Task 4.2

Task Title

Global observatory of electricity resources

Research Partners

Technology Assessment Group, Energy Economics Group at Paul Scherrer Institute (PSI), Institute of Geophysics (IfG) at ETH Zurich

Current Projects (presented on the following pages)

At the annual conference 2015, seven posters were presented for Task 4.2, which can be assigned to three topical areas:

Energy Perspectives Extension & Update

Costs & potentials of future Swiss electricity supply
C. Bauer, S. Biollaz, P. Burgherr, B. Cox, T. Heck, S. Hirschberg, A. Meier, K. Treyer, W. Schenler, F. Vogel, X. Zhang

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A Linked Economic & LCA Model of Geothermal Generation in Switzerland
W. Schenler, K. Treyer, H. Oshikawa, P. Burgherr, S. Hirschberg

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Global Observatory: Preliminary Results for Fuel Cell µCHP
B. Cox

Health Effects

Health Effects of Technologies for Power Generation: Contributions from Normal Operation, Severe Accidents and Terrorist Threat
S. Hirschberg, C. Bauer, P. Burgherr, E. Cazzoli, T. Heck, M. Spada, K. Treyer

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Comparative Risk Assessment of Accidents in the Energy Sector using PSI's ENSAD Database
P. Burgherr, M. Spada, A. Kalinina, S. Hirschberg

Scenario Comparison

Review and Meta-Analysis of Swiss Electricity Scenarios 2050
M. Densing, E. Panos S. Hirschberg, H. Turton

Review of Global Energy Scenarios
K. Volkart, E. Panos, M. Densing"

Task Objectives

The Global Observatory provides a comprehensive analytical framework for technology characterization and trend identification that can be applied in a consistent manner across a broad portfolio of current and future technologies. In addition to geo-energies and hydropower, a variety of technologies are considered, including new renewables (e.g. solar photovoltaic, solar-thermal, wind onshore and offshore, biomass, geothermal, wave and tidal), fossil energy carriers (with and without CCS), nuclear energy and consideration of co-generation. Its two main objectives are the following:

- Characterization and sustainability assessment of current and future technologies
- Evaluation of existing trends, projections, and scenarios

Interaction Between the Partners – Synthesis

The Global Observatory has established links with the various work packages within the SCCER-SoE to make use of the available expertise in this SCCER. In addition, there are collaborations with several other SCCERs, namely Biosweet (for biomass), Storage, Mobility and Furies. Finally, the involvement of PSI's Laboratory for Energy Systems Analysis in many different projects ensures that results relevant for the Global Observatory can be easily incorporated.

Highlights 2015

- The Global Observatory focuses on Switzerland, but also considers European and global scales.
- Detailed technology characterization forms the basis for a holistic sustainability assessment of electricity generation options.
- The key challenge is to evaluate the current status and innovation potential of emerging and future highly advanced technologies with regard to their costs, environmental and social performance aspects, resource potentials, and possible future deployment scenarios using energy economic modelling.
- The developed framework will allow the establishment of a trend-based and partially quantitative comparative perspective on the prospective developments of electricity technologies.
- Furthermore, a common format of a status report will be established that is published in regular intervals.

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Costs & potentials of future Swiss electricity supply

C. Bauer, S. Biollaz, P. Burgherr, B. Cox, T. Heck, S. Hirschberg, A. Meier, W. Schenler, K. Treyer, F. Vogel, X. Zhang
Technology Assessment Group, Laboratory for Energy Systems Analysis, Paul Scherrer Institut (PSI)

Introduction

The Technology Assessment group at PSI (http://www.psi.ch/ta/), toghether with PSI internal and external partners, is evaluating costs, potentials, and environmental impacts of future Swiss electricity supply. The project can be considered as a substantial extension and update of PSI's previous study (Hirschberg et al. 2005). It is carried out on behalf of the Swiss Federal Office of Energy SFOE and is part of the "Global Observatory" within the SCCER SoE, in collaboration with SCCER BIOSWEET. The results will contribute to further specification of the Swiss energy strategy 2050 and to its ongoing implementation. The complete evaluation will be available mid 2016.

Scope

All power generation technologies which will or might contribute to Swiss electricity supply until 2050 will be included in the evaluation: both domestic generation as well as electricity imports will be taken into account.

Energy carrier	Technology	Location
Hydro	Small hydro	Domestic generation
	Reservoir	Domestic generation
	Run-of-river	Domestic generation
Wind	Onshore	Domestic generation
	Offshore	Imports from North Sea
Solar Photovoltaics	Different technologies, roof-top and open ground	Domestic generation
Solar thermal	Different technologies for oncentrating solar power	Imports from Southern Europe
Geothermal energy	Deep petrothermal (Engineered heat exchanger)	Domestic generation
	Hydrothermal	Domestic generation
Wave and tidal energy	Different technologies	Imports from the Atlantic ocean and the North Sea
Biomass, wet and dry	Large range of conversion technologies	Domestic biomass supply and power generation
Natural Gas	Combined cycle plants without and with Carbon capture & storage (CCS)	Domestic generation
	Fuel cells	Domestic generation
Coal	Plants with and without CCS	Imports from Germany
Nuclear	Different reactor concepts	Domestic generation
Others	Novel technologies	Domestic generation and imports

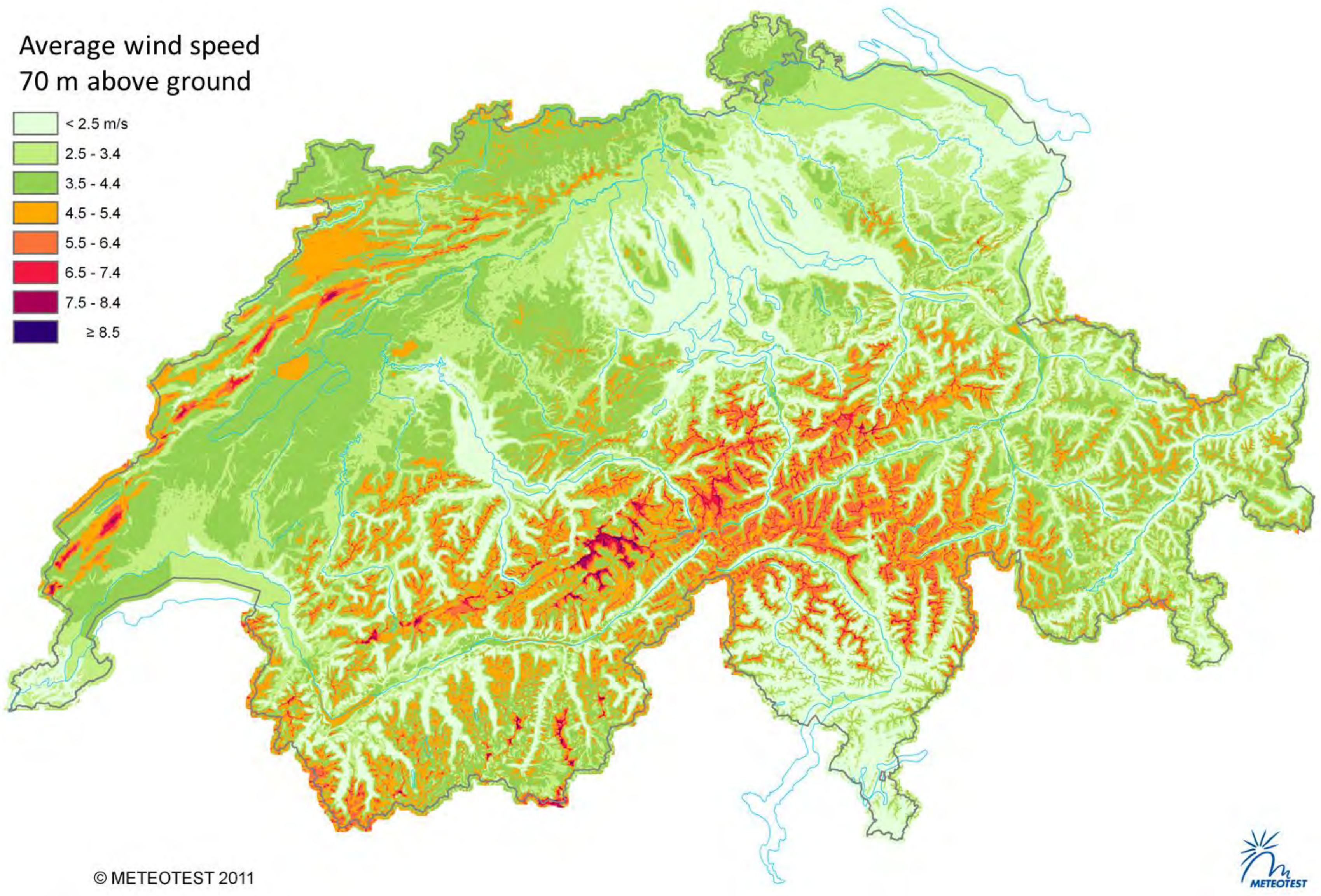
Methodology

Evaluation of technology-specific, domestic generation **potentials** will be based on current best estimates. Experts from industry and academial will be consulted. Technological, political, economic, and environmental boundary conditions and constraints will be considered.

Future development of **electricity generation costs** will be estimated based on current state-of-the-art knowledge and consider the expected future technology developments, long-term forecasts for the costs of energy resources, and other decisive factors such as political regulation and climate policy.

Quantification of technology-specific **environmental burdens** will be based on **Life Cycle Assessment** (LCA). LCA literature and the ecoinvent database (www.ecoinvent.org) will be reviewed and used for estimating the impacts of current technologies. Impacts of future technologies will be estimated considering expected technology development. The assessment will focus on life-cycle greenhouse gas emissions, and take into account additional impacts on human health and ecosystems.

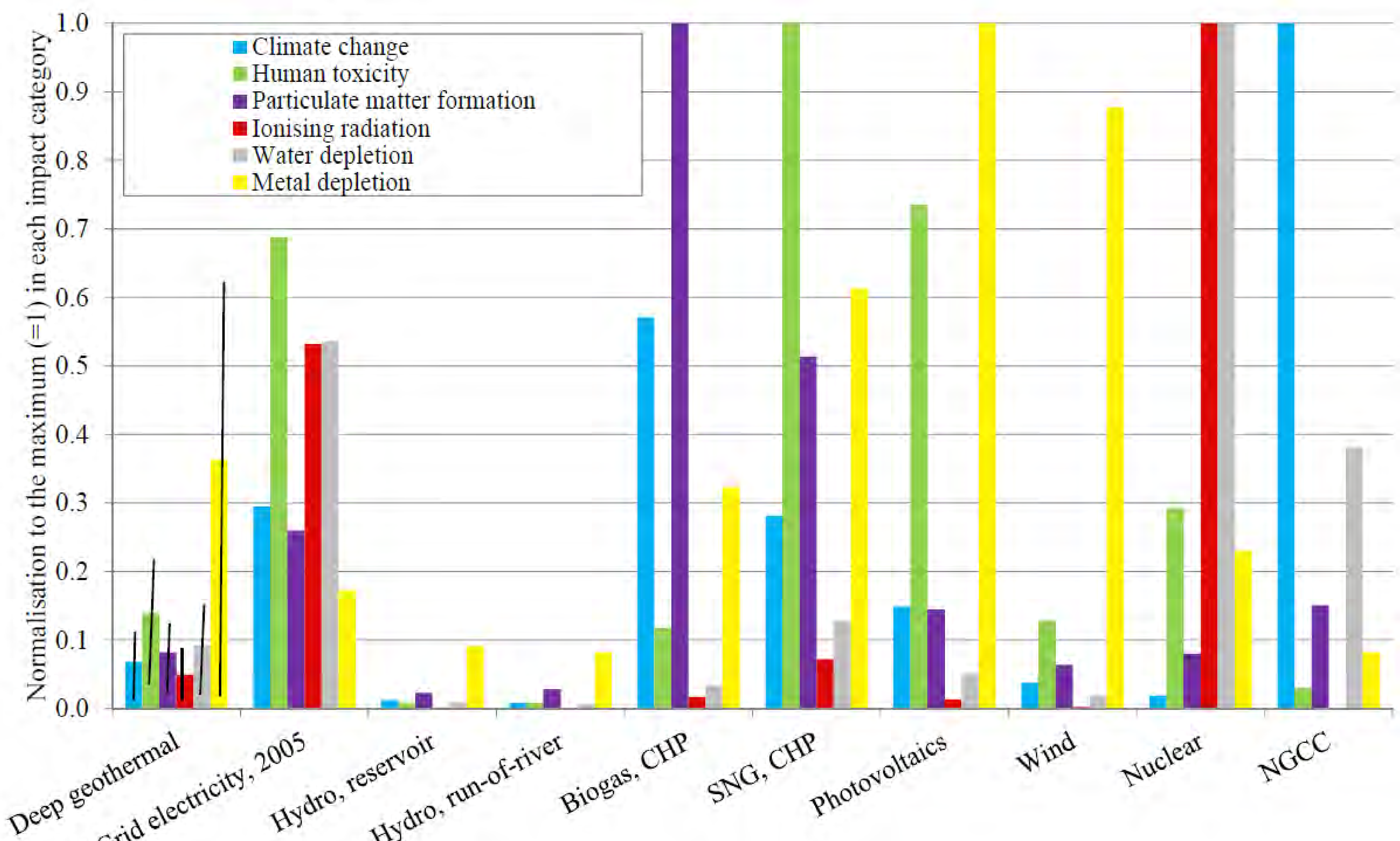
Wind map for Switzerland



Types of biomass and conversion technologies to be considered for electricity generation

Converter (electricity generator)		Biomass: Solid – Wood	Solid – Non-wood	Liquid – Sewage sludge, etc	Liquid – Biofuel	Gas – Biogas
IC Engine	Power Plant	x	x	tbd	x	x
Gas turbine	Heavy duty	x	x	tbd	-	-
	Micro	x	x	tbd	-	x
Steam turbine	Water	x	x	-	-	-
	ORC	x	x	-	-	-
Stirling		x	x	-	-	-
Fuel Cell	PEM	tbd	tbd	tbd	-	tbd
	MCFC	tbd	tbd	tbd	-	x
	SOFC	tbd	tbd	tbd	-	x

Environmental burdens of Swiss electricity generation



Hirschberg et al. 2015

References

Hirschberg, S., et al (2005) Neue Erneuerbare Energien und neue Nuklearanlagen: Potenziale und Kosten.PSI-Report Nr. 05-04., Paul Scherrer Institut, Villigen PSI, Switzerland.

Hirschberg, S., Wiemer, S. and Burgherr, P. (Eds.) (2015). Energy from the Earth. Deep Geothermal as a Resource for the Future?, TA-SWISS Study TA/CD 62/2015, vdf Hochschulverlag AG, Zurich, Switzerland

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A Linked Economic & LCA Model of Geothermal Generation in Switzerland

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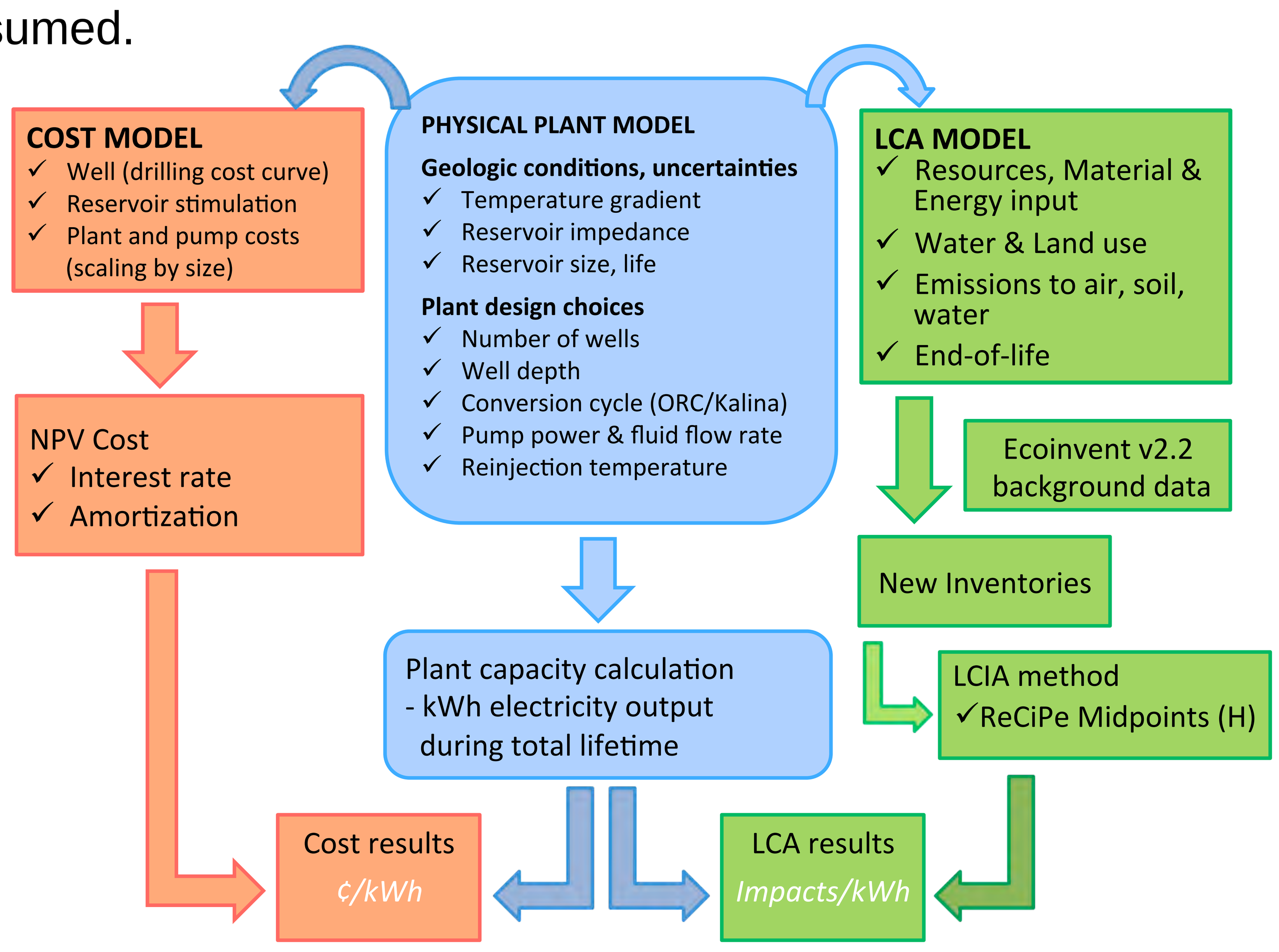
The Model

As part of a major study performed for TA-SWISS, the Technology Assessment group at PSI (http://www.psi.ch/ta/) has evaluated the costs, life cycle environmental burdens, and risks of geothermal generation in Switzerland. The cost and LCA results of this work were based on a model developed at PSI that links an underlying physical model of the geothermal fluid flow between the deep geothermal reservoir and the surface generation plant with an economic model that scales component costs and an LCA model that determines full-chain environmental burdens based on energy, resources and materials consumed.



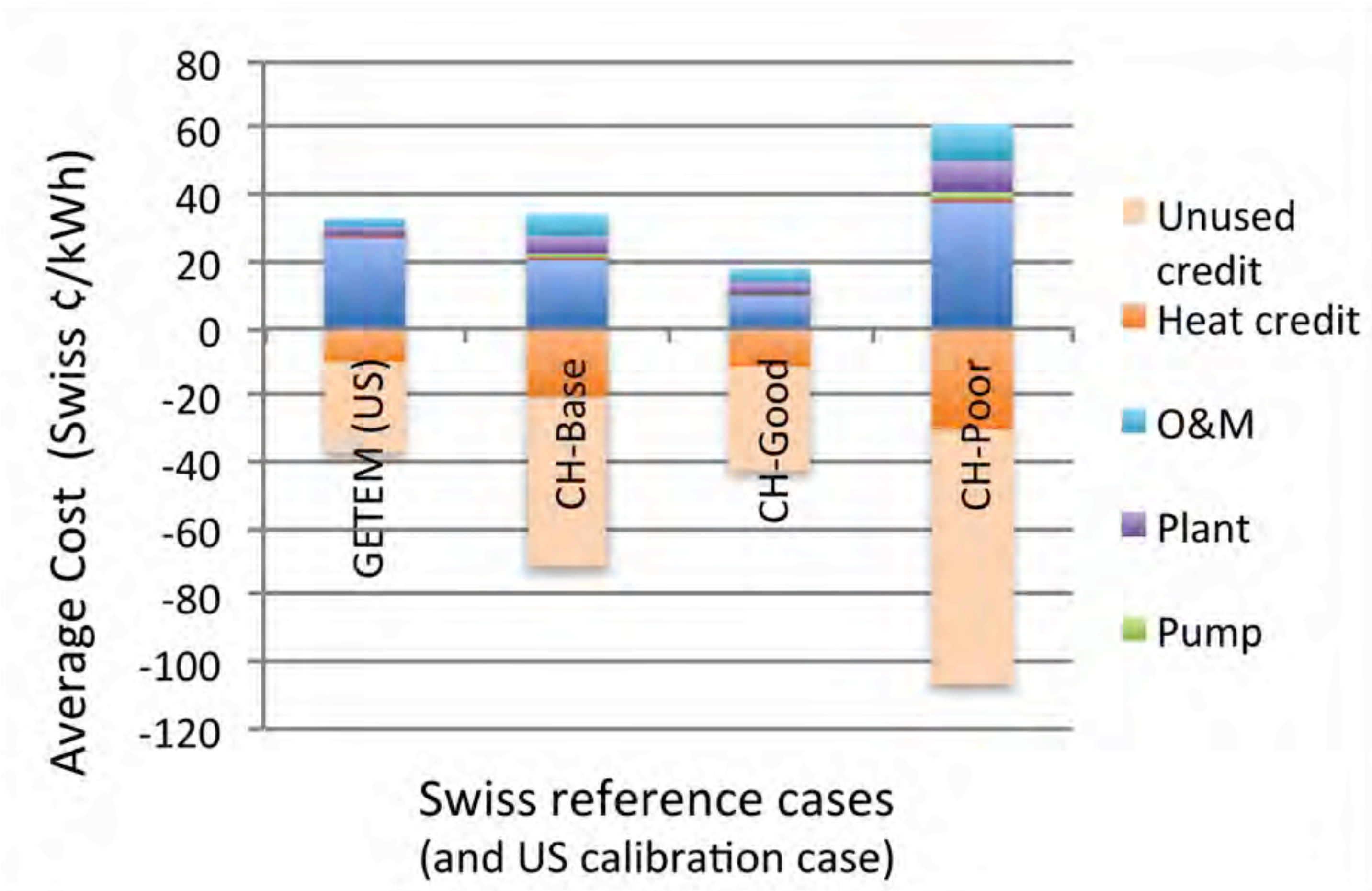
Data Assumptions

The data assumptions required include local geological conditions, well and plant design choices, costs and LCA inventories. The table shows some key assumptions and model results for a calibration case based on the USDOE geothermal model GETEM, and low, medium and high Swiss cases.

	Parameter	Unit	US GETEM	CH-medium	CH-high	CH-low	Sensitivity range
Plant	Geothermal gradient	˚C/km	35	35	40	30	20 - 50
Plant	Well depth	km	6	5	6	5	3 - 8
Plant	Reservoir temperature	˚C	225	190	255	165	
Plant	Reservoir impedance	MPa*s/L	0.113	0.2	0.2	0.2	0.05 - 0.5
Plant	Well diameter (I.D.)	Inches	10" (25.4 cm)	10"	10"	10"	6" - 16" (cost), 3.3" - 20" (LCA)
Plant	Flow rate (injection well)	L/s	147	147	147	147	49 - 294
Plant	Well (reservoir) life	years	5	20	30	20	5 - 30 (cost), 5 - 50 (LCA)
Plant	Surface plant lifetime	years	30	30	30	20	20 - 45
Plant	Wells during plant life		na	6	3	3	3 - 18 (3 => 1 injection, 2 prod.)
Plant	Gross plant power	MWe	13	8.9	17.3	6.4	
Plant	Downwell pump depth	m	470	1350	1289	1366	
Plant	Pump power (for 2)	MWe	1	3.4	2.7	3.5	
Plant	Net plant power	MWe	12	5.5	14.6	2.9	-∞ - 29
Plant	Annual net generation	GWh	100	46	122	24	
Cost	Well cost	M$/well	25.5	20.9	34.1	20.9	10 - 57
Cost	Fracturing cost/well	M$/well	1				
Cost	Plant cost	$/kW$_e$	3000	4200	4200	4200	2500 - 5500
Cost	Interest rate		10%	5%	5%	5%	2% - 10%
LCA	Rig power source		nd	Electricity			
LCA	Energy use, drilling	kWh/m	nd	3932	4719	3932	1750 - 11650
LCA	Rock stimulation, water use	m^3	nd	40000	40000	40000	10’000 - 200’000
LCA	Surface system		nd	Organic Rankine Cycle (ORC) using benzene			
LCA	Cooling system		nd	Air cooling			

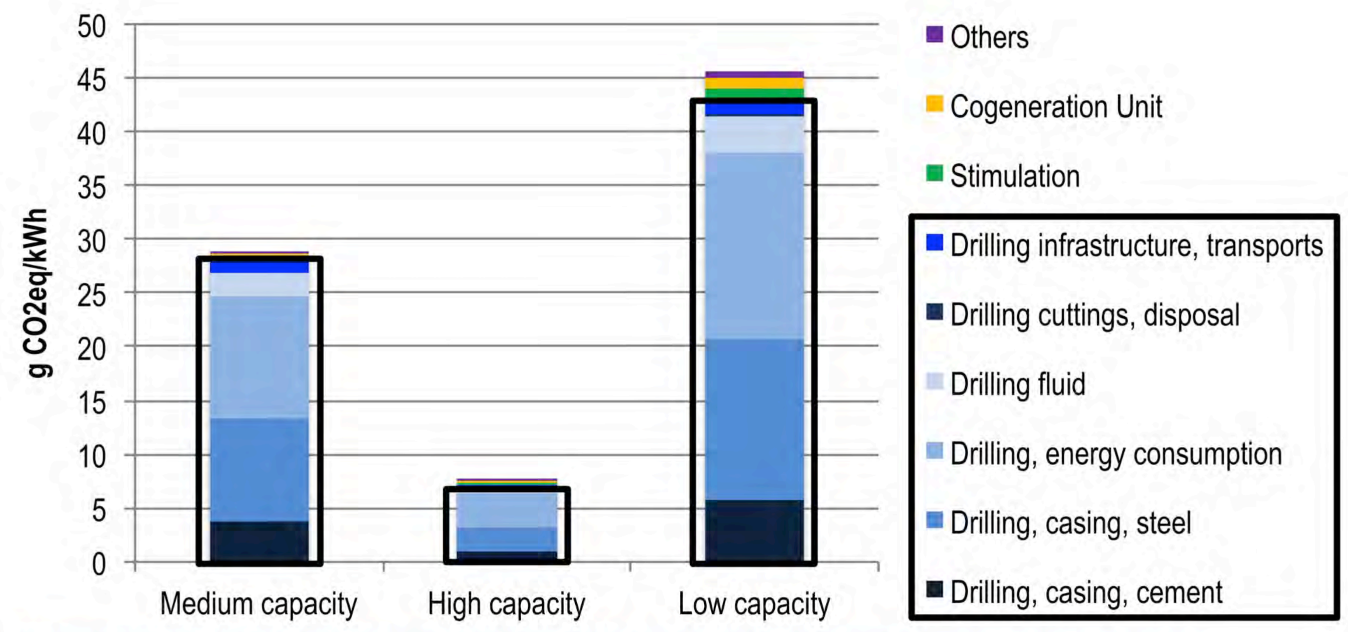
Cost Results

Cost results show that well costs dominate other cost components. Low thermal efficiency means that if some of the „waste“ heat can be sold (e.g. for district heating), this can greatly reduce average costs.



LCA Results

Life cycle environmental burdens are heavily dominated by well drilling, as shown below for CO2 emissions (drilling related contributions grouped within boxes).

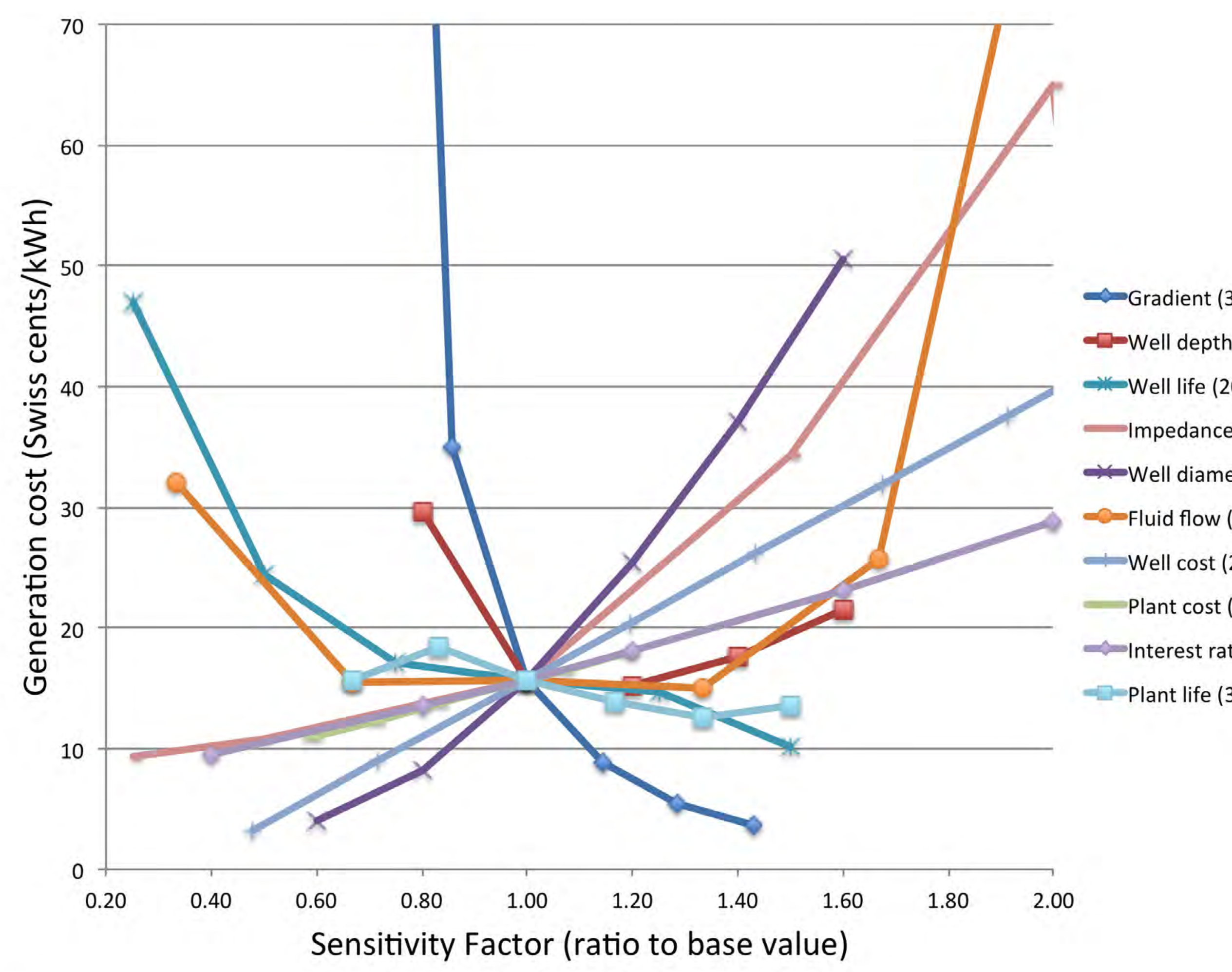


	Medium capacity	High capacity	Low capacity
Plant net capacity [Mwel]	**5.5**	**14.6**	**2.9**
Gradient [°C/km]	35	40	30
Depth of wells [km]	5	6	5
Number of wells	6 (2 well triplets)	3 (1 well triplet)	3 (1 well triplet)
Surface plant life time [years]	30	30	20
Well life time [years]	20	3	20
Production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

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

Parameter Sensitivities

Sensitivity analysis shows that both cost (shown) and LCA environmental burdens are most sensitive to well construction, and to factors that affect net lifetime plant generation.



Conclusions

- Costs vary strongly, depending on conditions and choices. The model allows detailed analysis.
- Well costs and reservoir assumptions dominate costs.
- Heat sales can greatly improve geothermal economics.
- The drilling phase dominates most environmental burdens.
- Energy and water used for drilling and well stimulation have smaller effects.
- Environmental burdens are in the same range or lower than other Swiss generation technologies.
- Geothermal potential is very large. It is locally depleted with long recovery periods, but the overall resource is sustainable.
- The Swiss GIS database combining resource, cost, heat demand, regulation and seismic risk data being developed as part of the SCCER will be very useful.

References

Hirschberg, S., Wiemer, S. and Burgherr, P. (Eds.) (2015). Energy from the Earth. Deep Geothermal as a Resource for the Future?, TA-SWISS Study TA/CD 62/2015, vdf Hochschulverlag AG, Zurich, Switzerland

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Global Observatory: Preliminary Results for Fuel Cell µCHP

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Project Overview

This work is part of a joint project between SCCER SoE, SCCER BIOSWEET, and the Swiss Federal Office of Energy. Within SCCER SoE this work is a part of Task 4.2: Global observatory of electricity resources.

The goal of the project is to analyze the potentials, costs and environmental burdens of electricity generation technologies that could play a role in future Swiss electricity generation. By characterizing different electricity generation technologies and their development trends, this project will contribute to sustainability assessment of the entire Swiss electricity system and its potential developments.

Introduction

Fuel cells can produce combined heat and power for decentralised locations at high efficiency and operational flexibility. As Swiss electricity and heating demand peaks during the winter, decentralised fuel cell Micro Combined Heat and Power (µCHP) technology could contribute to our energy system when and where it's needed most. The systems considered here have 0.5-50 kW electrical capacity and operate on natural gas with an internal reformer.

This work assesses the current and future environmental and economic life cycle costs of Polymer Electrolyte Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) and compares them to competing technologies, in this case, a micro gas turbine.

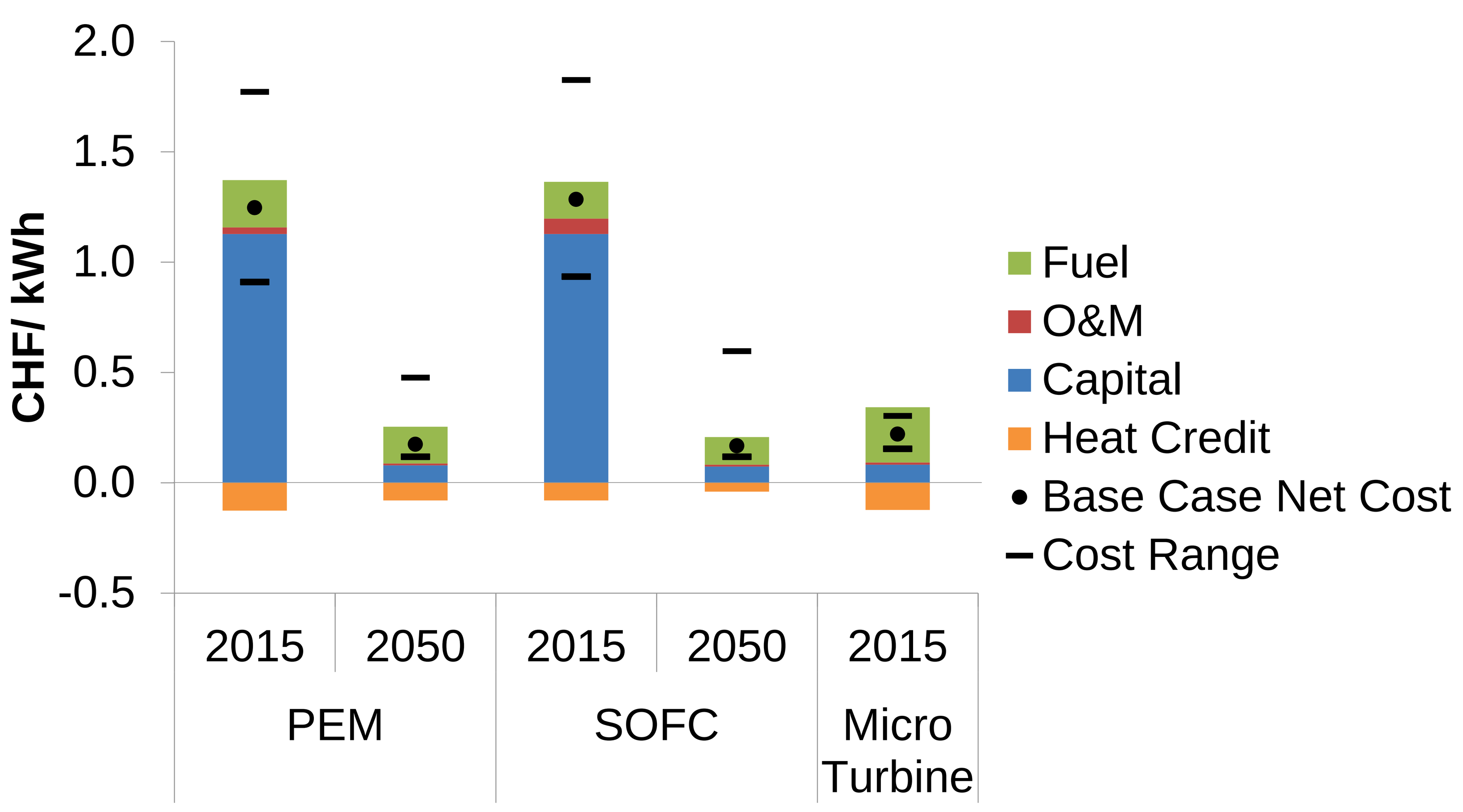
Methods

Assessment is done using a life cycle approach, including not only operation, but also component manufacturing and end-of-life treatments. Input data are based on literature review. Future capital costs are based on [1,2]; expected future improvements are due to mass production, increased competition and technical learning. A discount rate of 6%, natural gas price of 75 CHF/MWh, and heat credit of 80 CHF/MWh are used for the calcuation.

Life cycle inventory data for fuel cells are taken from [2,3] and updated to match the performance assumptions used in this assessment. Environmental impacts are allocated between electricity and heat production on an exergetic basis.

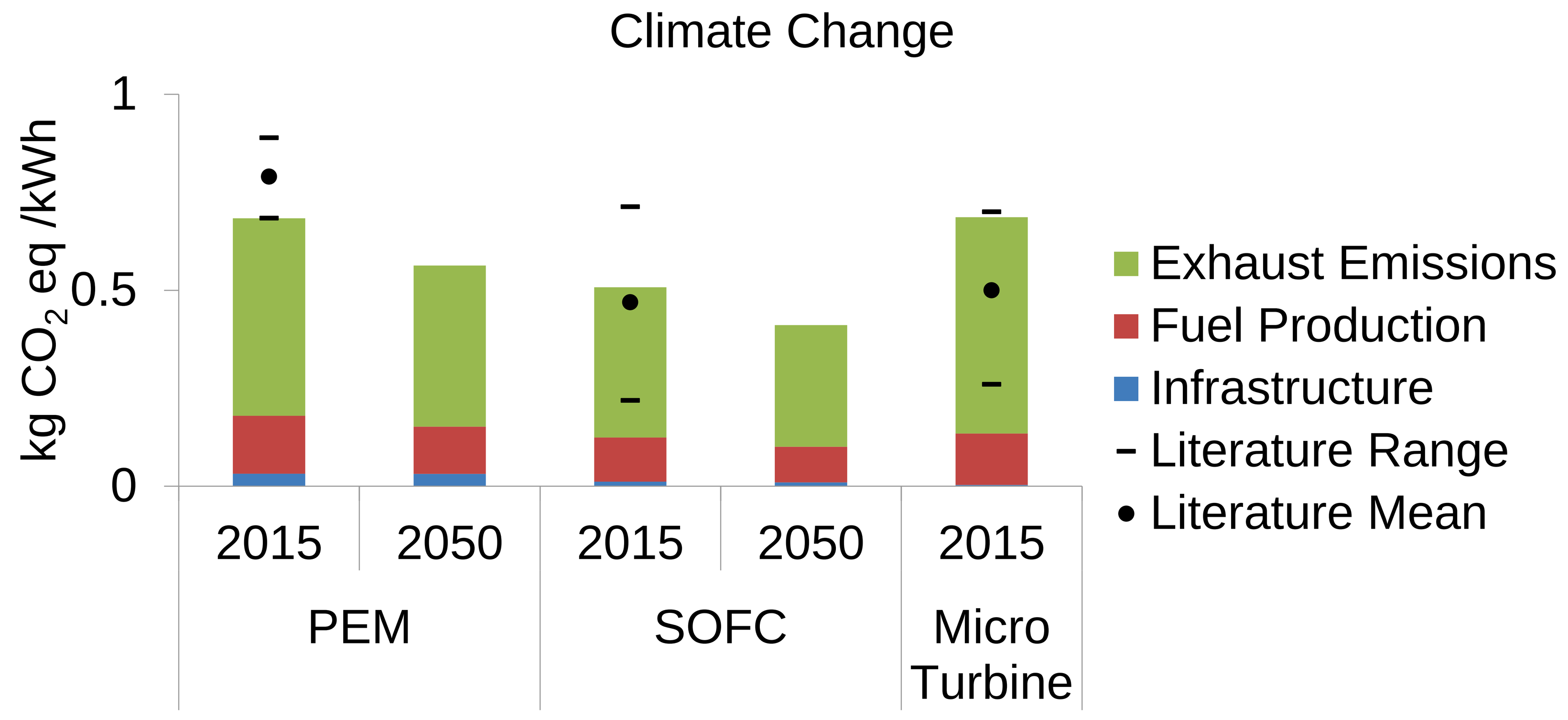
	PEMFC		SOFC		Micro
	2015	2050	2015	2050	Turbine
Electrical Efficiency (%)	30-40	40-50	40-50	55-65	25-35
System Efficiency (%)	85-95	85-95	85-95	85-95	70-80
Stack Lifetime (1000 Hours)	30-50	60-100	30-50	70-110	70-80
Capital Cost (1000 CHF/kW)	30-40	2-15	30-40	2-15	2-6

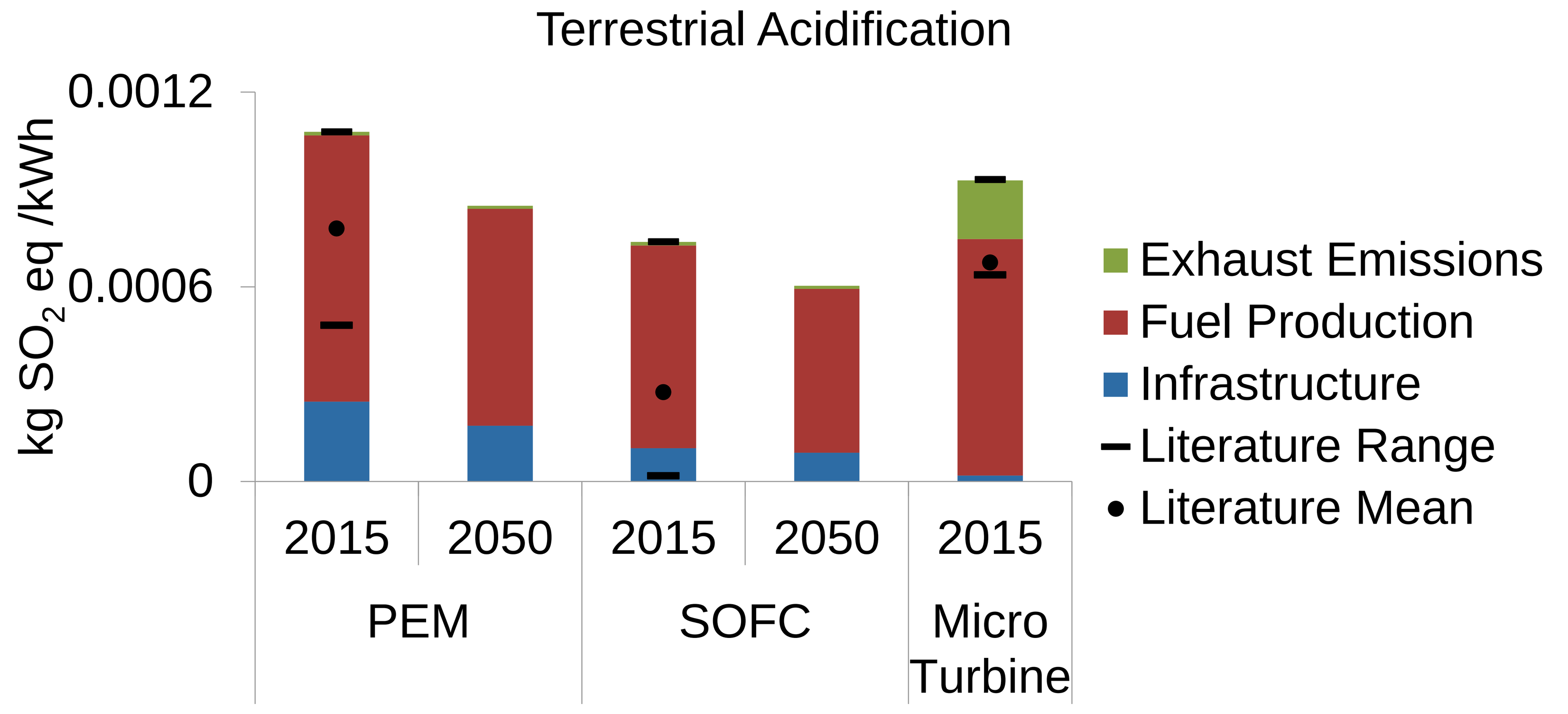
Cost Results



Selected Environmental Results

The literature range given for 2015 fuel cell and micro turbine environmental burdens is the maximum and minimum values found in the literature.





Discussion

The life cycle environmental impacts are mostly due to fuel production and operating emissions. For some impact categories (not shown here due to space contraints) infrastructure production also contributes significantly, though this decreases with improved fuel cell lifetimes in the future.

SOFCs appear to have the best environmental performance. Future fuel cells are expected to significantly outperform current designs.

Very large cost reductions are expected for fuel cell manufacture until 2050, though uncertainty is very large. Potential cost reductions will reduce electricity costs to levels similar to those of micro turbines. However, generation costs will remain higher than those of large scale stationary technologies.

Conclusions

Fuel cell µCHP is expected to provide decentralised heat and electricity with similar costs and environmental burdens to competing systems by 2050. However very large cost reductions are required before they are economically competitive.

The largest cost and environmental drivers for fuel cell µCHP systems are electrical efficiency, stack lifetime and installation cost.

Particularly SOFCs are interesting due to their high efficiency, lack of platinum group metals and ability to easily reform lower purity fuels, such as biomethane.

References

[1] Staffel I. and Green R. (2013) The cost of domestic fuel cell micro-CHP systems. doi: 1016/j/ijhydene.2012.10.090
[2] NEEDS (2008) New Energy Externalities Development for Sustainability Project. www.needs-project.org
[3] Primas A. (2007) Life Cycle Inventories of new CHP systems. Ecoinvent report No. 20. Swiss Center for Life Cycle Inventories, B&H AG, Dübendorf & Zürich

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Health Effects of Technologies for Power Generation: Contributions from Normal Operation, Severe Accidents and Terrorist Threat

PAUL SCHERRER INSTITUT PSI

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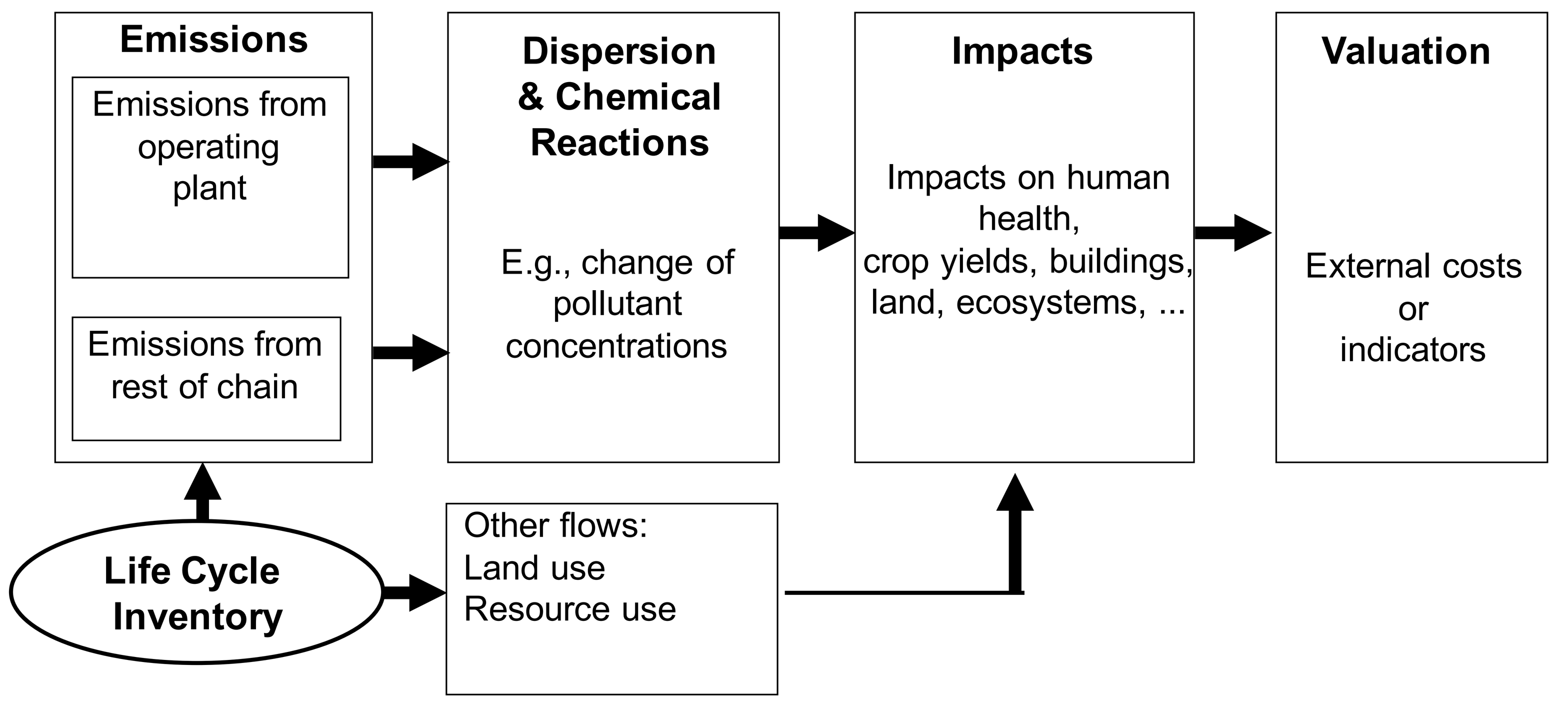
Introduction

Within SCCER SoE this work is part of PSI's contribution to Task 4.2 on "Global Observatory" of geoenergies and hydropower.
The goals of sustainability include minimization of negative health impacts of energy systems. Such effects may arise due to emissions of pollutants from the normal operation of power plants and the associated fuel cycles as well as from accidents and terrorist threats, thus contributing to increased mortality and morbidity. By using state-of-the art methods, the scope of current analysis covers full energy chains, addressing the following questions (Hirschberg et al, 2014):

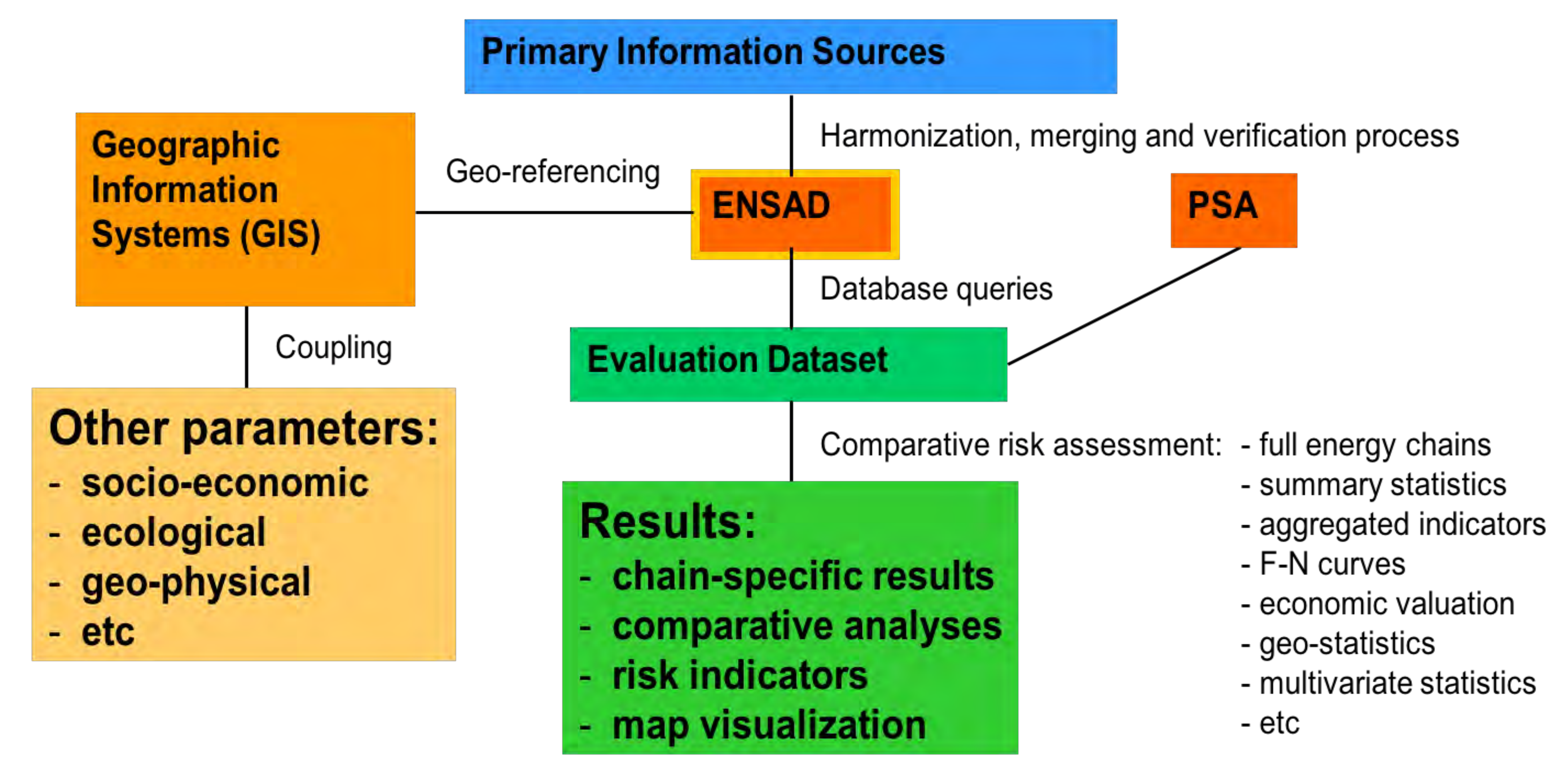
- How large are health effects associated with various electricity generation technologies and fuel cycles?
- How do health risks from normal operation compare with those resulting from accidents and hypothetical terrorist attacks?
- Which are the major limitations of the current estimates?

Mortality Impact of Normal Operation



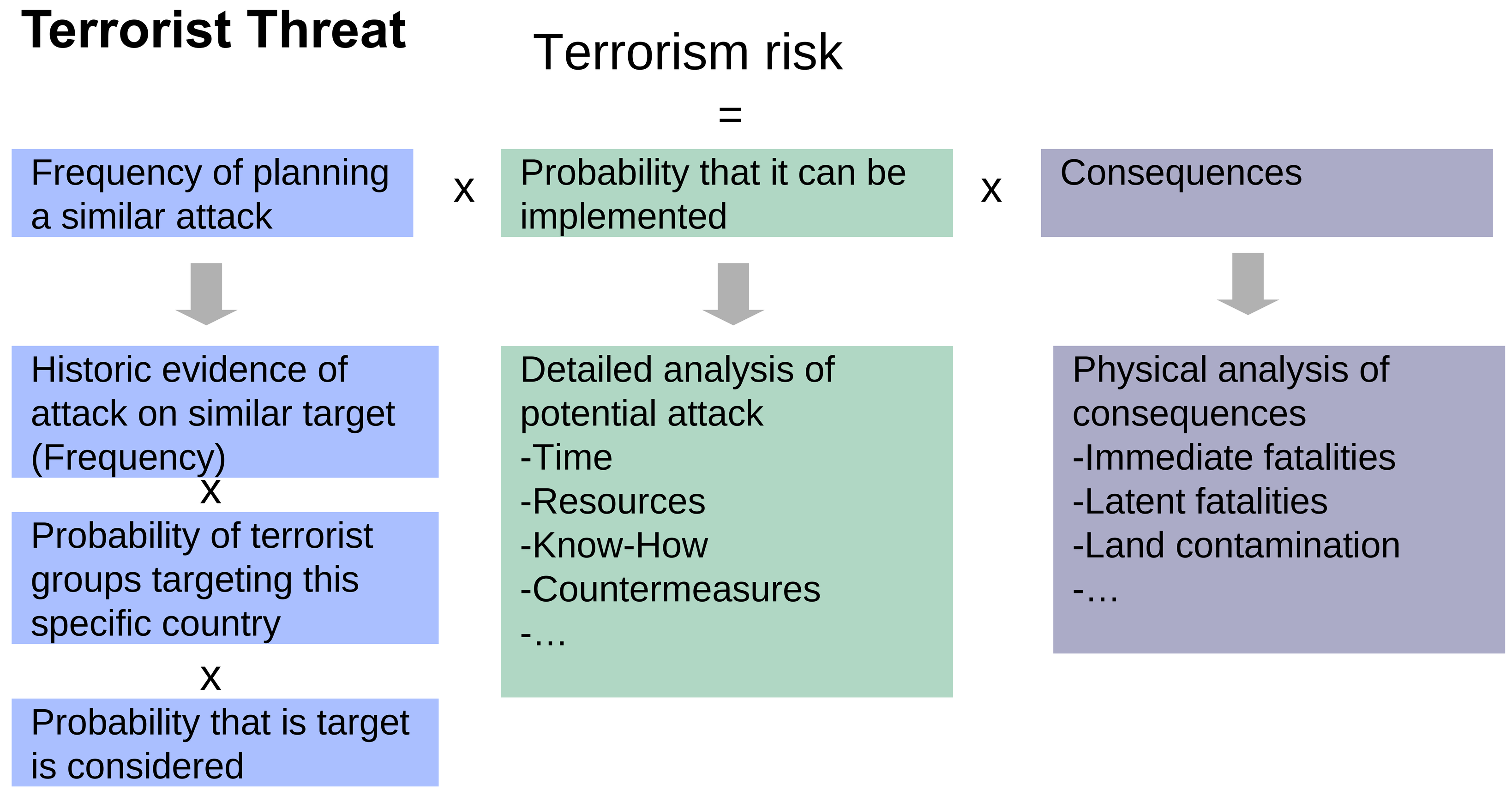
Health effects of normal operation are estimated using methods of Environmental Impact Assessment (EIA). The Impact Pathway Approach (IPA) allowing accounting for site-specific effects, is combined with detailed Life Cycle Assessment (LCA).

Severe Accidents

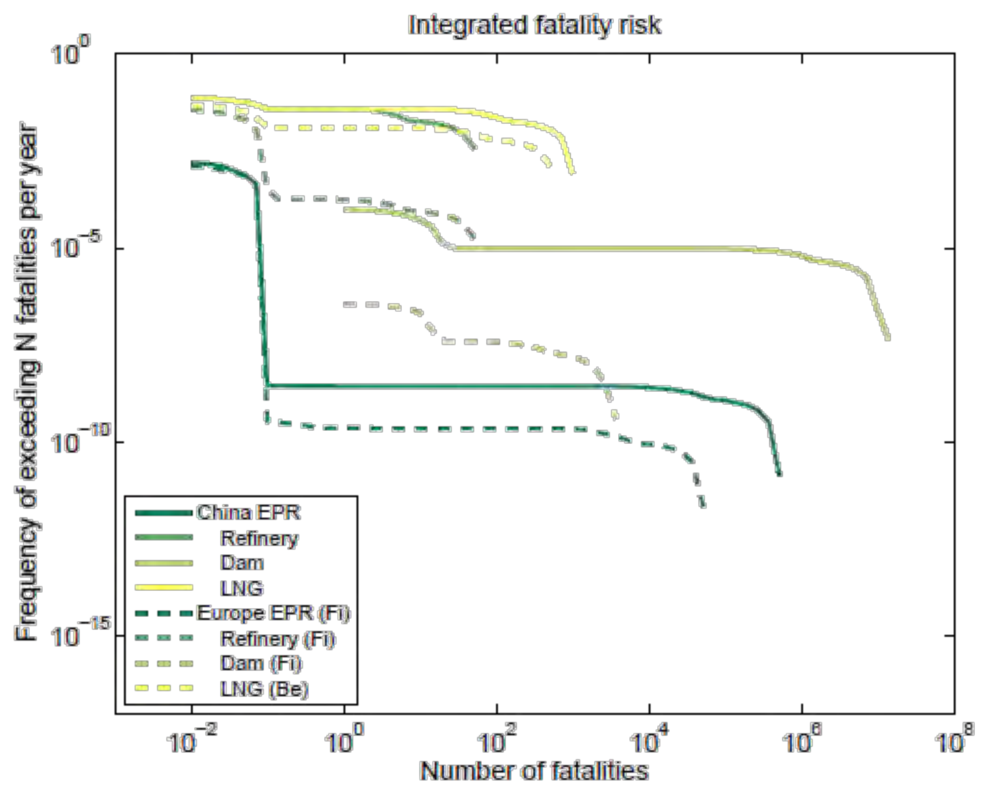


PSI's comprehensive framework for comparative assessment of severe accidents used in this study (e.g., Burgherr & Hirschberg, 2014)

Terrorist Threat

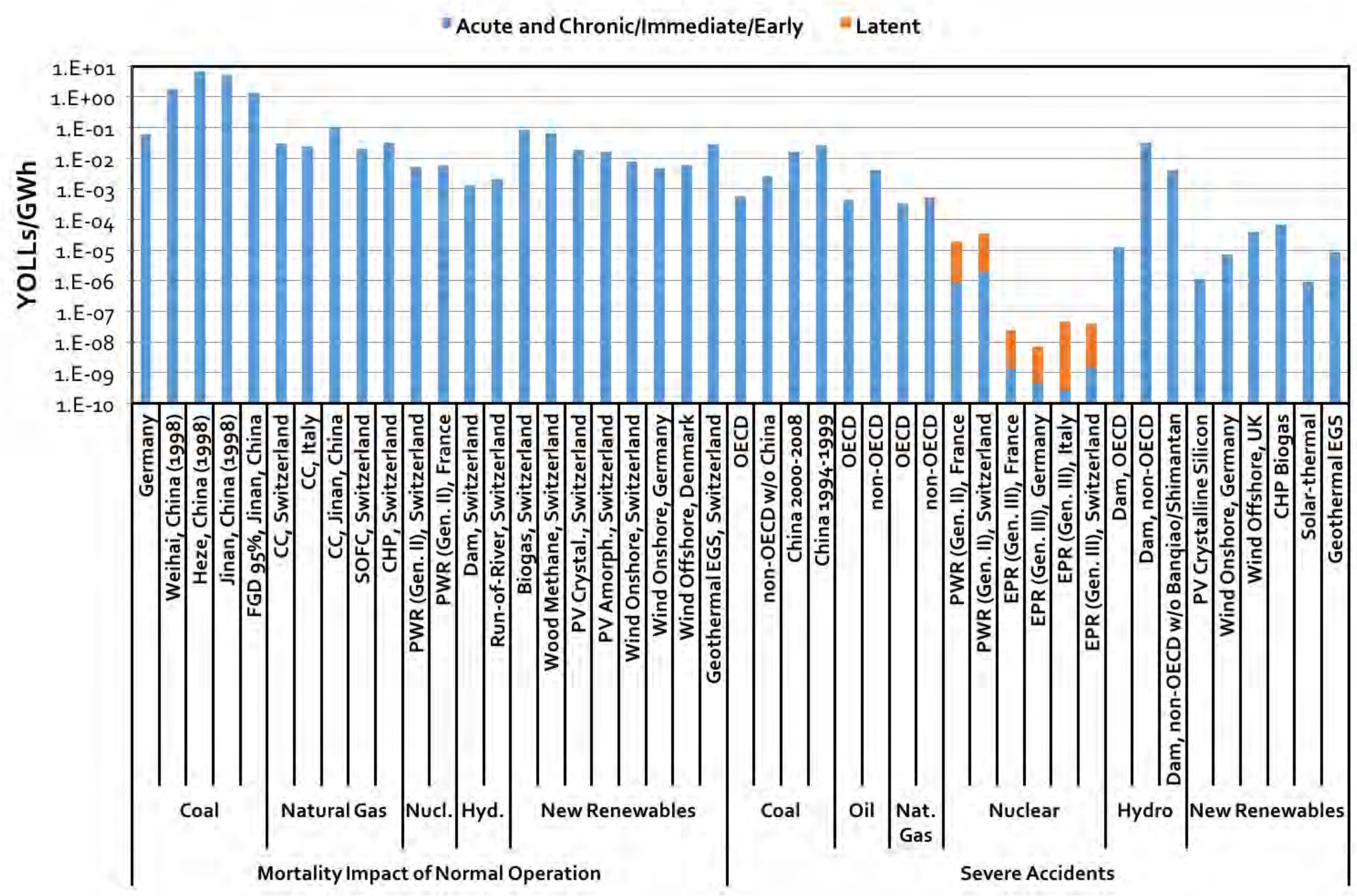


Analytical framework for the analysis of the terrorist threat against energy infrastructures (Eckle et al, 2011)



Frequency-Consequence curves for hypothetical terrorist attacks on energy infrastructure (Eckle et al, 2011)

Example: Comparison between Mortality Impact of Normal Operation and Severe Accidents



Mortality due to normal operation and severe accidents in Years of Life Lost (YLL) per GWh electricity produced for different systems and different locations.

Conclusions

- **General:** State-of-the art approaches to comprehensive comparative assessment of the various contributions to health risks of energy systems established and applied showing strong dependence on technologies, location and operational environment.
- **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. Fatality rates due to normal operation are much higher than the corresponding rates due to severe accidents.
- **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, treatment of morbidity, solar PV accident risks, cyber risks and implementation of terrorist risk assessment.

References

Burgherr P, Hirschberg S. Comparative risk assessment of severe accidents in the energy sector. Energy Policy. 2014;74, Supplement 1:S45-S56. http://dx.doi.org/10.1016/j.enpol.2014.01.035
Eckle P, Cazzoli E, Burgherr P, Hirschberg S. Analysis of terrorism risk for energy installations, Confidential Report, SECURE Deliverable No 5.7.2b, SECURE project "Security of Energy Considering its Uncertainty, Risk and Economic Implications". Brussels, Belgium2011. http://www.psi.ch/ta/SecureEN/WP5D7.2b.pdf
Hirschberg, S., Bauer, C., Burgherr, P., Cazzoli, E., Heck, T., Spada, M. & Treyer, K. (2014) Health Effects of Technologies for Power Generation: Contributions from Normal Operation, Severe Accidents and Terrorist Threat. *12th Probabilistic Safety Assessment and Management (PSAM12).* Honolulu, HI, USA

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Comparative Risk Assessment of Accidents in the Energy Sector using PSI's ENSAD Database

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Introduction

Comparative assessment of accident risks in the energy sector is a key aspect in a comprehensive evaluation of sustainability and energy security concerns. Safety performance of energy systems can have important implications on the environmental, economic and social dimensions of sustainability as well as energy security. Therefore, a comparison of different energy technologies needs to be based on objective risk indicators, considering complete energy chains because an accident can occur at any stage. For this purpose, the PSI initiated a long-term activity on comparative risk assessment of accidents in the energy sector since the early 1990s. At the core of this analysis is the Energy-related Severe Accident Database (ENSAD) that comprehensively collects worldwide accident data.

While accident risks of deep geothermal energy and hydropower are analyzed in Task 4.1, the risk assessment for other technologies is carried out in the Global Observatory (Task 4.2).

Energy-related Severe Accident Database (ENSAD)

Within ENSAD the focus is clearly on so-called severe accidents. The reason for this is that there are differences in the completeness and accuracy of accident reporting among countries, and thus to ensure consistent and meaningful comparisons across the globe, the definition of severity thresholds is inevitable. The actual specification of such thresholds can vary between databases because of differences in their purpose and scope. With regard to ENSAD the applied thresholds are considered to operationalize and facilitate worldwide analysis, while still keeping a sufficient level of completeness. It should also be noted that ENSAD also contains accidents with minor consequences, but these are not collected with the same effort as for severe ones, and also differences among countries are larger for smaller accidents because of the before mentioned reporting differences. In ENSAD an accident is considered severe if it fulfills at least one severity threshold of seven criteria representing different impact categories, as shown in the table below.

Risk description	Impact Category	ENSAD severity threshold	Consequence indicator
Human health	Fatalities Injuries	≥ 5 ≥ 10	Fatalities per GWeyr Injured per GWeyr
Societal	Evacuees Food consumption ban	≥ 200 yes	Evacuees per GWeyr Nominal scale
Environmental	Release of hydrocarbons Land/water contamination	≥ 10'000 t ≥ 25 km²	Tonne per GWeyr km² per GWeyr
Economic	Economic loss	≥ 5 Mio USD (2000)	USD per GWeyr

As the nature of risks continuously evolves, ENSAD too evolves to ensure it remains an up-to-date and vital resource to assess risk. Since its first release (Hirschberg et al., 1998), the methodological framework of ENSAD has been refined and extended by adding numerous new elements and broadening the analytical scope and coverage. These include:

- Consideration and inclusion of new information sources
- Estimation of external costs
- Simplified level-3 Probabilistic Safety Assessment (PSA) for nuclear
- Coupling ENSAD with Geographic Information System (GIS)
- Evaluation of new renewable and future technologies
- Risk indicators for Multi-Criteria Decision Analysis (MCDA)
- Methodological developments (e.g. extreme events, Bayesian approaches
- Consideration of accidents triggered by natural hazards (Natech)
- Intentional attacks on energy facilities

Despite all these advancements, ENSAD has remained a simple MS Access database, but the complexity of its structure and table relationships has substantially increased to accommodate all the additional needs and functionality that emerged in many different projects over the past two decades (Burgherr et al., 2013).

ENSAD "Version 2.0"

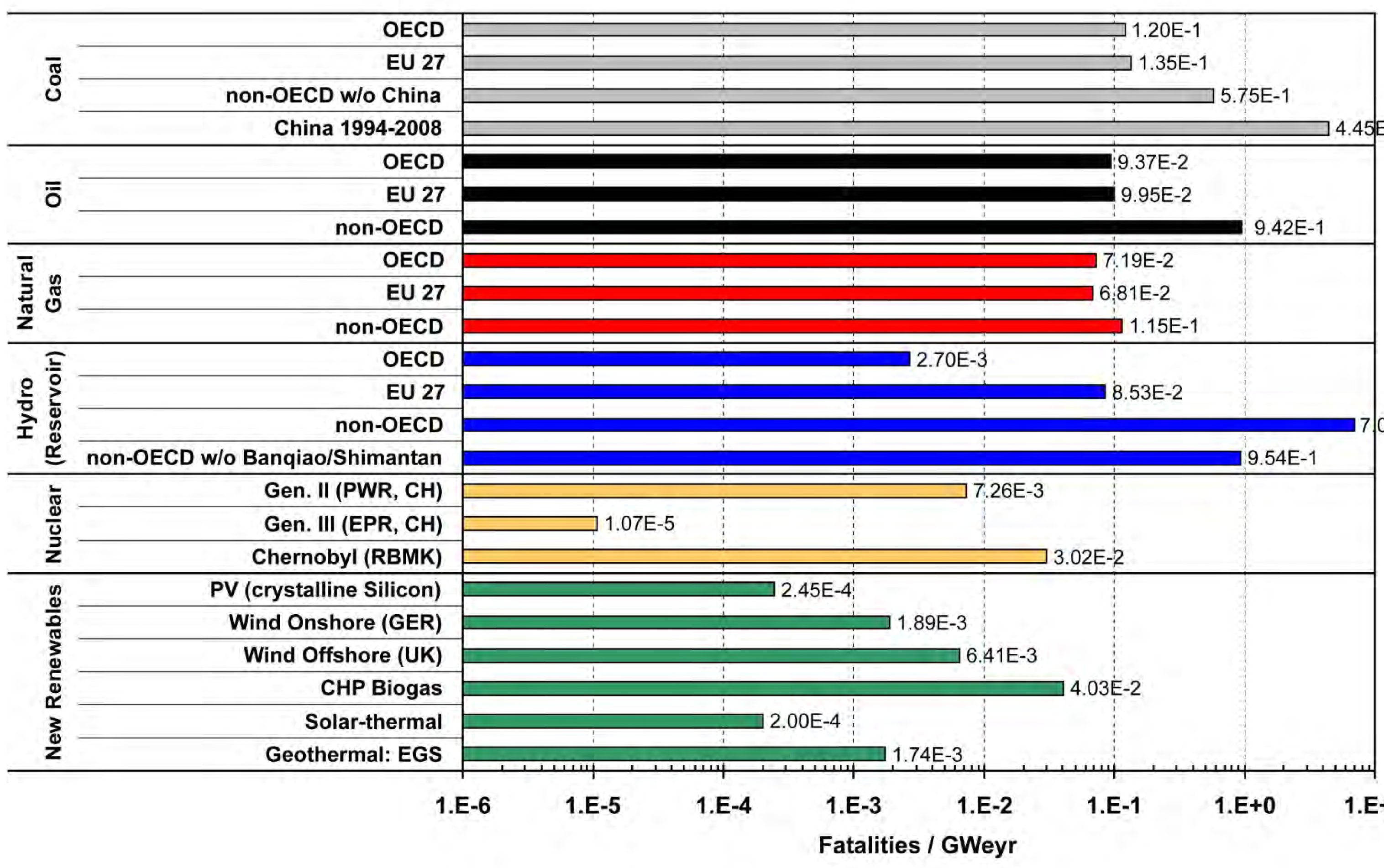
To ensure that ENSAD can keep up with future demands, it was decided to develop a new version of the database that relies on current, state-of-the-art IT technologies. In particular ENSAD will become a fully interactive and web-based application that can be accessed through the browser. This basic change is accompanied by several structural and organizational modifications, including streamlining of the actual data record structure, the implementation of different user roles (e.g. administrator, editor, user) to allow tailored database access, and new modules for visualization, data analysis and export. Since this is a demanding and time consuming task, it is conducted within several long-term projects, with SCCER SoE playing a key role.

The preliminary accident record structure in "ENSAD V2.0" can be grouped into several modules that then contain the actual fields:

- Identification: Record Identifier, Accident Date, etc.
- Location: Coordinates, Country, Region, etc.
- Event Classification: Energy Chain, Energy Chain Stage, etc.
- Infrastructure Characterisation: Type, etc.
- Event Analysis: Trigger, Event Chain, etc.
- Consequences: Fatalities, Injuries, Economic Damage etc.

Risk Indicator Example

The below figure shows fatality rates normalized to the unit of energy (i.e. Gigawatt-electric-year, GWeyr). For this comparison a broad portfolio including fossil hydro, nuclear and new renewable technologies was considered. Among centralized technologies expected accident risks are lowest for hydro and nuclear in Western countries, while fossil chains exhibit highest risks. Decentralized energy systems appear to be less sensitive to severe accidents, however, current analyses for new renewables have limited scope and do not include probabilistic modeling of hypothetical accidents.



(Burgherr and Hirschberg, 2014)

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Hirschberg, S., Spiekerman, G. & Dones, R. (1998) Severe accidents in the energy sector - first edition. PSI Report No. 98-16, Villigen PSI, Switzerland, Paul Scherrer Institut.

Swiss Competence Center on Supply for Electricity
Annual Conference 2015

Review and Meta-Analysis of Swiss Electricity Scenarios 2050

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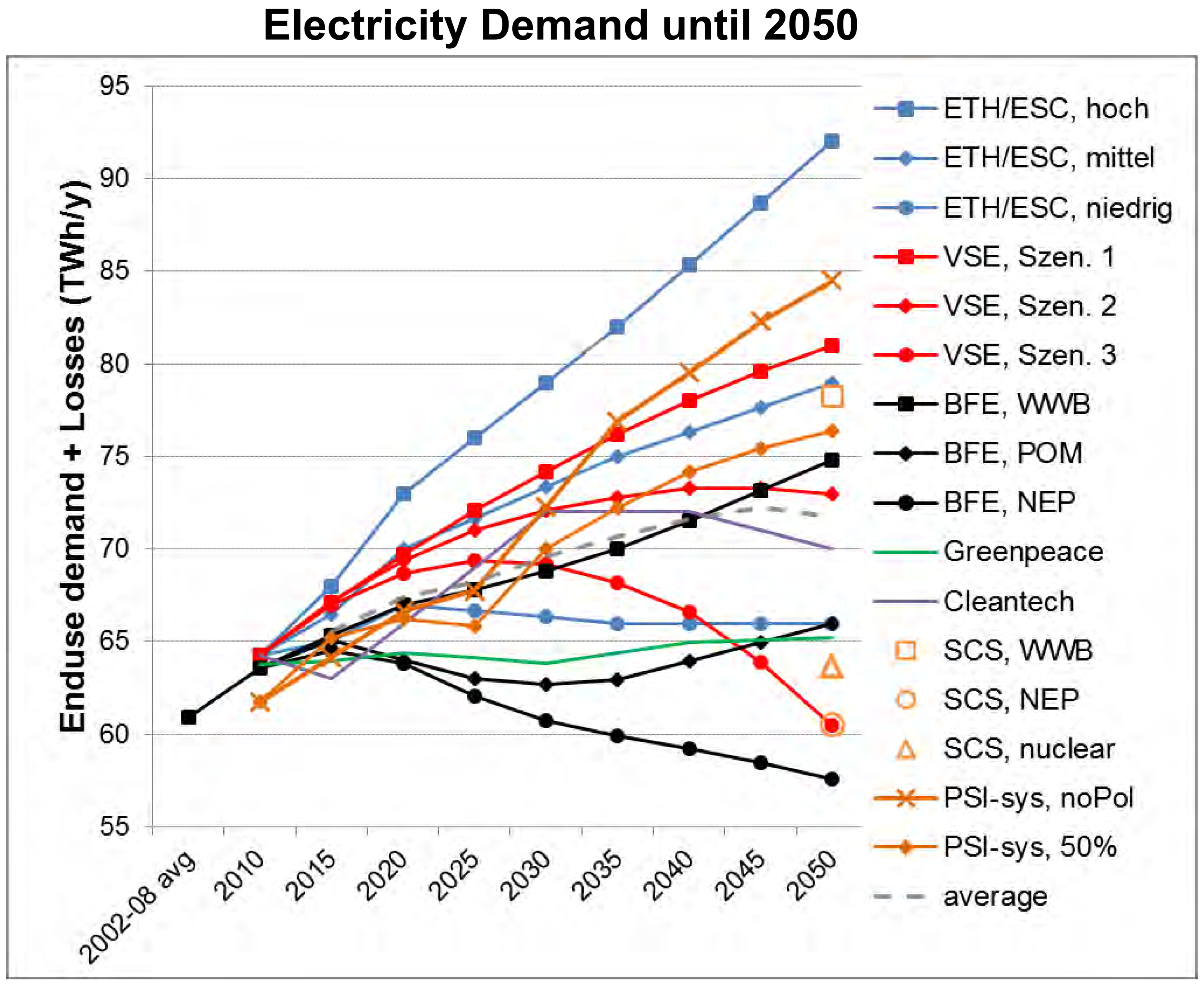
1. Introduction

Electricity scenarios until 2050 of energy studies for Switzerland are reviewed. The selected studies have a sufficiently high detail of the electricity sector:

Study (publ.)	Name (abbrv.)	Author of model	Year	System scope
BFE	Energieperspektiven	Prognos AG	2012	Energy system
VSE	Stromzukunft	Pöyry AG	2012	Electricity
ETH (ESC)	Energiezukunft	Andersson et al.	2011	Energy system
SCS	SCS-Energiemodell	Gunzinger (SCS AG)	2013	Electricity
Greenpeace	Energy [r]evolution	DLR, SCS AG	2013	Energy system
Cleantech	Energiestrategie	Barmettler et al.	2013	Energy system
PSI-sys	Transformations	Weidmann (PSI)	2013	Energy system
PSI-elc	Energie-Spiegel 21	Kannan, Turton (PSI)	2012	Electricity

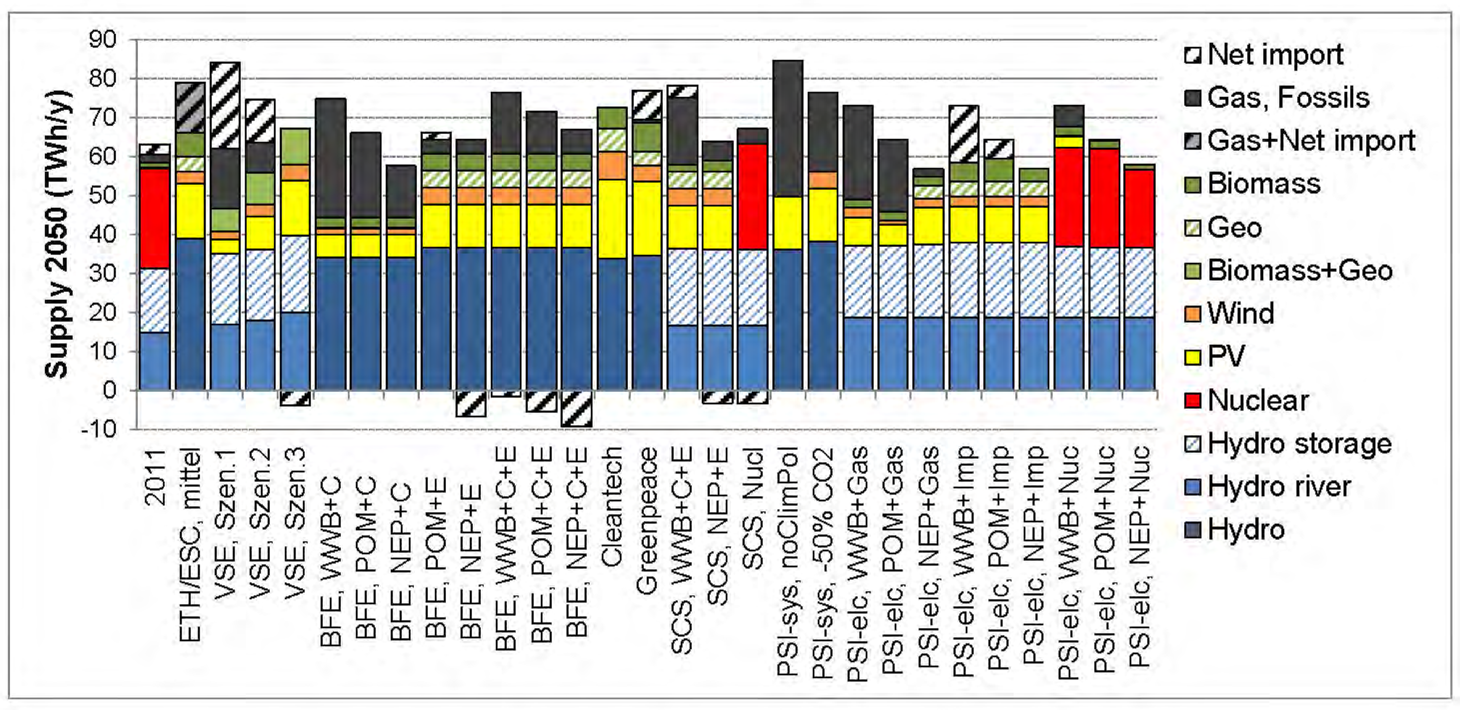
For example, model methodologies were reviewed, e.g., the degree of integrated modelling: High integration (whole energy system, demand + supply) vs. only electricity supply models. On this poster, visual scenario outputs are compared:

Electricity Demand until 2050

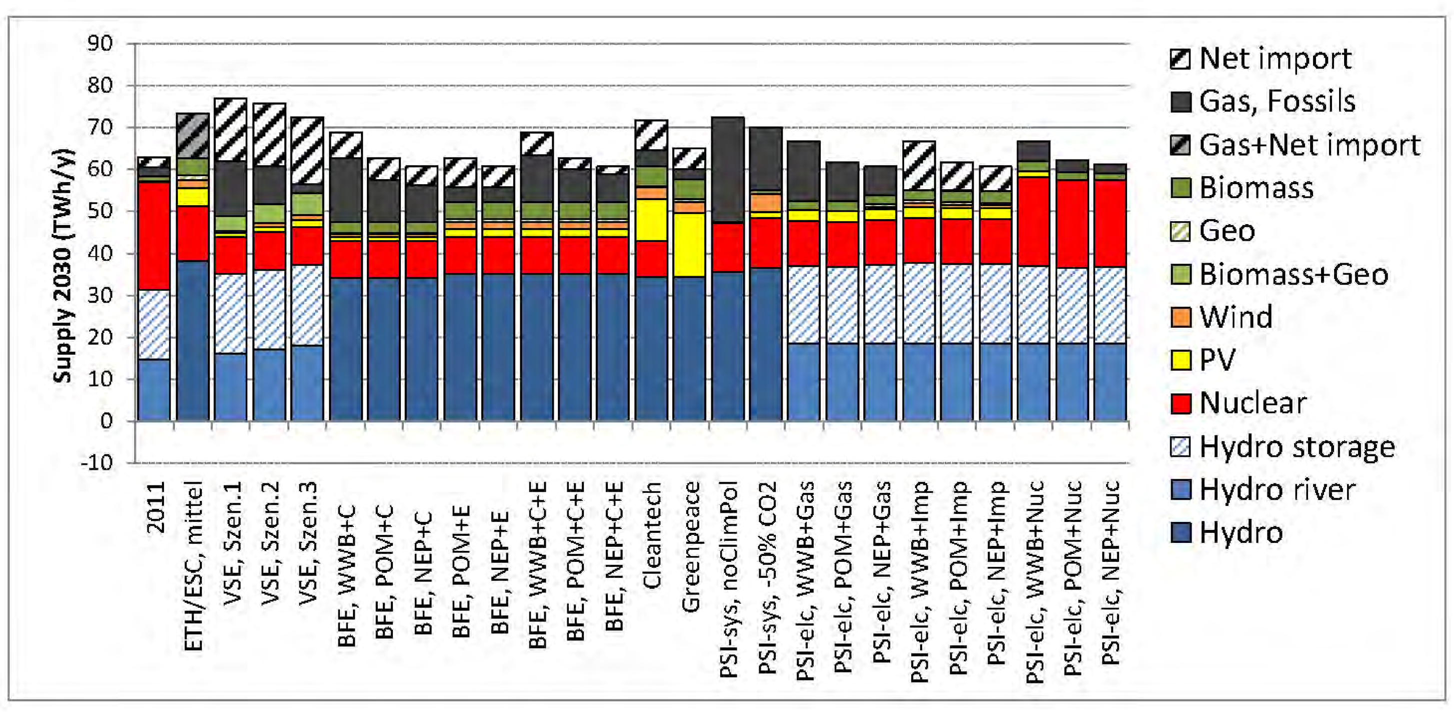


BFE's NEP and POM scenarios assume drastic efficiency measures (no cost-optimization). VSE assumes inertia in growth ("producer's view").

Annual supply mix 2050 and 2030

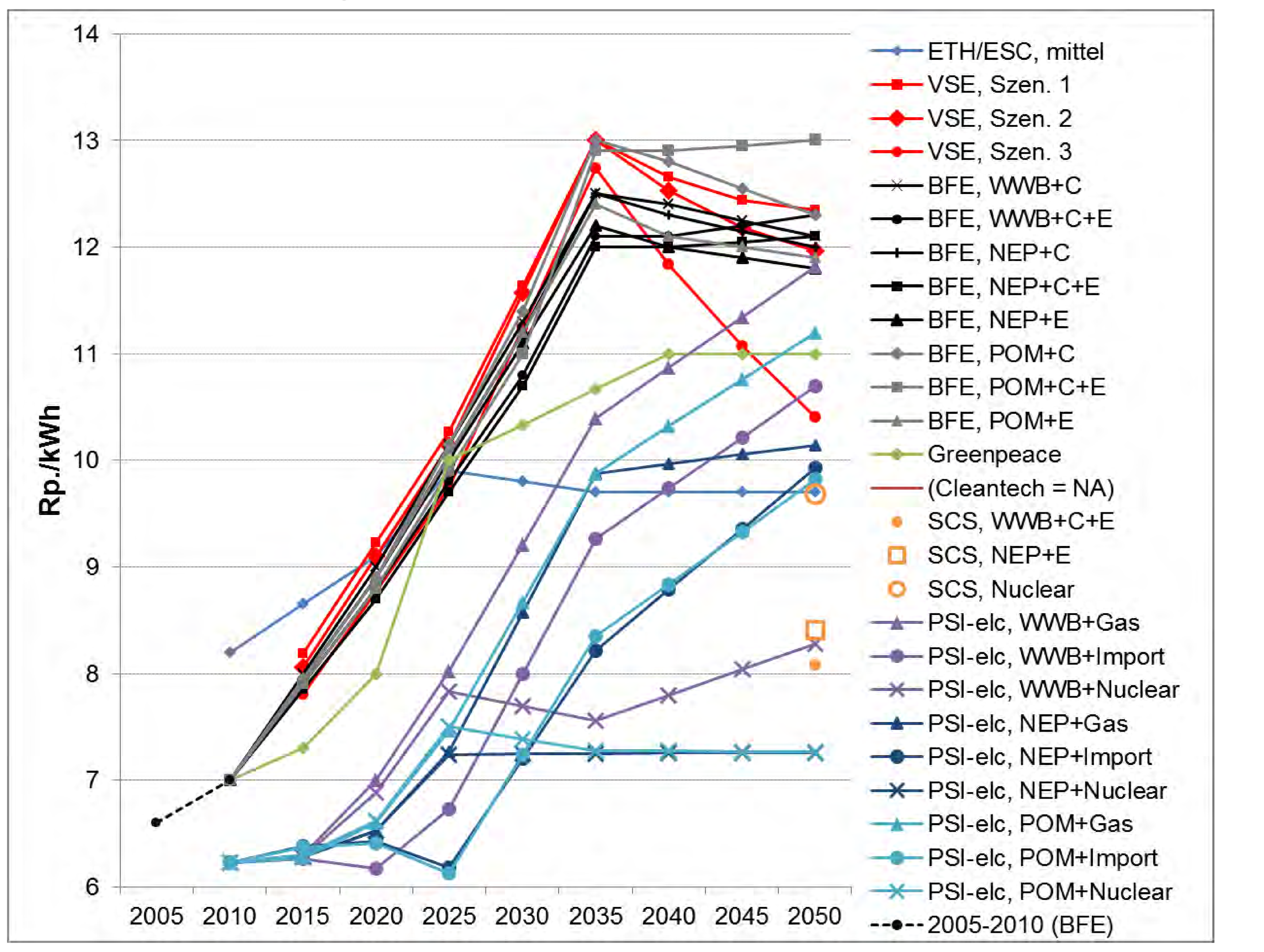


In scenarios having low demand and high new renewables, Switzerland can become a net exporter in 2050. New Hydropower is limited.



In many scenarios in the critical year 2030, Switzerland will be an annual importer: Nuclear is phasing-out while renewables are not fully deployed.

Electricity Production Cost of Generation Mix

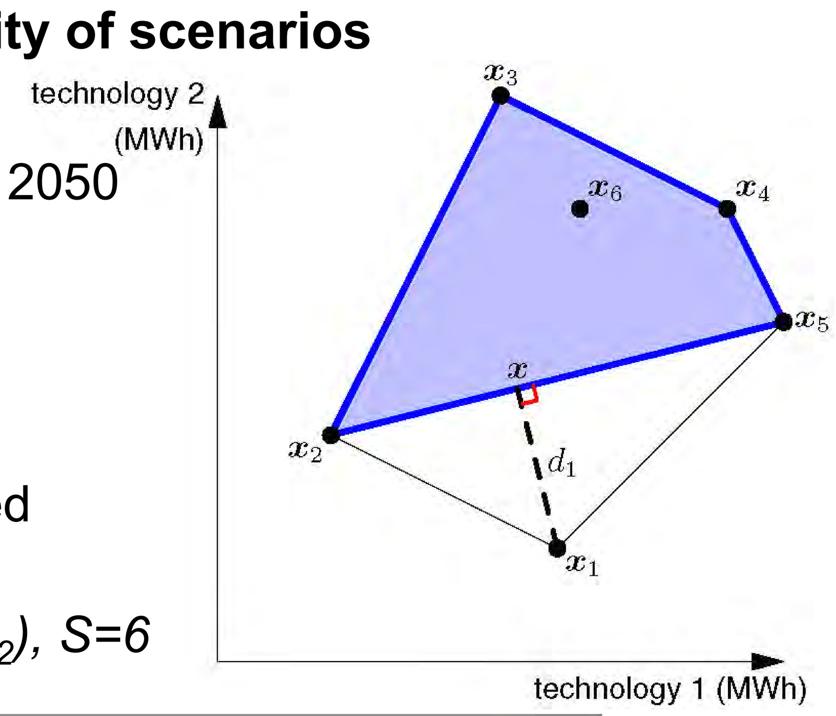


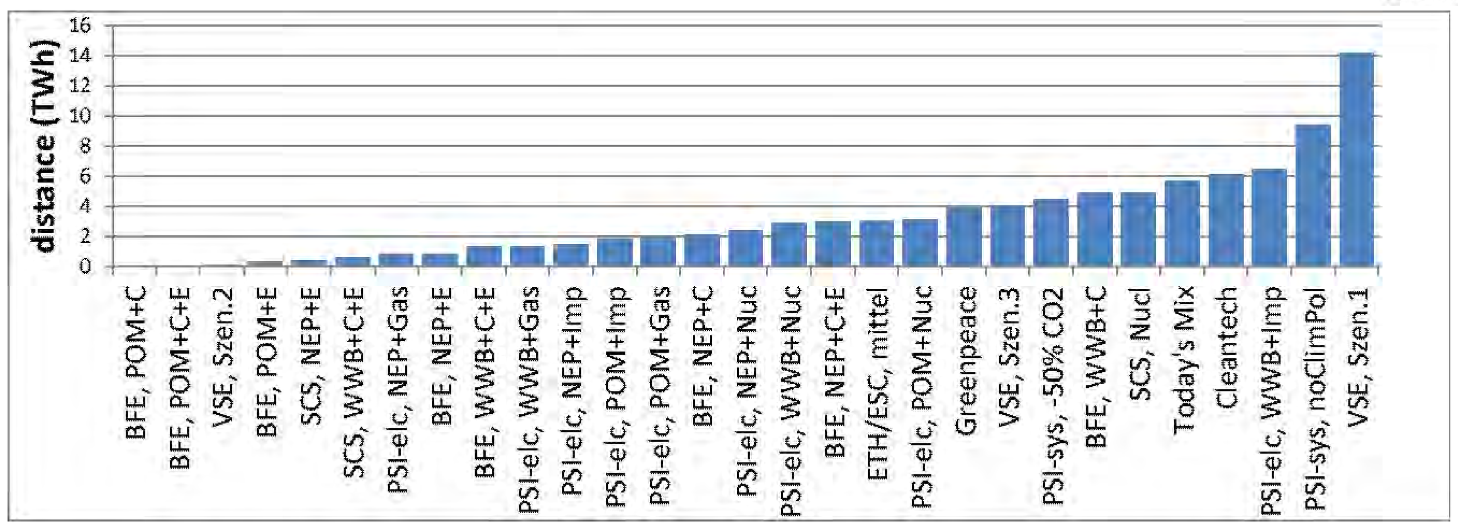
Many scenarios have rising production costs (grid costs are excluded; imports are usually included). Nevertheless, with low demand and high renewables in 2050, costs may decline long-term (VSE's Scenario 3).

Meta-Analysis

Example: Extremality of scenarios

- **Production mix** in scenario *i* in year 2050 by technology: $x_i=(t_1,\dots,t_N)^T$, $i=1,\dots,S$.
- **Convex set** spanned by all points x_i: $conv(x_1,\dots,x_S)$.
- **Def. *Extremality***: Distance of x_i to $conv(x_1,\dots,\cancel{x_i},\dots,x_S)$, *i.e.*, to the reduced convex set without x_i.
- **To the right:** 2-dim example: $x_i=(t_1, t_2)$, $S=6$





Some BFE-scenario's supply mixes in 2050 are merely convex combinations of other (BFE-)scenarios; the mix of VSE's Scenario 1 is highly unique

Conclusions

- **Switzerland and surrounding countries:** Most models consider only Switzerland (exception: VSE) and no market aspects → addressed in forthcoming models of e.g. PSI, UniBasel.
- **Power grid is not modelled:** (exception: SCS has simplified grid voltage levels, but no topology) → Open question: which detail needed?
- **Deterministic modelling:** All models are deterministic (exception: VSE considers 6 yearly weather profiles simultaneously for given capacity)
- **Capacity expansion and dispatch modeling:** Combining long-term capacity expansion of power technologies with the hourly dispatch decision is numerically demanding (if the model uses optimization).
- **Storage:** Currently the hydropower reservoirs are lumped together, and competing storage (e.g. batteries, power-to-gas) are not fully modelled → new PSI project "SwissHydro" (with support from VSE).
- **Meta-Analysis:** Relatively new research area: Statistical analysis of heterogeneous multivariate scenarios results

This work was also supported by the Group Energy Perspectives.

- **M. Densing, S. Hirschberg, H. Turton (2014):** Review of Swiss Electricity Scenarios 2050, PSI-Report, 14-05, www.psi.ch/eem
- **M. Densing, E. Panos, S. Hirschberg (preprint):** Meta-Analysis of Energy Scenario Studies: Example of Electricity Scenarios for Switzerland

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Review of Global Energy Scenarios

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1. Background

The deployment of energy technologies can be at a different pace in the world regions. To identify key long-term trends, energy system scenarios are developed.

The **Paul Scherrer Institut (PSI)** and the **World Energy Council (WEC)** established a modelling partnership to develop such global energy scenarios: The ***WEC-PSI JAZZ*** scenario is market- and energy access-oriented, with focusing on economic growth. The ***WEC-PSI SYMPHONY*** scenario is more state-driven and regulation-oriented, with a focus on achieving environmental sustainability and energy security within international cooperation.

2. Approach

Besides the *WEC-PSI* collaboration, there exist various other energy system models and published scenarios with the goal of exploring the future of the global energy system (►Table).

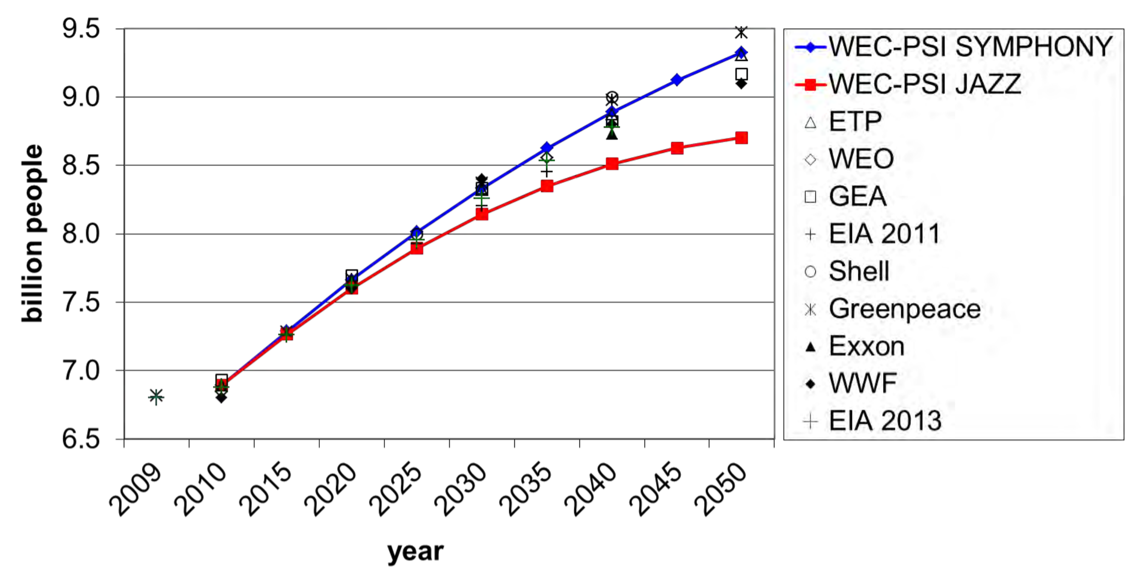
For the Global Observatory (Task 4.2), which monitors technology characterization and development, the scenario studies were reviewed and compared. The comparison was regarding the roles of specific technologies (e.g. CCS) and key driving factors (e.g. population, Gross Domestic Product (GDP)).

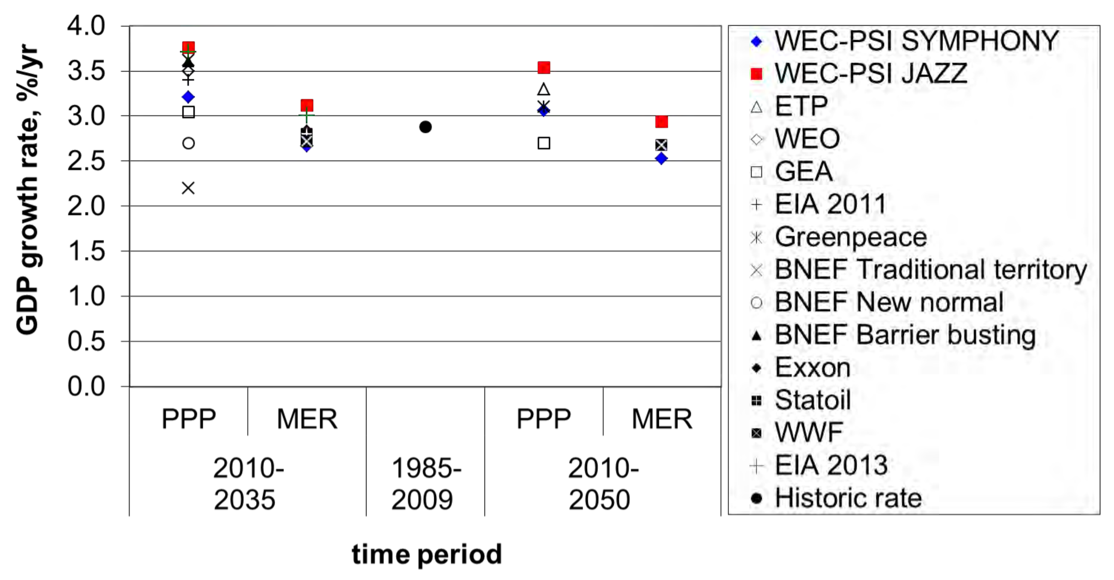
Organisation / Report	Year
Bloomberg New Energy Finance (BNEF)	2013
Exxon	2013
Shell	2013
EIA	2012
Greenpeace	2012
IEA/OECD Energy Technology Perspectives (ETP)	2012
IEA/OECD World Energy Outlook (WEO)	2012
IIASA Global Energy Assessment (GEA)	2012
Statoil	2012
WWF	2011

http://www.psi.ch/eem/wec-comparison

3. Scenario comparison

(a) Population & GDP





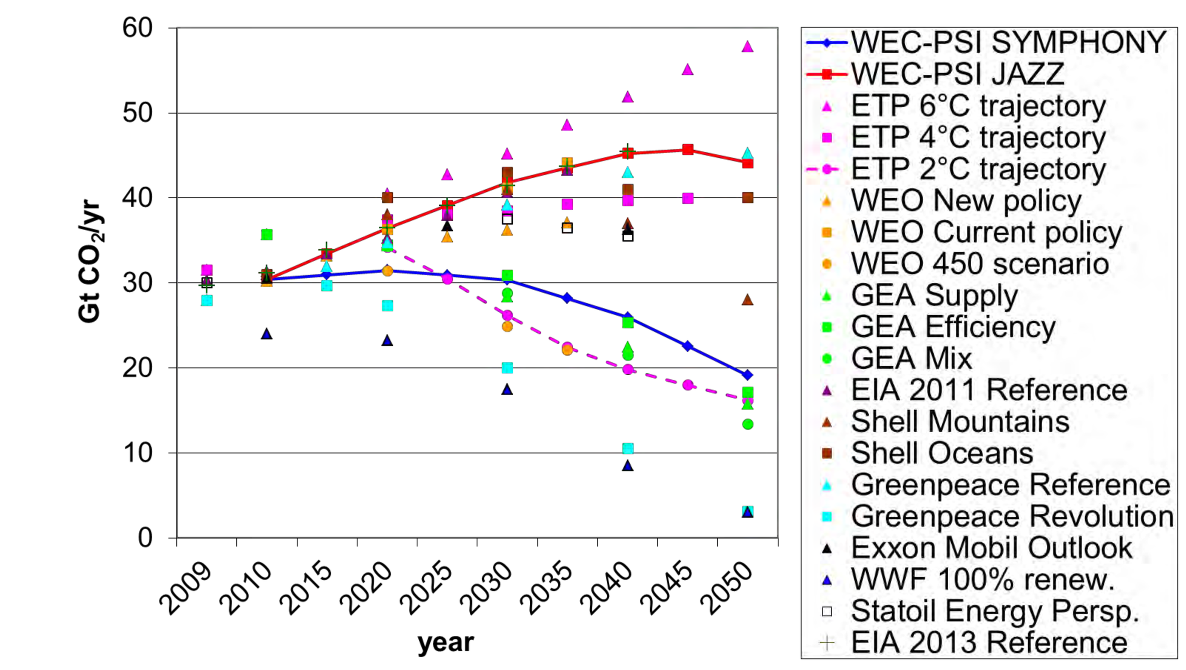
◄ Most scenarios assume 9 to 10 billion people in 2050. *WEC-PSI JAZZ* has a lower population growth up to 2050. This is related to the faster rate of economic development (see also GDP figures).

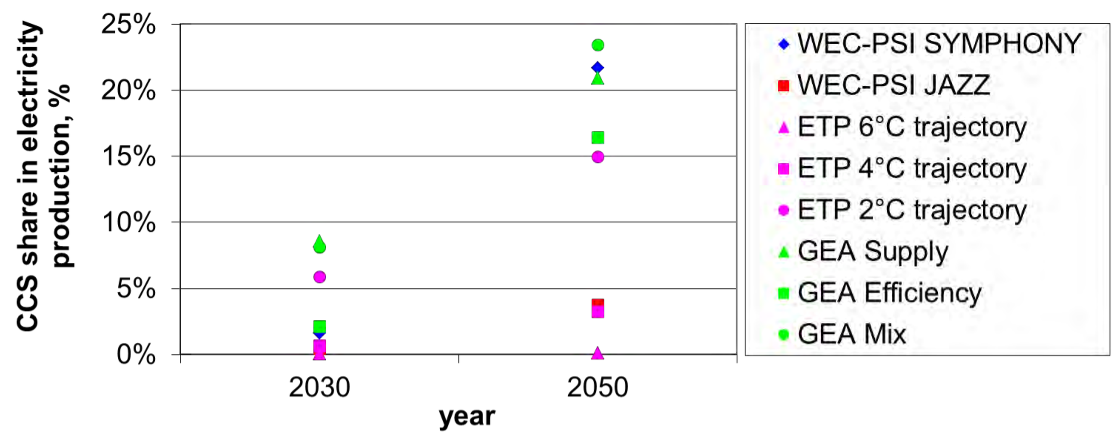
► *WEC-PSI SYMPHONY* nearly reaches the *ETP 2°C trajectory* for CO_2 (- - -). *WWF 100% renewables* and *Greenpeace Revolution* scenarios have very low CO_2 emissions.

◄ The assumed GDP growth rates are in the range of average historic rates; no severe economic disruptions are expected.

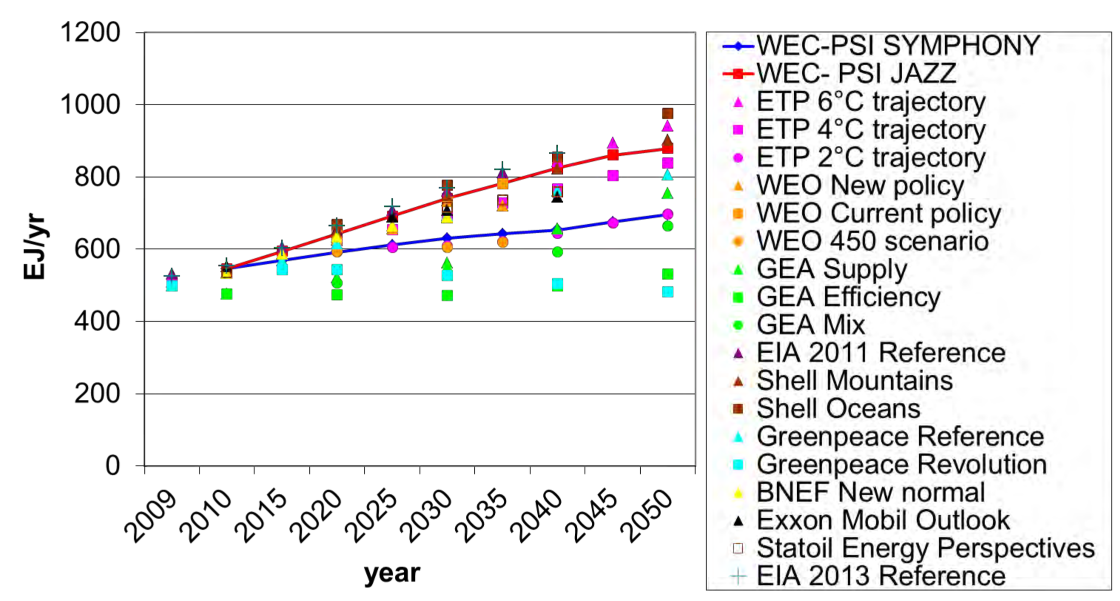
► CCS is deployed more in 2050 than in 2030. *WEC-PSI SYMPHONY* includes strong governmental support for CCS along with high CO_2 prices and – thus – high CCS shares.

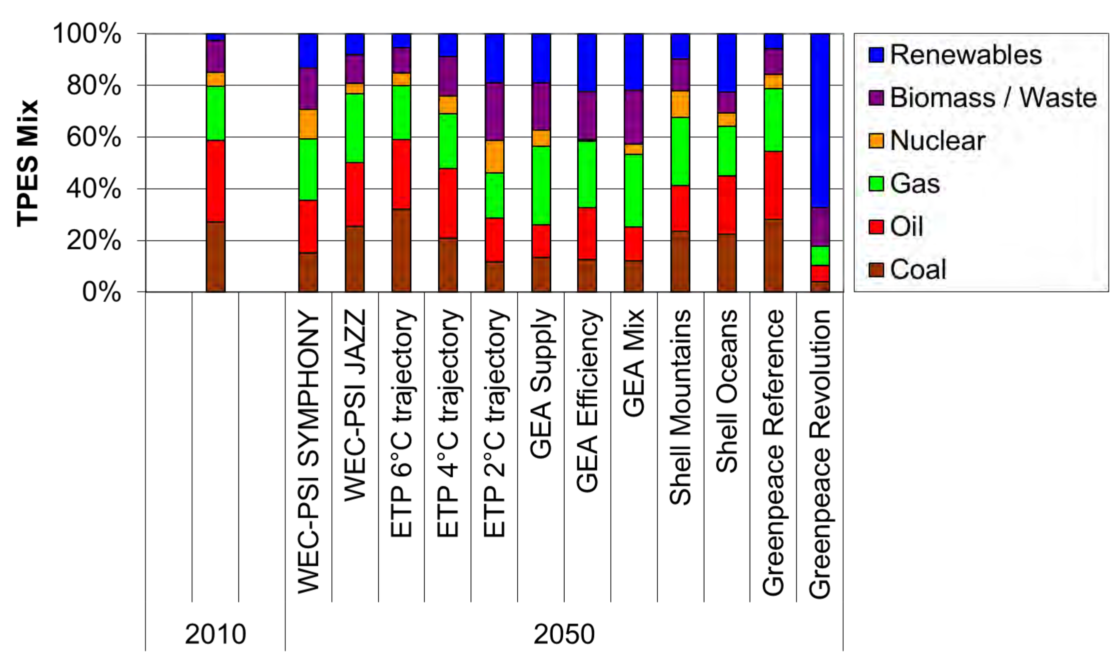
(b) CO_2 Emissions & CCS





(c) Total Primary Energy Supply





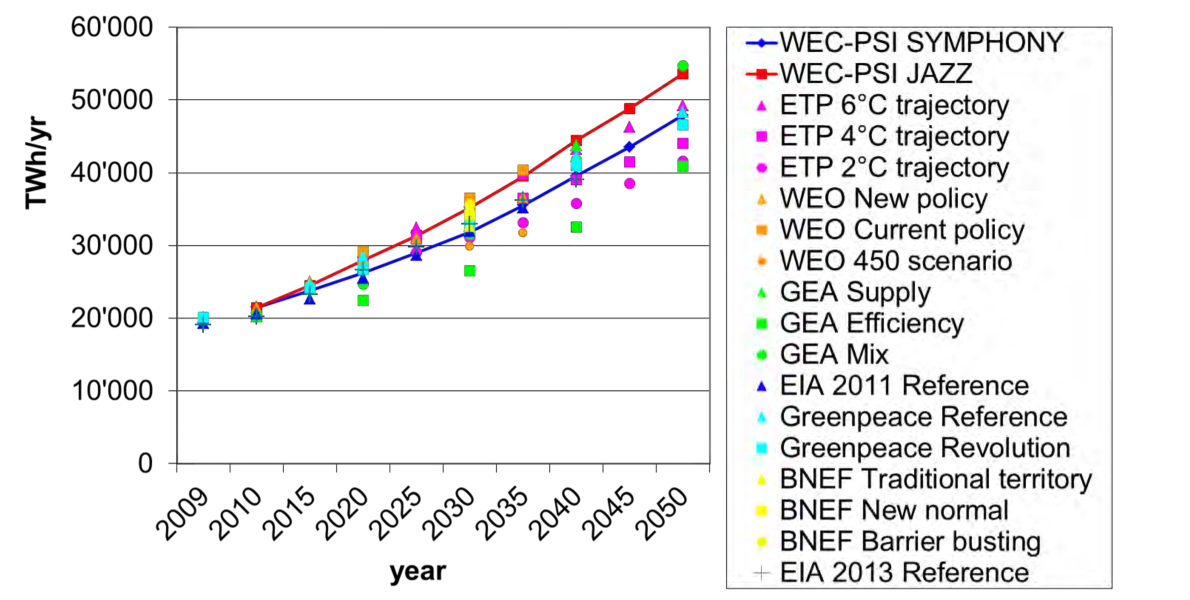
◄ The Total Primary Energy Supply (TPES) is expected to increase in almost all scenarios. The *WEC-PSI* scenarios are in the medium range of the other studies.

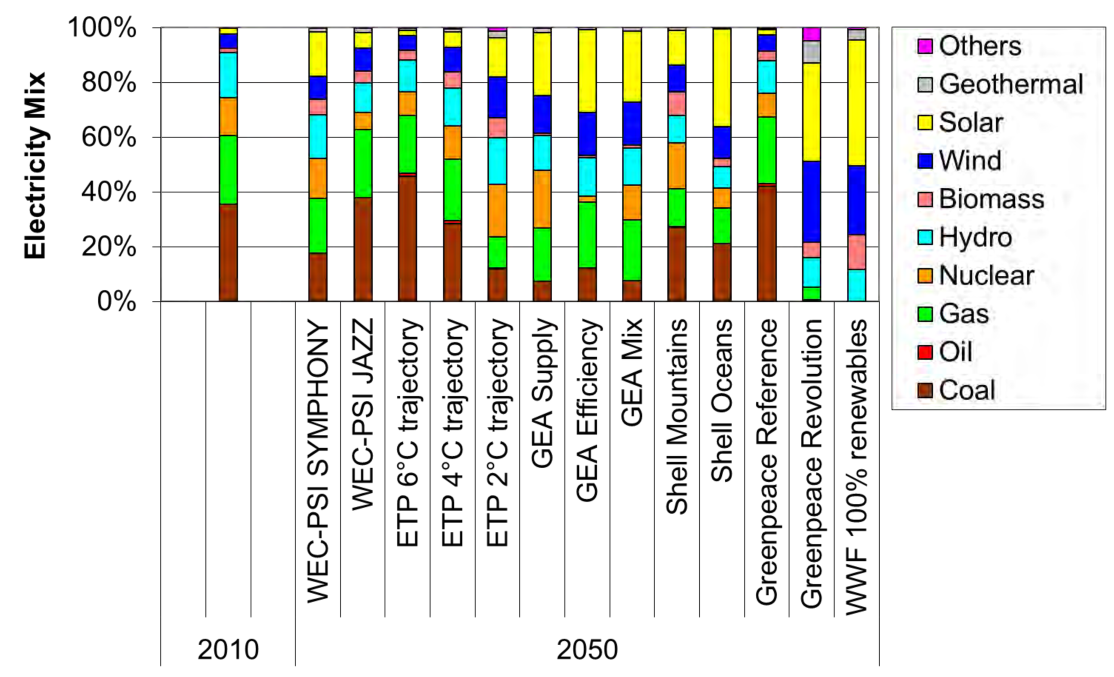
► Electricity production increases more than TPES in all scenarios. *WEC-PSI SYMPHONY* has more electricity per TPES than *WEC-PSI JAZZ* due to its cost-effective decarbonisation of the energy sector.

◄ In *ETP 2°C trajectory*, *GEA Supply* and *GEA Mix* as well as *Greenpeace Revolution* more renewables are deployed due to the more ambitious and in some cases "normative" climate change goals.

► *WEC-PSI SYMPHONY* has less coal than *WEC-PSI JAZZ* due to additional climate change mitigation action. In *WEC-PSI JAZZ* the gas share is substantial due to shale gas.

(d) Electricity Production





Further information

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