Stefan Hirschberg :: Laboratory for Energy Systems Analysis :: Paul Scherrer Institut

Consequences of accidents in the energy sector

OECD NEA International Workshop, Paris, 20 January 2016

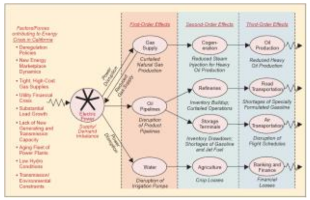
Energy Infrastructure Accidents - Technological

Factors increasing societal vulnerability towards accident and catastrophe hazards:

Urbanization

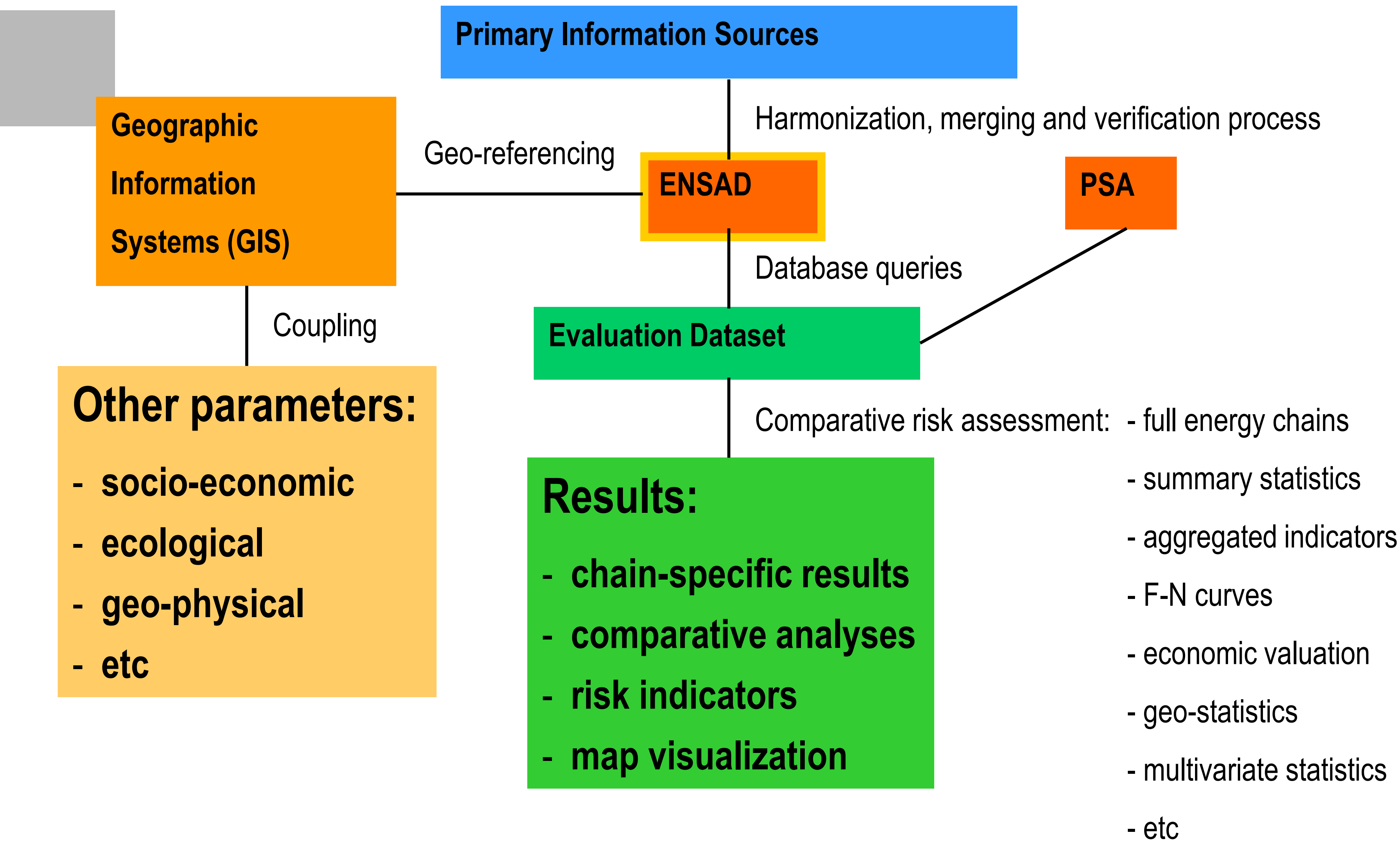
Industrialization

Development of coastal and other risk-prone areas



Complex inter-related infrastructures

Methodological Framework



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Severe Accident Definitions

Consequence indicator	ENSAD	Sigma	EM-DAT	NatCat	WOAD
Fatalities	≥ 5	≥ 20 (dead or missing)	≥ 10	> 20	≥ 1
Injured persons	≥ 10	≥ 50	aff.	-	-
Evacuees	≥ 200	≥ 2000 (homeless)	aff.	-	-
Extensive ban on consumption of food	yes	-	-	-	-
Release of hydrocarbons	≥ 10000 t	-	-	-	≥ 1000 t
Enforced clean up of land and water area	≥ 25 km^2	-	-	-	-
Economic loss	≥ 5 million USD(2000)	≥ 82.2 million USD(2007)	-	> 50 million USD (2007)	-

Sigma: sigma insurance research (Swiss Re)

EM-DAT: The International Emergency Disasters Database (Centre for Research on the Epidemiology of Disasters, CRED)

NatCat: Natural Catastrophes Service (Munich Re)

WOAD: Worldwide Offshore Accident Databank (Det Norske Veritas, DNV)

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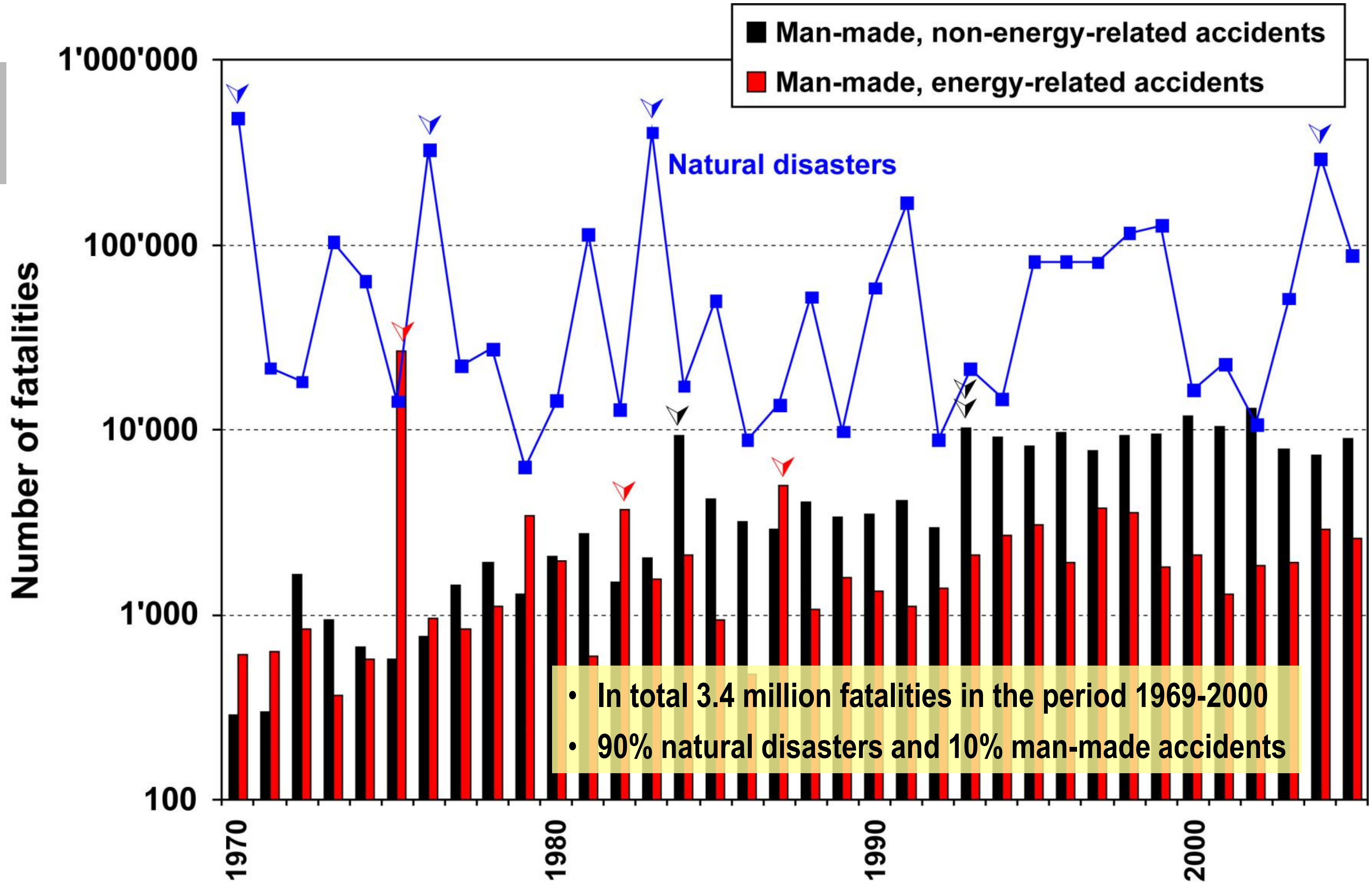
Severe Accidents and Natural Disasters



Burgherr & Hirschberg, 2008

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Severe Accidents with at least 5 fatalities (1970-2008)

	OECD		EU 27		non-OECD	
Energy chain	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	88	2313	45	989	164 1440 (a)	8153 25'821 (a)
Oil	179	3383	64	1236	351	19'376
Natural Gas	109	1257	37	366	78	1554
LPG	60	1880	22	571	69	2796
Biogas	—	—	—	—	2	18 (c)
Hydro	1	14	1	116 (b)	12	30,007 (d)
Geothermal	—	—	—	—	1	21 (e)
Wind (f)	54	60	24	24	6	6
Nuclear	—	—	—	—	1	31 (g)

(a) First line: coal non-OECD without China; second line: coal China

(b) Belci dam Romania (1991)

(c) Waste gas (13 fat., China, 2004), wastewater (5 fat., Pakistan, 2008)

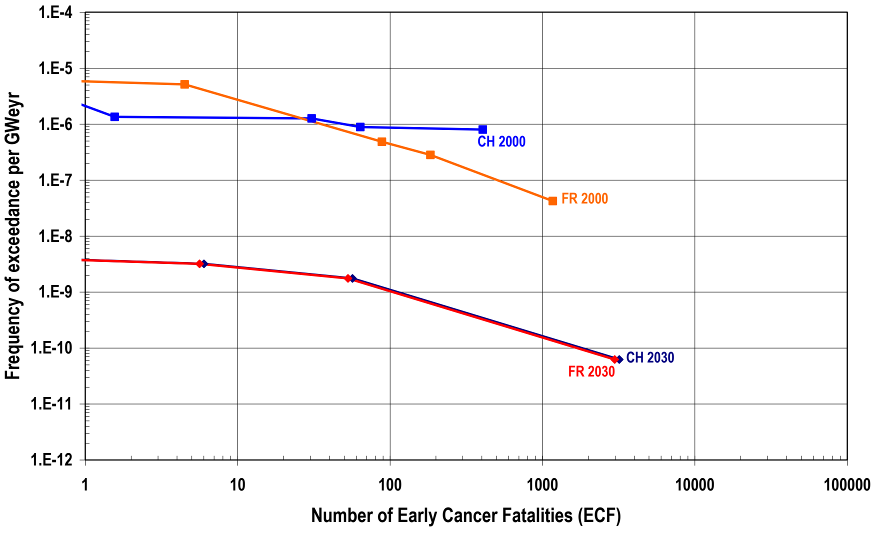
(d) Banqiao and Shimantan dam failures alone caused 26'000 fatalities

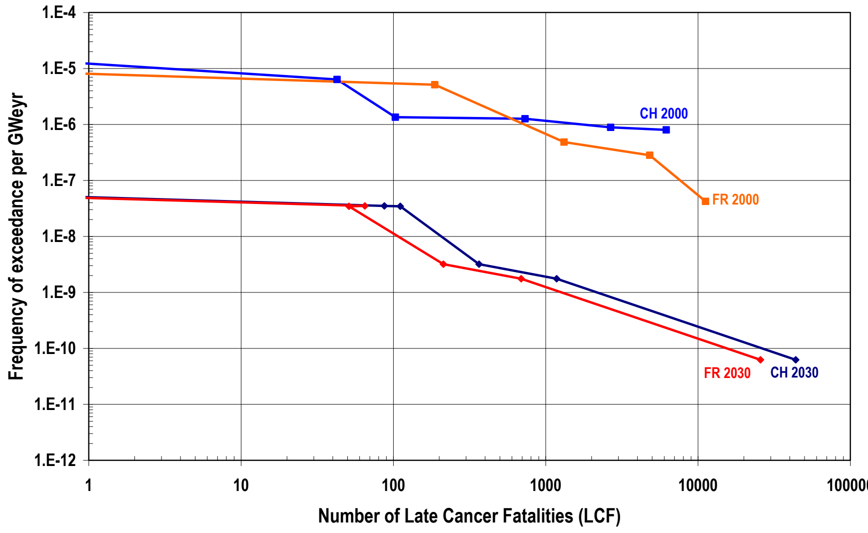
(e) Guatemala (1991)

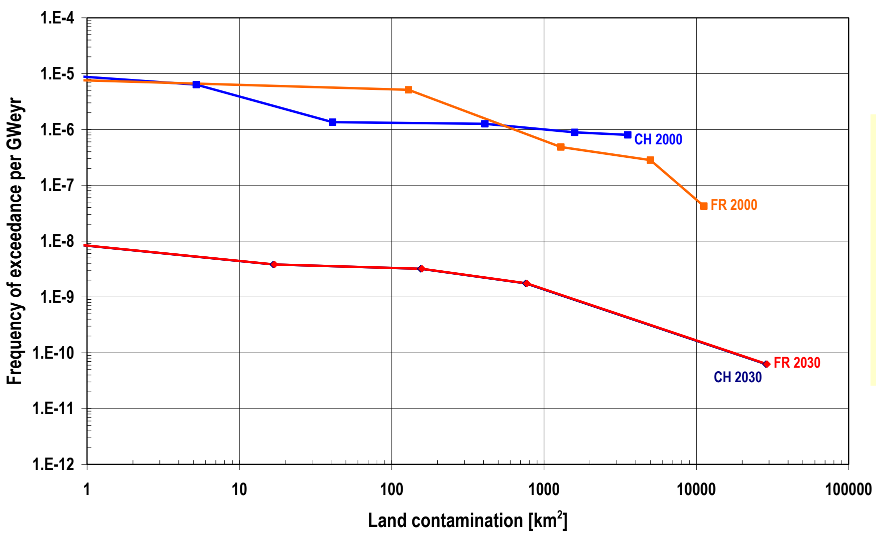
(f) Only small accidents

Burgherr et al., 2010

Current NPP vs. EPR (2030)



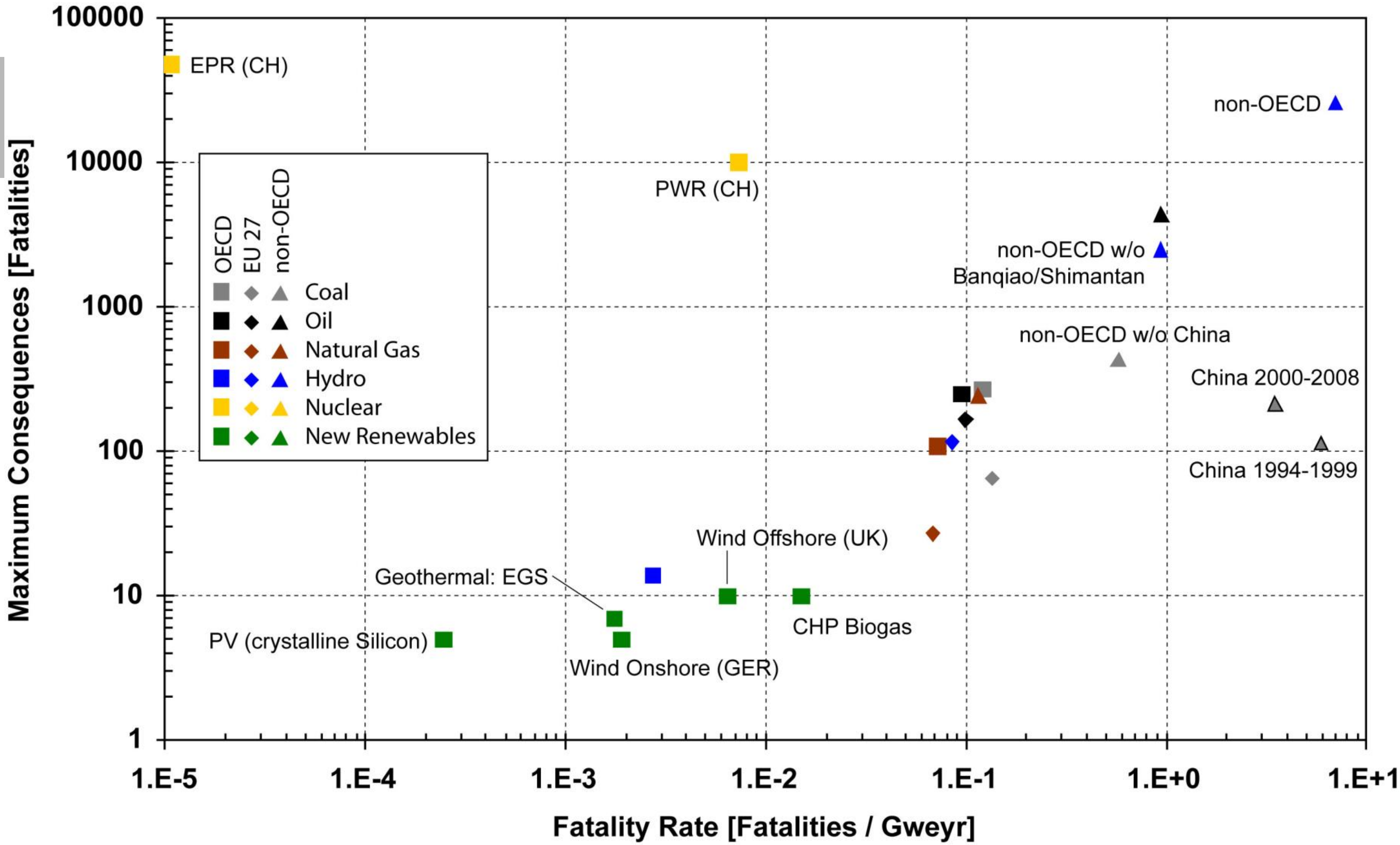




- **The results indicate that the expected risks for the EPR are significantly lower compared to currently operating plants.**
- **On the other hand, maximum consequences could substantially increase for EPR.**

Hirschberg et al., 2008

Severe accident fatality rates and maximum



Burgherr et al., 2011

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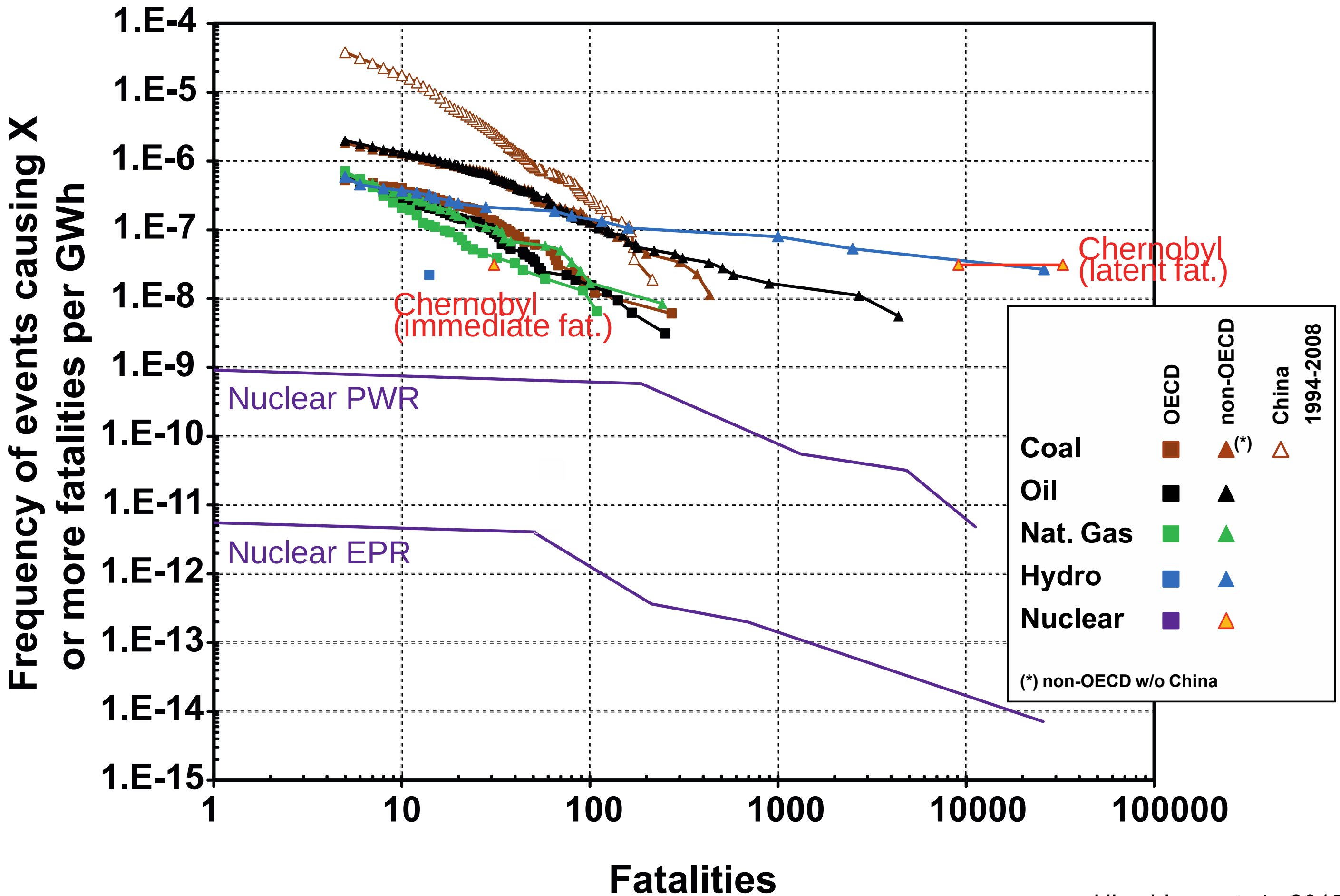
Frequency-consequence curves for full energy chains in OECD and non-OECD countries (1970 – 2008)



Hirschberg et al., 2015

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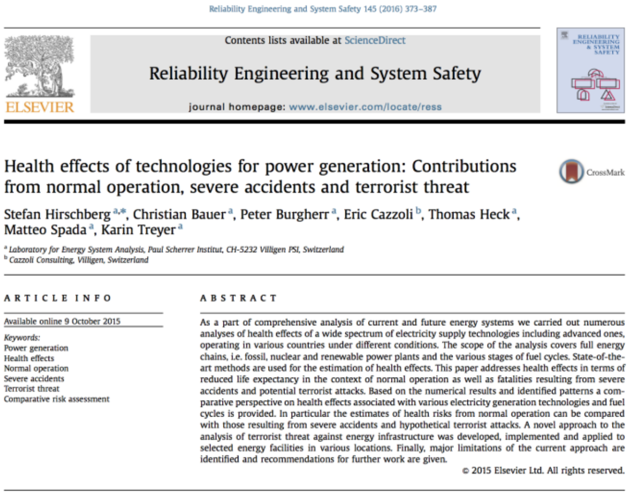
Health Effects of Technologies for Power Generation: Normal Operation, Severe Accidents & Terrorist Threat

Addressed questions:

- 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?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Health effects of technologies for power generation: Contributions from normal operation, severe accidents and terrorist threat

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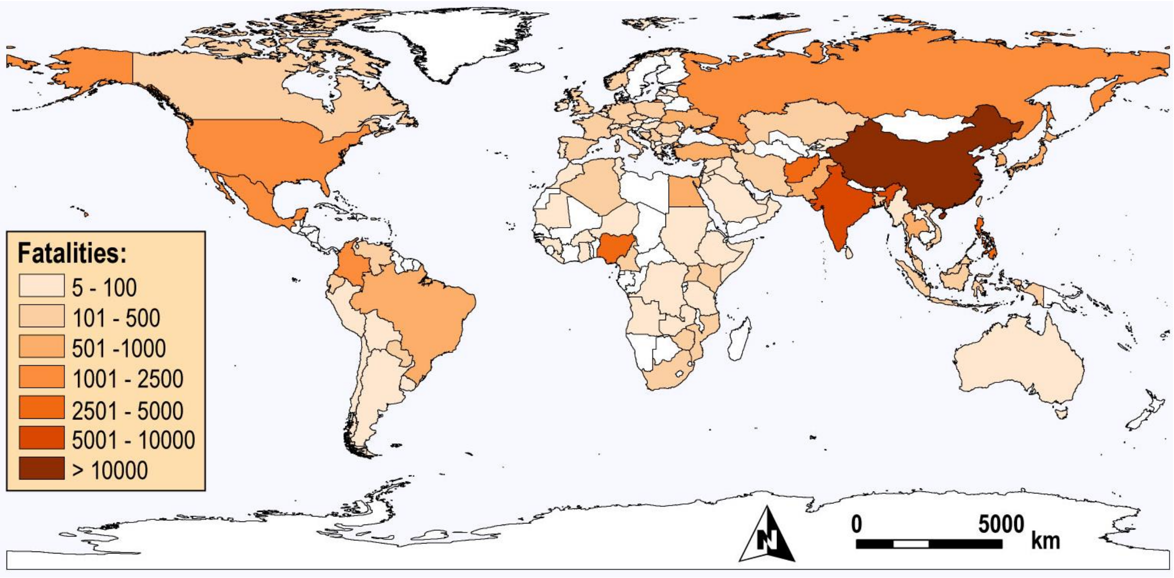
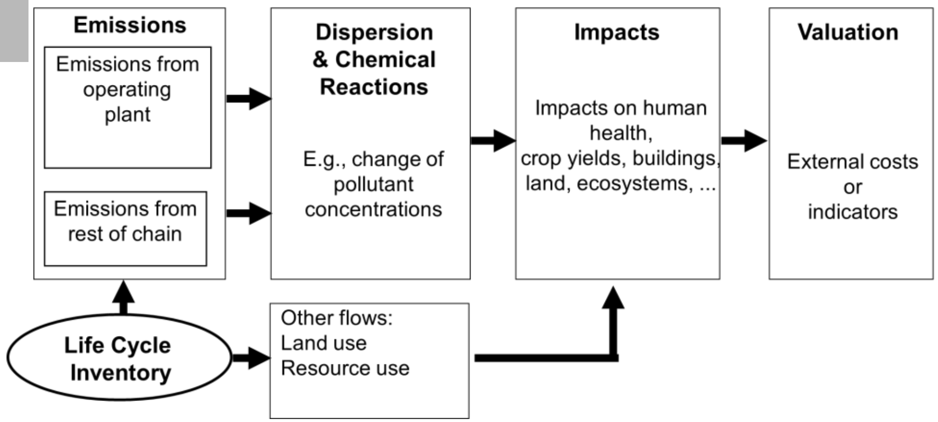
ABSTRACT

As a part of comprehensive analysis of current and future energy systems we carried out numerous analyses of health effects of a wide spectrum of electricity supply technologies including advanced ones, operating in various countries under different conditions. The scope of the analysis covers full energy chains, i.e. fossil, nuclear and renewable power plants and the various stages of fuel cycles. State-of-the-art methods are used for the estimation of health effects. This paper addresses health effects in terms of reduced life expectancy in the context of normal operation as well as fatalities resulting from severe accidents and potential terrorist attacks. Based on the numerical results and identified patterns a comparative perspective on health effects associated with various electricity generation technologies and fuel cycles is provided. In particular the estimates of health risks from normal operation can be compared with those resulting from severe accidents and hypothetical terrorist attacks. A novel approach to the analysis of terrorist threat against energy infrastructure was developed, implemented and applied to selected energy facilities in various locations. Finally, major limitations of the current approach are identified and recommendations for further work are given.

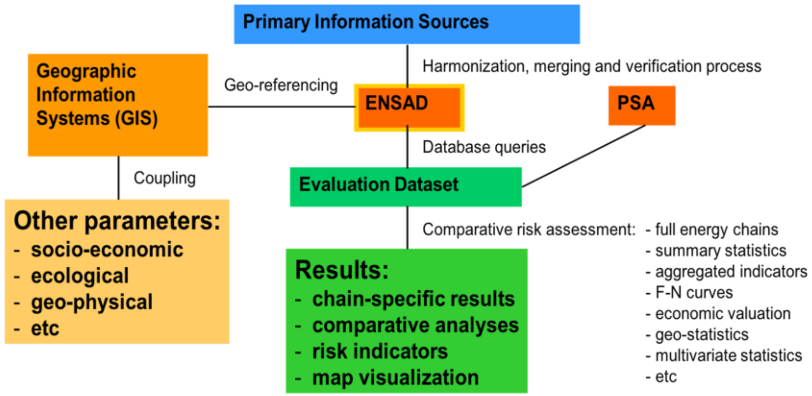


Methodological Frameworks

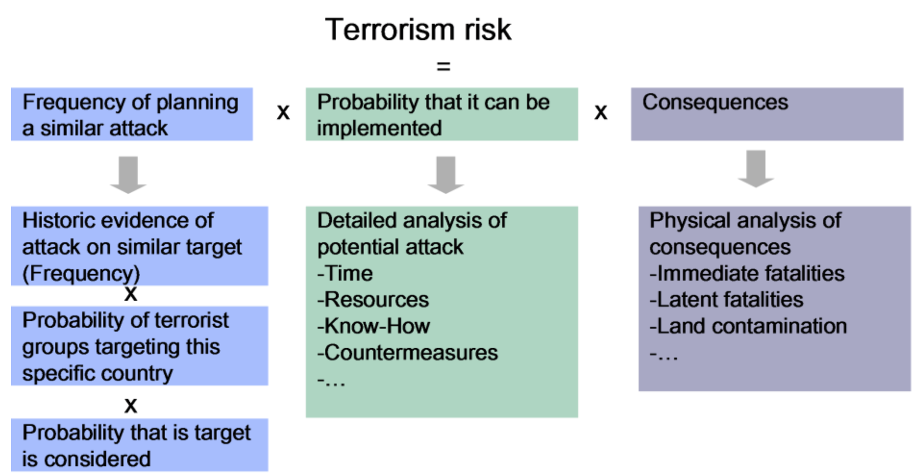
Mortality Impact of Normal Operation



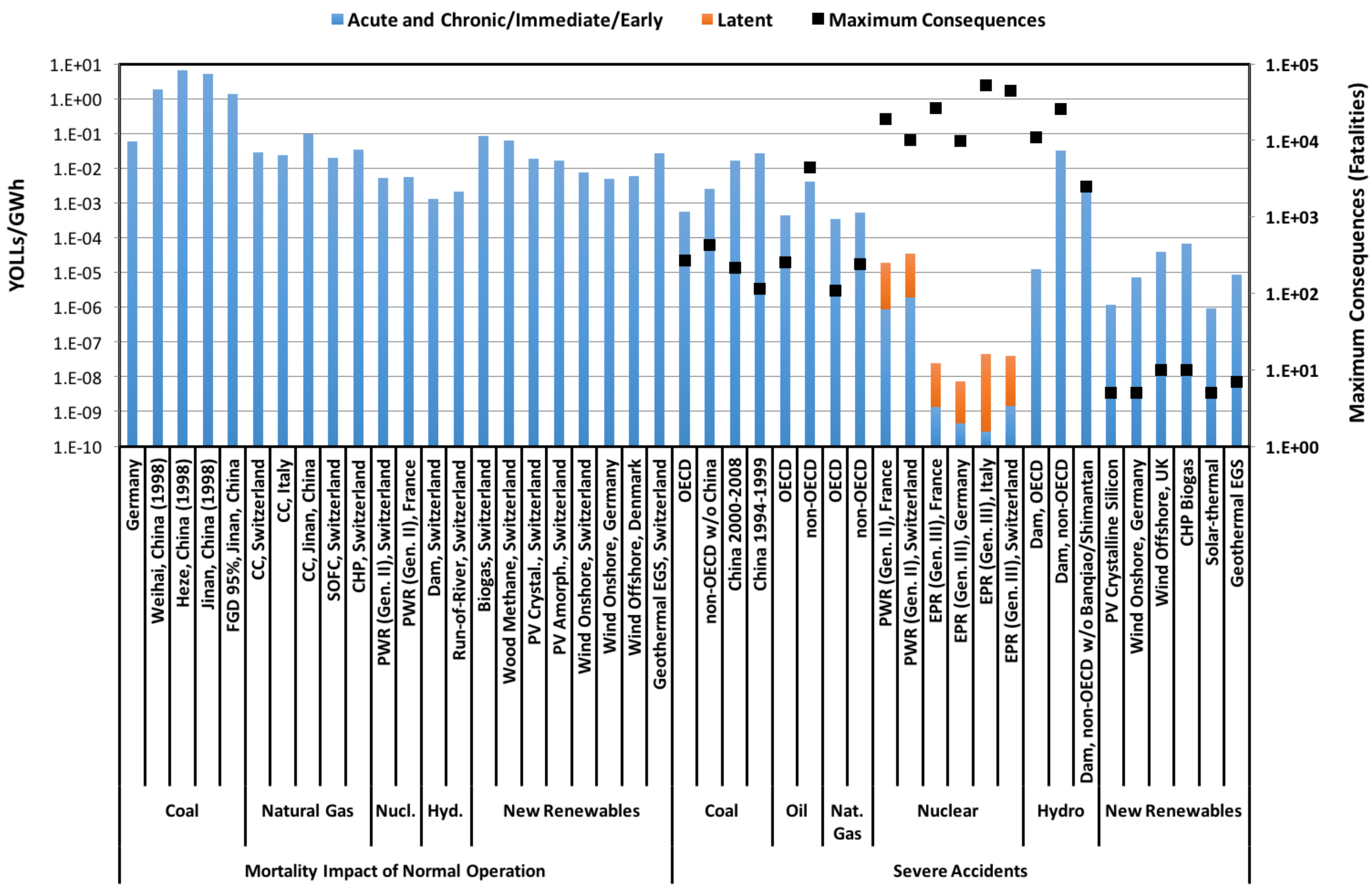
Severe Accidents



Terrorist Threat



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



Conclusions on health effects of accidents

- **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, treatment of uncertainties, solar PV and deep geothermal accident risks, cyber risks and implementation of terrorist risk assessment.

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Damage costs and external costs of non-nuclear accidents
Underlying monetary values and parameters

Monetary values	*€ (2002)*	
Mortality valuation: Value of Statistical Life (VSI	1'045'000	
Morbidity (typical injury)	70'000	
Evacuation (fixed costs per household)	144	
Degree of internalisation	*OECD*	*Non-OECD*
Occupational fatalities/damages	80 %	50 %
Public fatalities/damages	50 %	20 %
Average number of people per household	*2.5*	*4.4*
Efficiency		
Coal	40 %	
Oil	31 %	
Natural gas	53 %	

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Damage and External Costs of Severe Accidents with Fatalities

Value of Statistical Life = 1.045 million €; reference coal, oil & natural gas plants have efficiencies of 41%, 30% & 53%

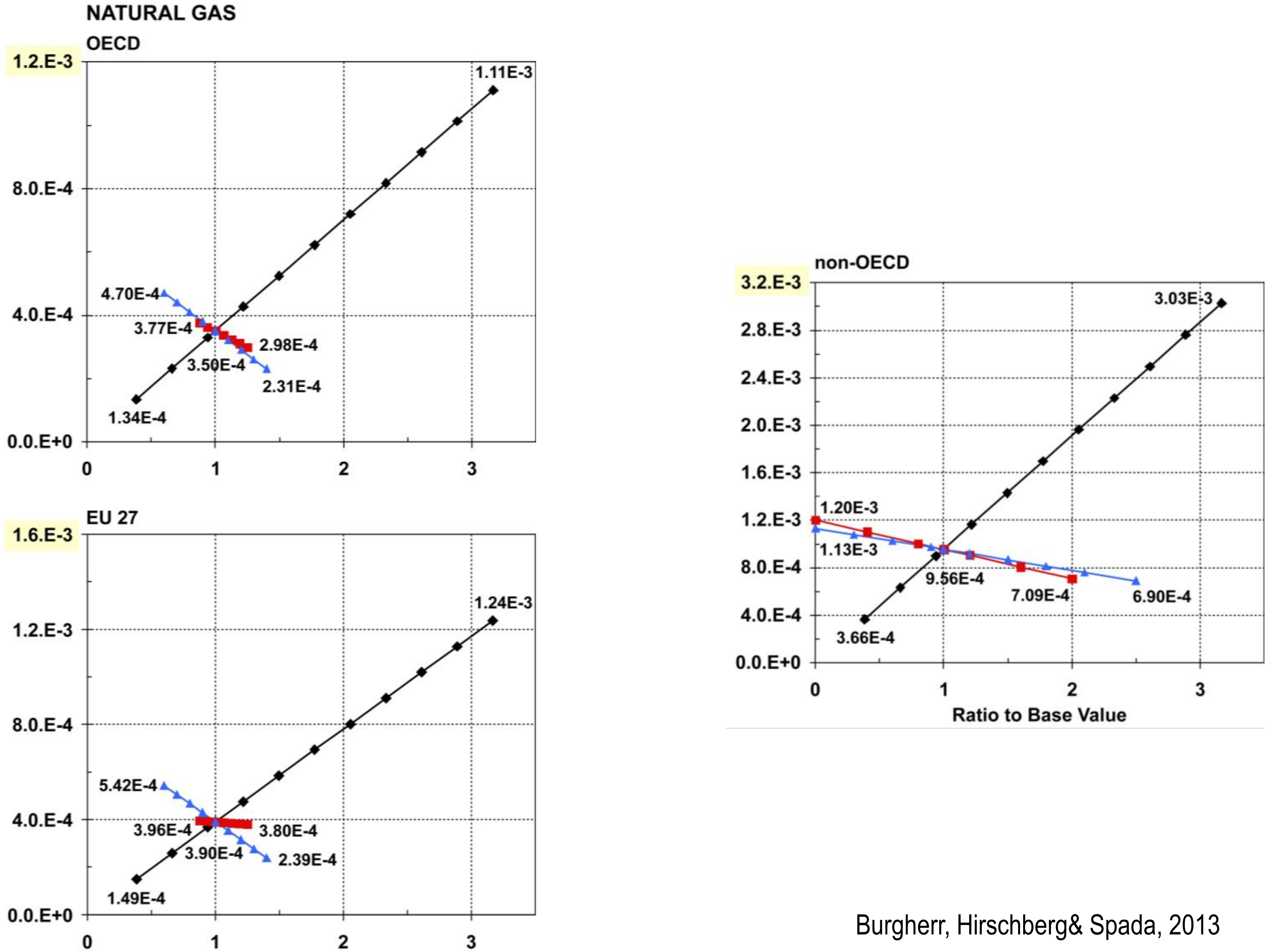
Energy chain	Reference countries	Damage costs in €-Cents(2002)/kWh$_e$			External costs in €-Cents(2002)/kWh$_e$		
		Occupa-tional	*Public*	*Total*	*Occupa-tional*	*Public*	*Total*
Coal	*OECD*	1.7E-3	1.2E-5	1.7E-3	3.4E-4	6.1E-6	3.5E-4
	non-OECD w/o China	6.5E-3	4.3E-5	6.5E-3	3.2E-3	3.5E-5	3.3E-3
	China (1994-1999)	1.2E-2	ng[3]	1.2E-2	6.1E-3	ng[3]	6.1E-3
Oil	*OECD*	9.9E-4	9.0E-4	1.9E-3	2.0E-4	4.5E-4	6.5E-4
	non-OECD	1.8E-3	1.1E-2	1.3E-2	9.1E-4	8.7E-3	9.6E-3
Natural Gas	*OECD*	2.2E-4	4.4E-4	6.6E-4	2.2E-4	2.2E-4	4.4E-4
	non-OECD	3.3E-4	5.9E-4	9.2E-4	1.6E-4	4.7E-4	6.3E-4
Hydro	*OECD*	ng[3]	4.1E-5	4.1E-5	ng[3]	2.0E-5	2.0E-5
	non-OECD	ng[3]	1.2E-1	1.2E-1	ng[3]	9.8E-2	9.8E-2
	non-OECD w/o Banqiao/Shimantan	ng[3]	1.6E-2	1.6E-2	ng[3]	1.3E-2	1.3E-2
Nuclear	*OECD*[1,4]	ng[3]	ng[3]	ng[3]	ng[3]	ng[3]	ng[3]
	non-OECD[2]	5.7E-4	ng[3]	5.7E-4	2.9E-4	ng[3]	2.9E-4

Burgherr & Hirschberg, 2005; Hirschberg et al., 1998

[1] Based on PSA for Swiss NPP Muehleberg **[2] Based on Chernobyl accident** **[3] ng = negligible**

[4] Damage costs for Muehleberg including latent fatalities and non-health effects estimated at 1.2E-3 \$-Cents/kWh$_e$

Natural Gas



Burgherr, Hirschberg& Spada, 2013

External costs in EUR cents per kWh of severe (≥ 5 fatalities) accidents in the natural gas chain (1970–2008) for OECD, EU 27, and non-OECD countries. In addition to central values, sensitivities are also shown for VSL (value of statistical life) and different degrees of internalization (Int) for occupational (Occ) and public (Pub) fatalities. Since maximum y-axis values are partially different, they are shaded in light yellow

Some observations and issues related to costs of accidents

- Cost of accidents are highly uncertain, incomplete and probably mostly underestimated.
- Dominance of natural catastrophes.
- Coal accidents seldom affect the public.
- Aggregated costs of small accidents can be very large.
- Degree of internalization of accident damages strongly varies.
- Nuclear accidents are difficult to evaluate in terms of costs particularly due to long-term contamination and public perception.
- Dealing with indirect effects of nuclear accidents has strong subjective components including establishment of scope and boundaries for the analysis.
- Which accidents should be modelled – full spectrum, selected, severe but not worst, extreme?
- Including probabilistic perspective on nuclear accidents is a must.

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