM-EU

STEM

STEM

CHP-Swarm

- CHP
- Distributed generation

ISCHESS

- Grid representation
- Storage

Electricity grid

STEM-SCCER-Mobility

Non-car fleet

*i*4City

ESI-P2G

- Power to gas
- Electricity storage

Electricity grid

~~SMM~~

CCS module

STEM

Electricity demands

Electricity marginal prices

**Outlook**
- **Electricity dispatch**
- **TIMES elastic demand**
- **TIMES Macro**

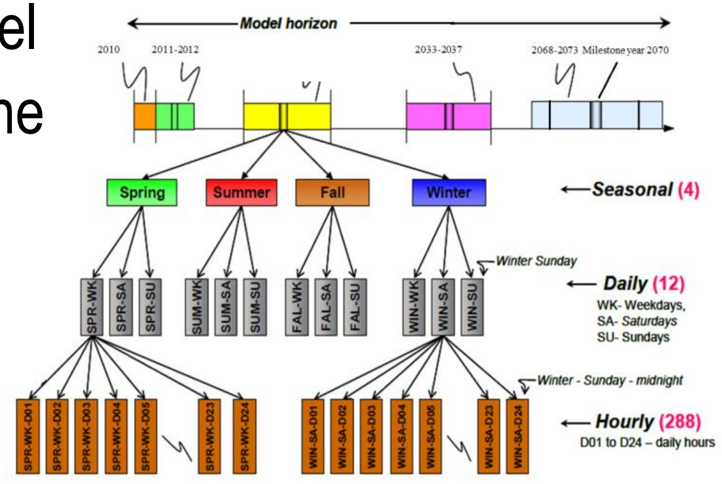
**Electricity model** **Energy system model** **Projects** **Modules** **Outlook**

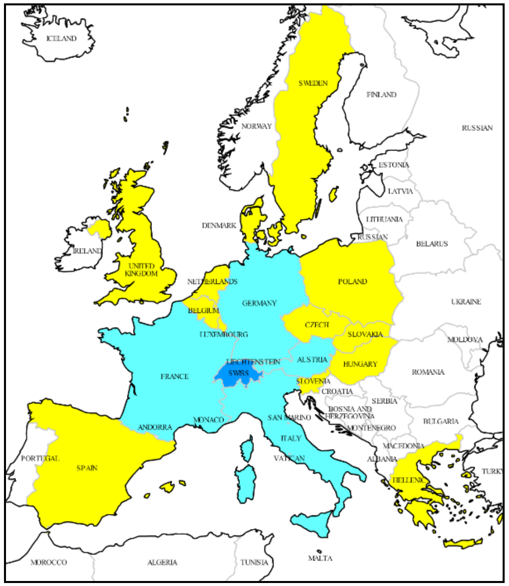
**External model (soft links or data flow)**

**Funding:** ● PSI ● BFE ● SER ● CCEM ● KIT ● SwissGrid ● EU

# CROSSTEM Model

- **CROS**s border **S**wiss **T**IMES **E**lectricity **M**odel
- Extension of the STEM-E model to include the four neighbouring countries
- Time horizon: 2010 – 2070
- An hourly timeslice (288 timeslices)
- Detailed reference electricity system with resource supply, renewable potentials and demands for 5 countries
- Calibrated for electricity demand and supply data between 2000-2010
- **Endogenous** electricity import / export based on costs and technical characteristics

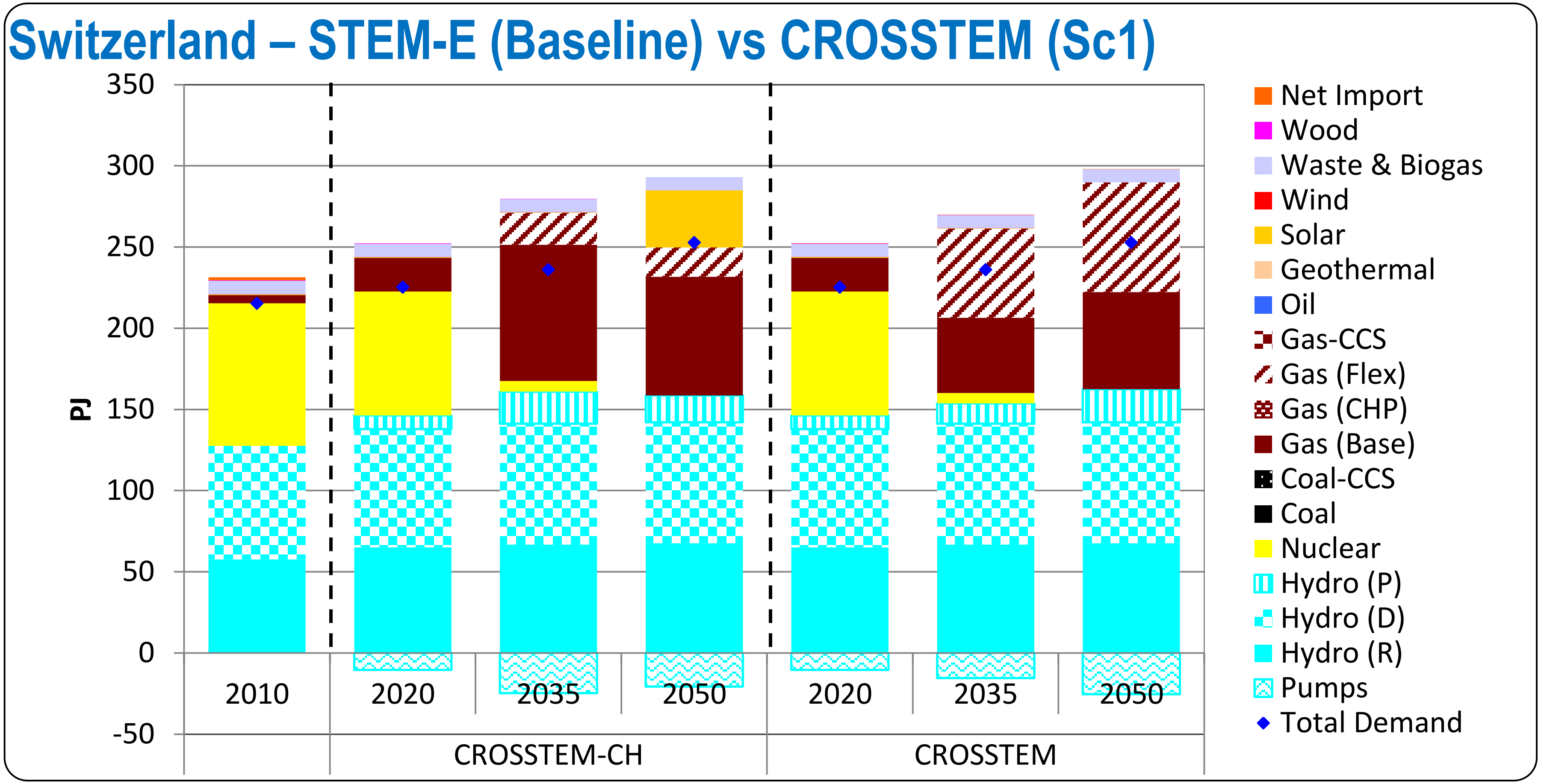




| | CROSSTEM Scenarios |
|---|---|
| Sc.1 | Baseline scenario<br>No particular constraints in technology investment*<br>Trade constraints applied – net exporter (France, Germany) cannot become net importer (Italy, Austria) and vice versa<br>Switzerland self-sufficient<br>$CO_2$ prices for allowances in the ETS as in WWB (SES 2050) |
| Sc.2 | De-carbonization of power sector (95% $CO_2$ reduction by 2050 from 1990 levels) for all five countries together<br>All other conditions same as Sc.1 (including trade constraints) |
| Sc.3 | No gas based generation in Switzerland<br>Trade constraints relaxed for CH only (allowed to be a net importer)<br>All other conditions same as Sc.2 |

* except where already part of policy: e.g., Nuclear phase-out in Switzerland (CH) and Germany (DE), no nuclear investment in Italy (IT) and Austria (AT). No Coal investment in Switzerland (CH).

# Results – Electricity generation mix

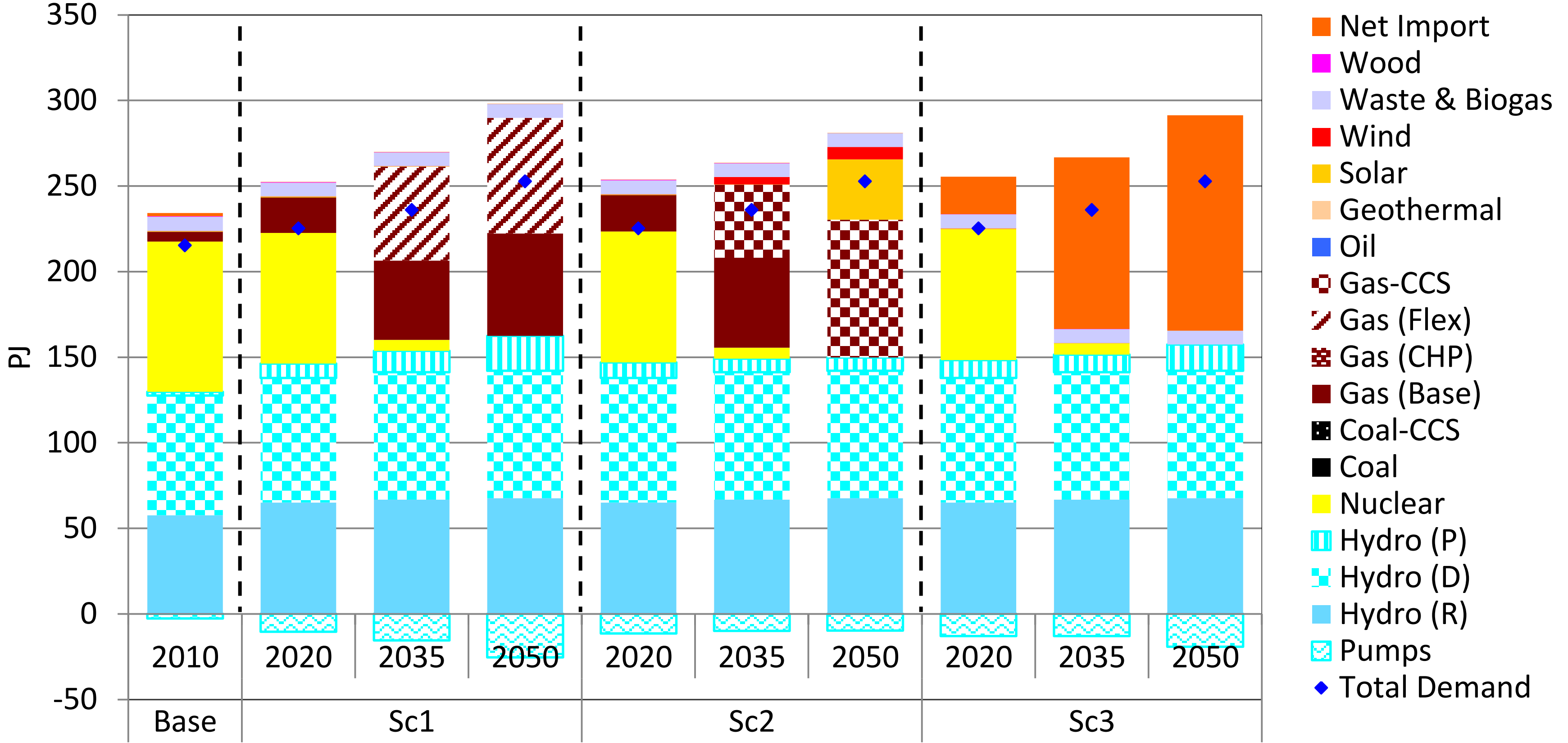


- No Solar PV in CROSSTEM, more flexible gas plants
- Import/Export costs as well as surrounding country electricity profiles cause this difference

Source: Pattupara & Ramachandran, 2014

# Results – Electricity generation mix

## Switzerland – All CROSSTEM scenarios

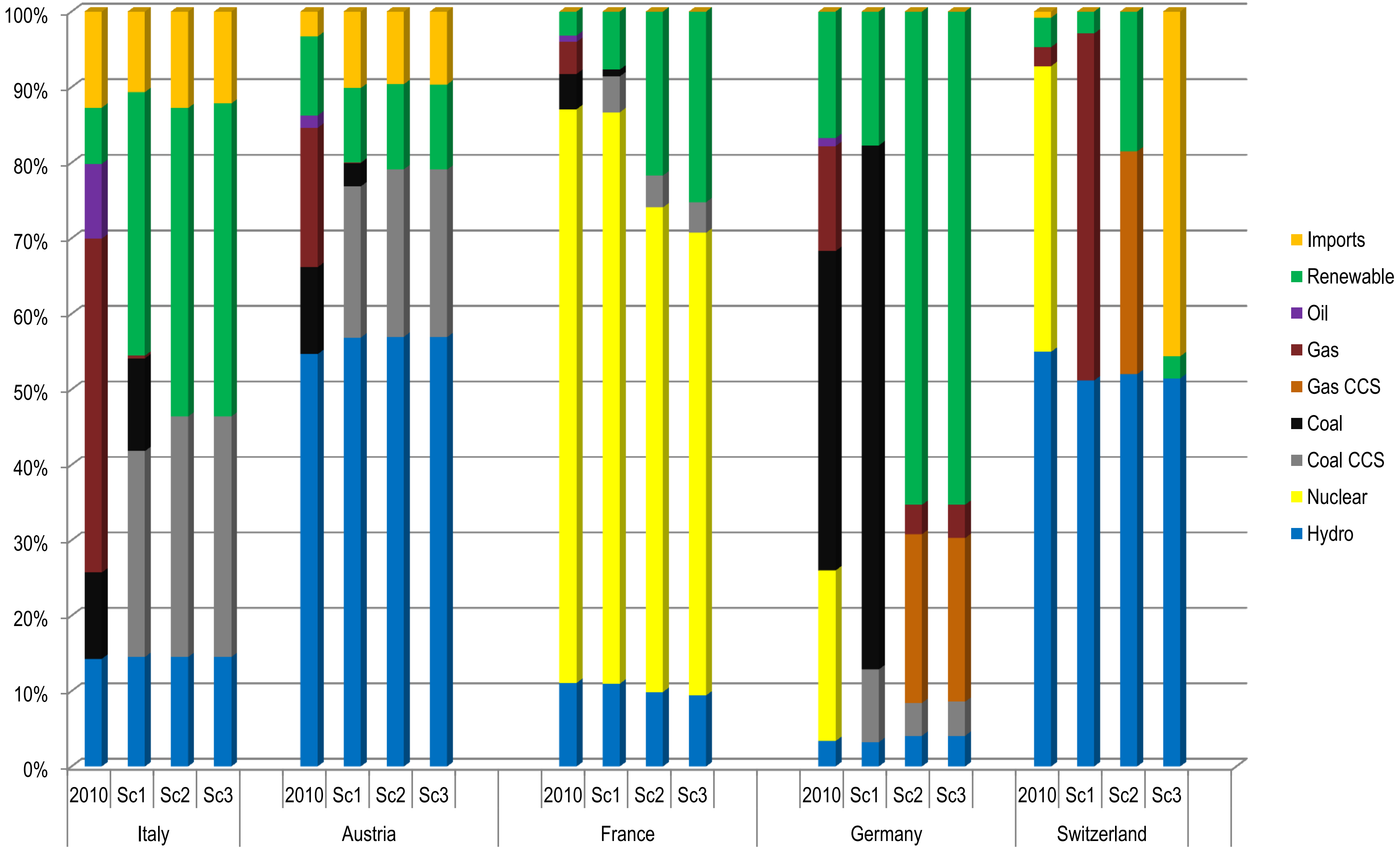


Source: Pattupara & Ramachandran, 2014

- Sc2 – Gas plants replaced by gas CCS + renewables, lower pump hydro (higher electricity price)
- Sc3 – Imports preferred to investments in renewables, Investments made elsewhere

# Results – Electricity generation mix

## Electricity generation mix 2050



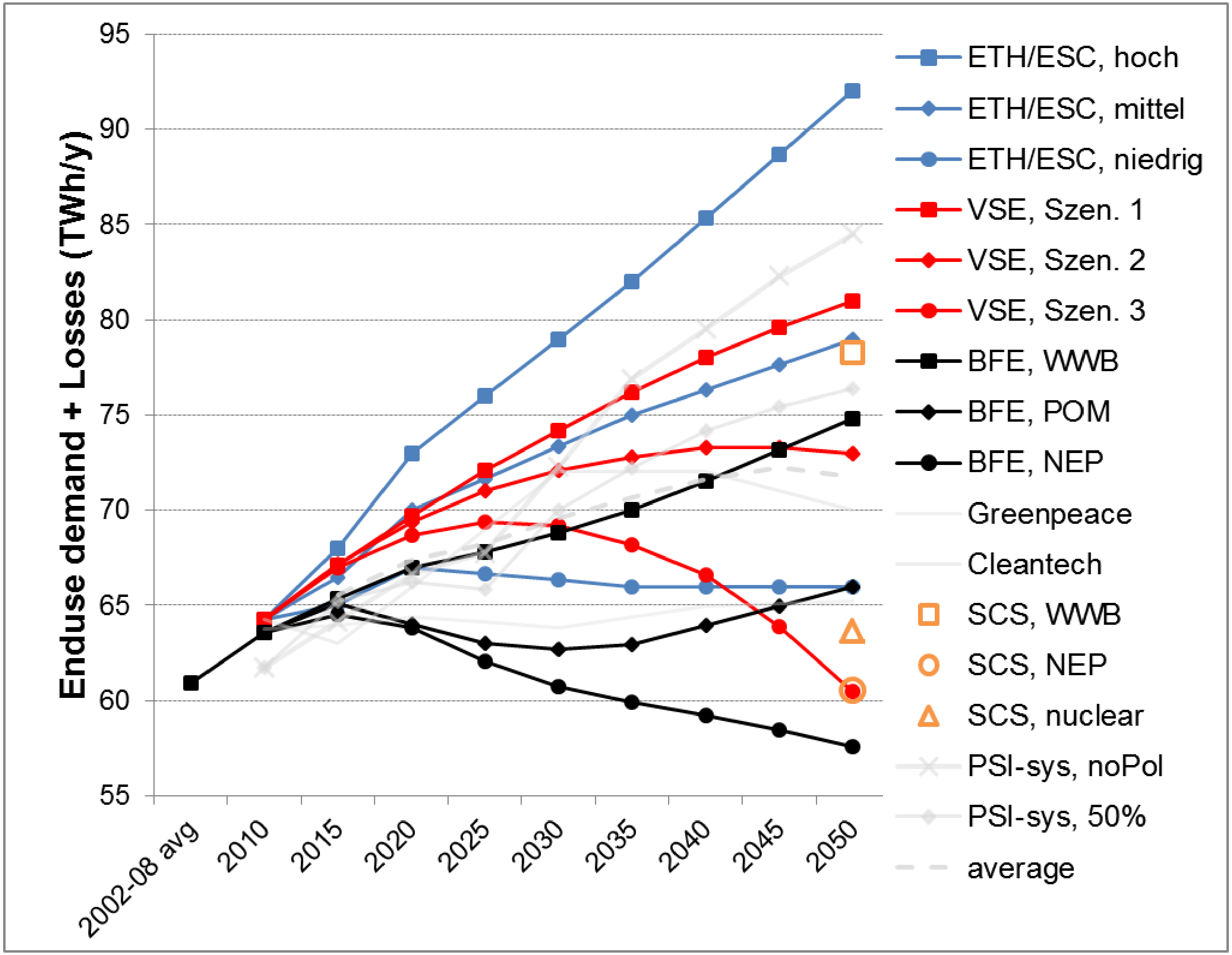
# Comparison of Swiss electricity supply scenario studies

| Study | Full name | Author (Modeller) | Year | System scope |
|---|---|---|---|---|
| **BFE** | Energieperspektiven für die Schweiz bis 2050 | BFE (Prognos AG) | 2012 | Energy system |
| **VSE** | Stromzukunft Schweiz | VSE (Pöyry AG) | 2012 | Electricity |
| **ETH / ESC** | Energiezukunft Schweiz | G. Andersson,<br>K. Boulouchos,<br>L. Bretschger | 2011 | Energy system |
| **SCS** | SCS-Energiemodell | A. Gunzinger (SCS AG) | 2013 | Electricity |
| **Greenpeace** | Energy [r]evolution | S. Teske, G. Heiligtag (DLR, SCS AG) | 2013 | Energy system |
| **Cleantech** | Energiestrategie | F. Barmettler,<br>N. Beglinger, C. Zeyer | 2013 | Energy system |
| **PSI-sys** | Transformation strategies towards a sustainable Swiss energy system – energy-economic scenario analysis | N. Weidmann | 2013 | Energy system |
| **PSI-elc** | Swiss electricity supply options (Energie-Spiegel 21) | R. Kannan, H. Turton | 2012 | Electricity |

# Overview of models

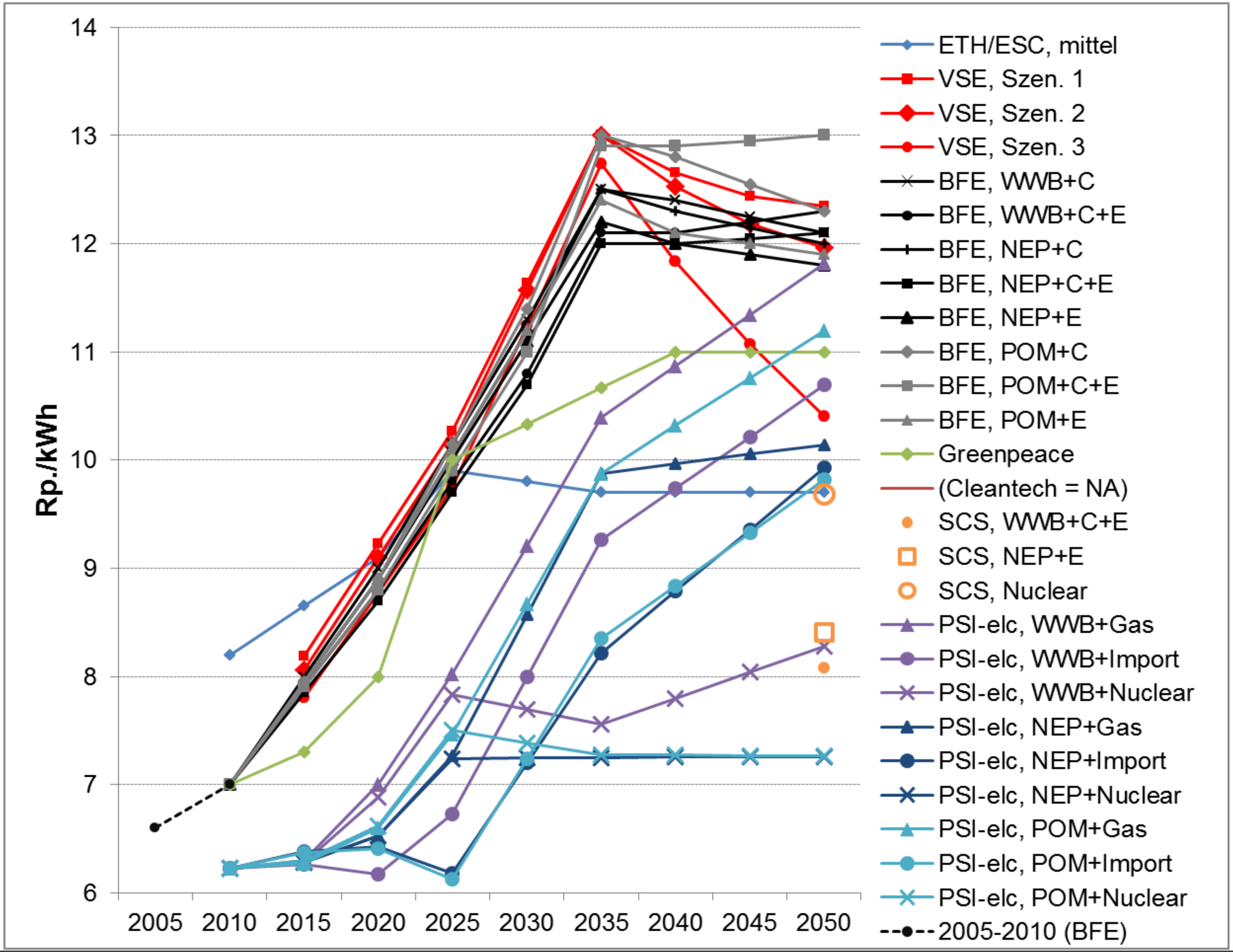
| Study (electricity only) | Electricity demand model (if no model: data from) | Capacity expansion model | Dispatch model | Modelling of energy system network | Speciality |
|---|---|---|---|---|---|
| **BFE** | Simulation | Simulation | Simulation | na | |
| **VSE (elc)** | Simulation | **Optimization** | | na | Cap./Disp. model also **for neighbouring countries** |
| **ETH/ESC** | Simulation | Simulation | na | na | 3rd model used for the whole economy (labour, capital, energy) |
| **SCS (elc)** | (from BFE) | na | Simulation | na | Model is only for year 2050 |
| **Greenpeace** | Simulation | Simulation | (from SCS) | yes | Electricity demand is endogenous (?) |
| **Cleantech** | Simulation | Simulation | na | na | **no costs** (not even ex-post) |
| **PSI-sys** | **Optimization** | | na | yes | Electricity demand is endogenous |
| **PSI-elc** | (from BFE) | **Optimization** | | na | «typical hour» for dispatch |

# Demand



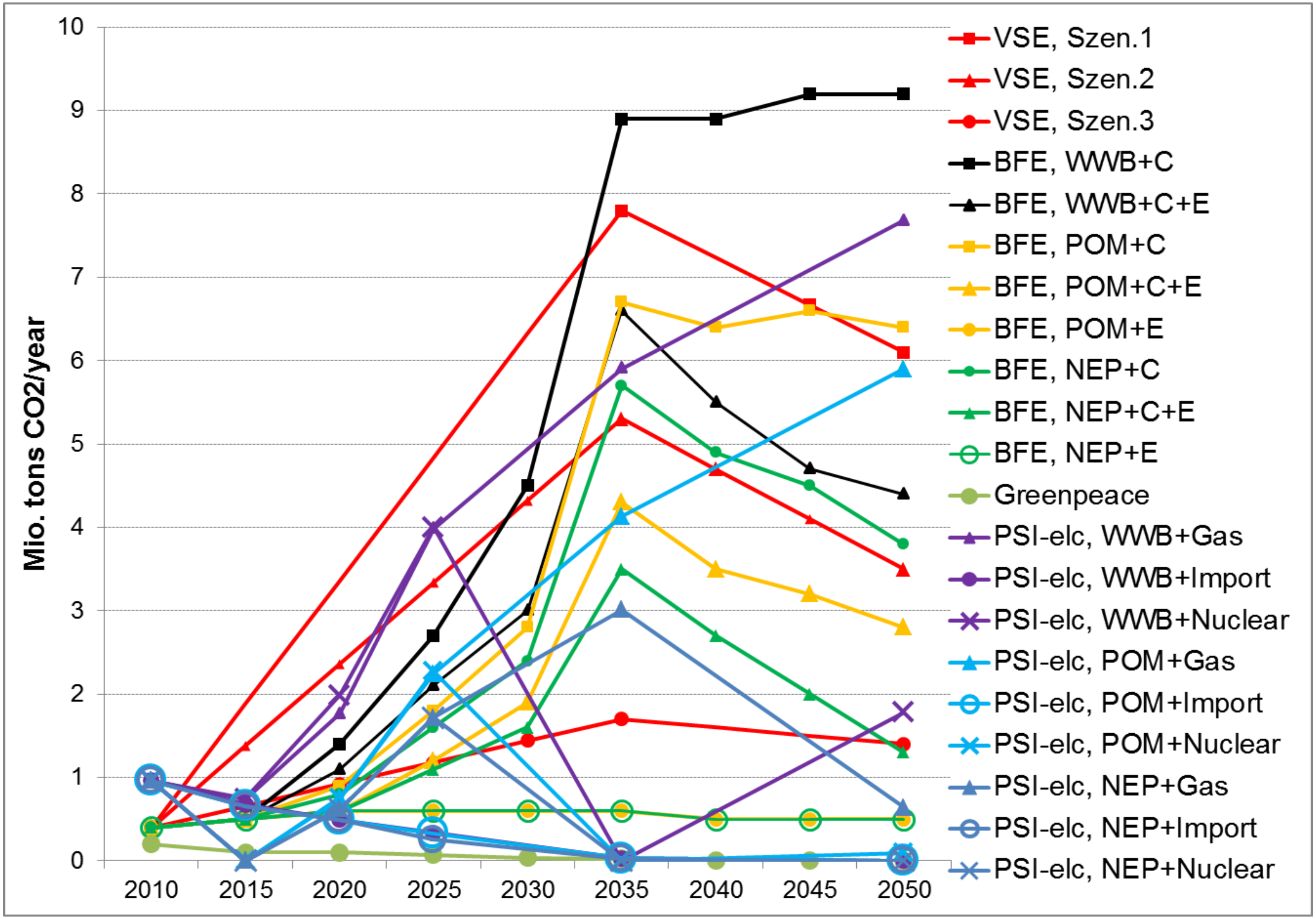
Sources: Densing et al., 2014

# Production cost of generation mix



Sources: Densing et al., 2014

# $CO_2$-emissions form power sector (without imports)



Sources: Densing et al., 2014

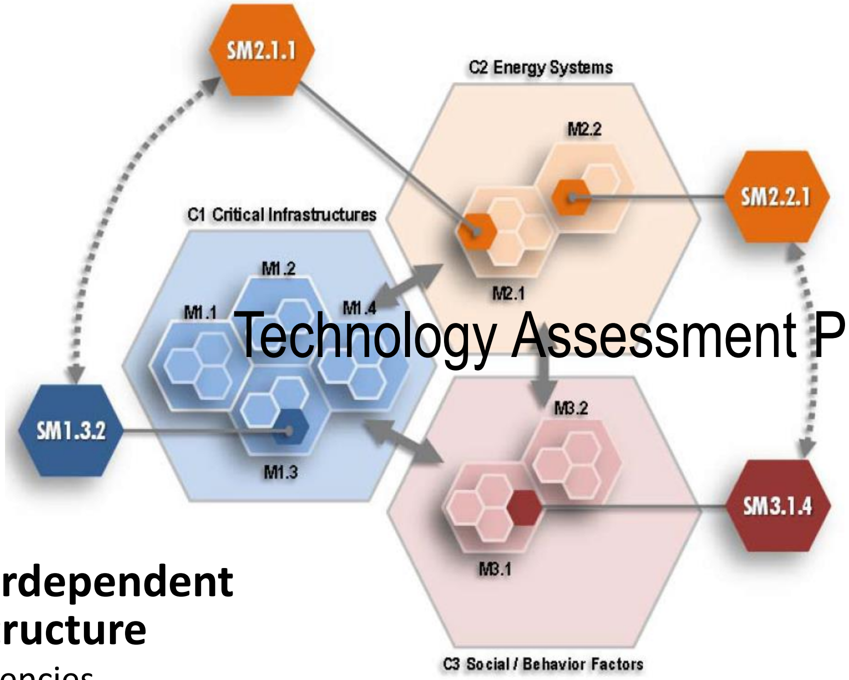
- **Comparison:** $CO_2$ from energy sector (+transport) today: ~40 Mio. tons/Jahr
- **BFE, NEP+E** and **BFE, POM+E** have same domestic emissions, but POM-E has more imports

# Future Resilient Systems (FRS)

|  | Sing. SNF (for PSI in C2) | PSI in-kind |
|---|---|---|
| Staff & students | **3.1 MSGD**<br>(2.1 MCHF) | **1.4**<br>(0.9) |
| Sachmittel | **0.24**<br>(160k) |  |
|  | 3 PhDs<br>4 Postdocs<br>2 specialists<br>(based in SNG) | In-kind:<br>PIs, staff |

## Cluster 2. Energy Systems & Comparative Assessment

M2.1 Energy System Resilience
M2.2 People and Operations



Technology Assessment Projects

## Cluster 1. Interdependent Critical Infrastructure

M1.1 Interdependencies
M1.2 Modeling
M1.3 Consequences
M1.4 Improving CI systems

## Cluster 3. Social and Behavioral Factors in Decision-Making

M3.1 Human Decision-Making
M3.2 Sustainable Energy Demand

# Thank you for your attention!

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