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

Health Risks of Power Generation Technologies

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Content

- Introduction
- Risks of normal operation
- Severe accident risks
- Terrorist threat
- Health risk comparisons
- Conclusions

Why Health Risks?

- 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?

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

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A R T I C L E I N F O

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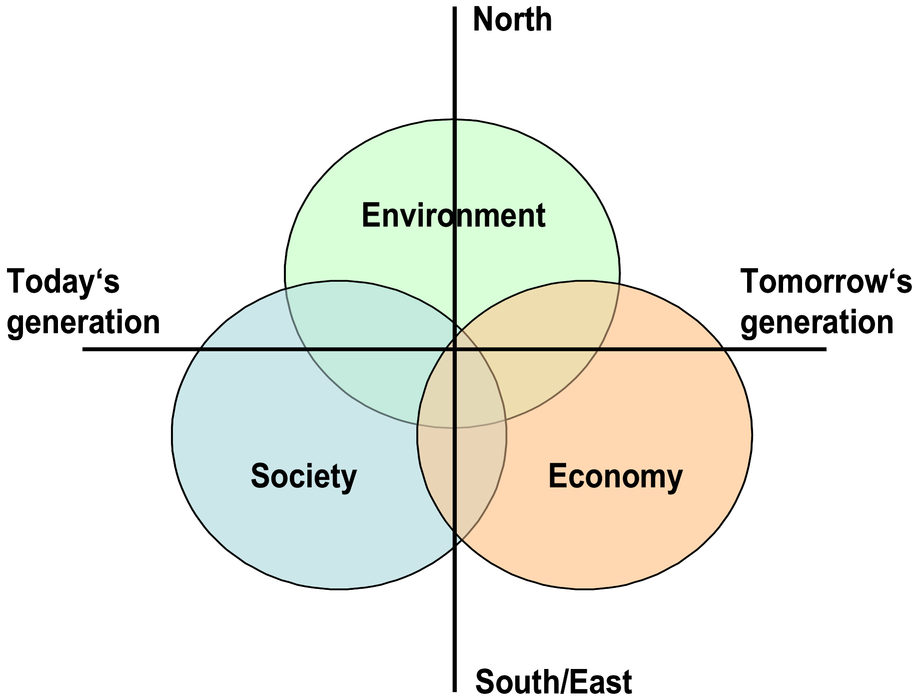
Keywords:
Power generation
Health effects
Normal operation
Severe accidents
Terrorist threat
Comparative risk assessment

A B S T R A C T

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.

Sustainability Criteria



	Criterion
Environmental Dimension	**RESOURCES**
	Energy Resources
	Mineral Resources (Ores)
	CLIMATE CHANGE
	IMPACT ON ECOSYSTEMS
	Impacts from Normal Operation
	Impacts from Severe Accidents
	WASTES
	Special Chemical Wastes stored in Underground Depositories
	Medium and High Level Radioactive Wastes to be stored in Geological Repositories
Economic Dimension	**IMPACTS ON CUSTOMERS**
	Price of Electricity
	IMPACTS ON OVERALL ECONOMY
	Employment
	Autonomy of Electricity Generation
	IMPACTS ON UTILITY
	Financial Risks
	Operation
Social Dimension	**SECURITY/RELIABILITY OF ENERGY PROVISION**
	Political Threats to Continuity of Energy Service
	Flexibility and Adaptation
	POLITICAL STABILITY AND LEGITIMACY
	Potential of Conflicts induced by Energy Systems.
	Necessity of Participative Decision-making Processes
	SOCIAL AND INDIVIDUAL RISKS
	Expert-based Risk Estimates for Normal Operation
	Expert-based Risk Estimates for Accidents
	Perceived Risks
	Terrorist Threat
	QUALITY OF RESIDENTIAL ENVIRONMENT
	Effects on the Quality of Landscape
	Noise Exposure

Source: Hirschberg et al., 2007&2008

Sustainability Assessment of Energy Technologies: Risk-relevant Criteria & Indicators (EU-Project NEEDS)

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SOCIAL DIMENSION

Criterion	Indicator [Unit]
SOCIAL AND INDIVIDUAL RISKS	
Expert-based Risk Estimates for Normal Operation	
Reduced life expectancy due to normal operation	Mortality due to normal operation [YOLL/kWh]
Non-fatal illnesses due to normal operation	Morbidity due to normal operation [DALY/kWh]
Expert-based Risk Estimates for accidents	
Expected health effects from accidents	Expected mortality due to severe accidents [Fatalities/kWh]
Maximum consequences of accidents	Maximum credible number of fatalities per accident [Fatalities/accident]
Perceived Risks	
Perceived risk characteristics for normal operation	Subjective health fears due to normal operation [Ordinal scale]
Perceived risk characteristics for accidents	Psychometric variables such as personal control, catastrophic potential, perceived equity, familiarity [Ordinal scale]
Terrorist Threat	
Potential of attack	Potential for a successful attack [Ordinal scale]
Likely potential effects of a successful attack	Expected number of fatalities [Ordinal scale]
Proliferation	Potential for misuse of technologies and substances within the nuclear energy chain [Ordinal scale]

Source: Hirschberg et al., 2008

RISKS OF NORMAL OPERATION

Air Pollutants and their Major Impacts

Impact category	Pollutant	Effects
Public health – mortality	PM_{10} [a], SO_2, Sulfates, Nitrates	Reduction in life expectancy due to acute and chronic mortality (all-cause mortality used, major associations for cardiopulmonary and lung cancer mortality)
Public health – morbidity	PM_{10}, Sulfates, Nitrates	respiratory hospital admissions restricted activity days cerebrovascular hospital admissions congestive heart failure cases of bronchodilator usage cases of chronic bronchitis cases of chronic cough in children cough in asthmatics lower respiratory symptoms
Crops	SO_2	Yield change for wheat, barley, rye, oats, potato, sugar beet, cotton, rice, rape, soyabean, vegetables

[a] PM_{10} are particulates with an aerodynamic diameter < 10 µm

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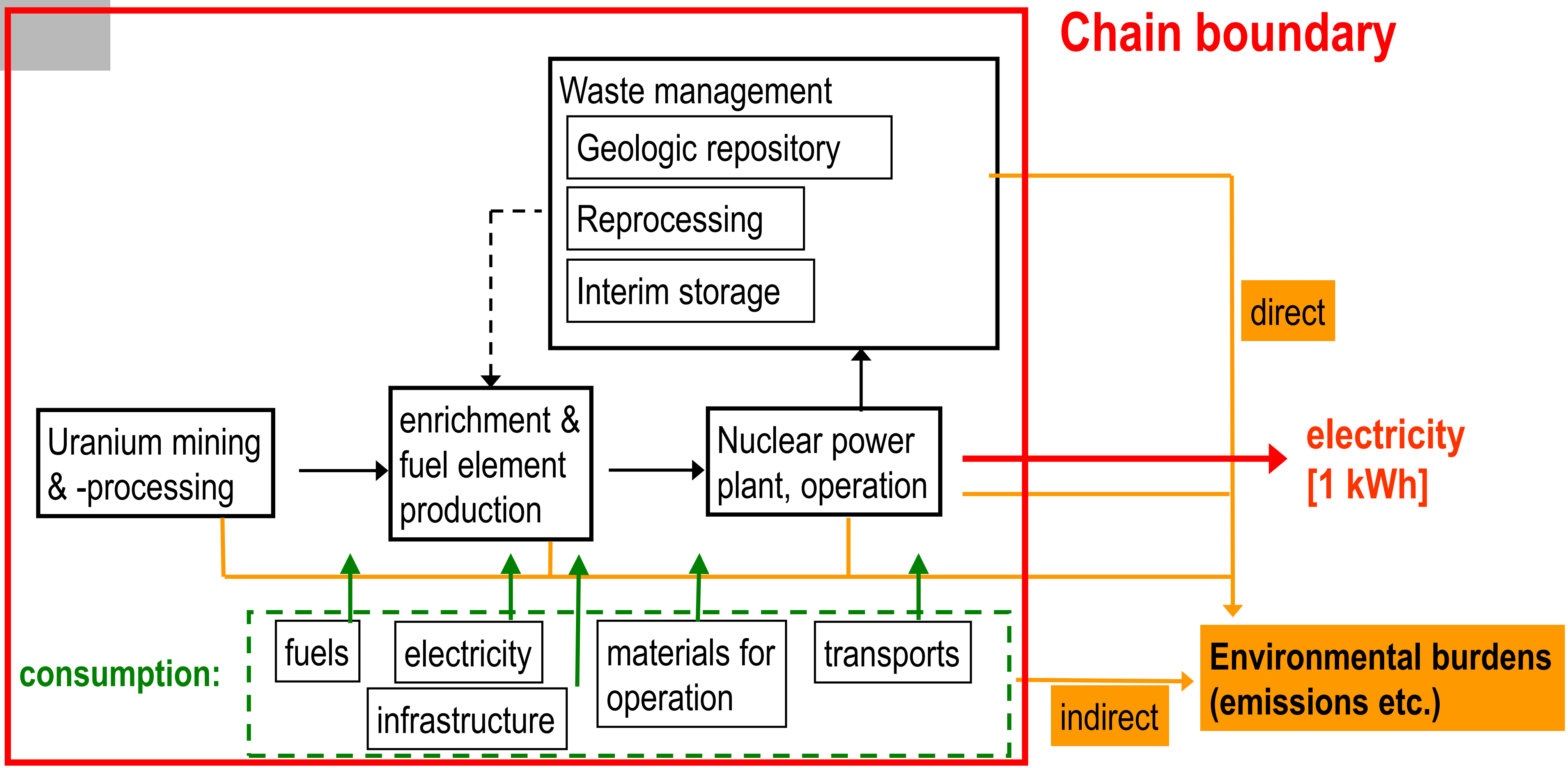
Major Health Exposure-Response Functions

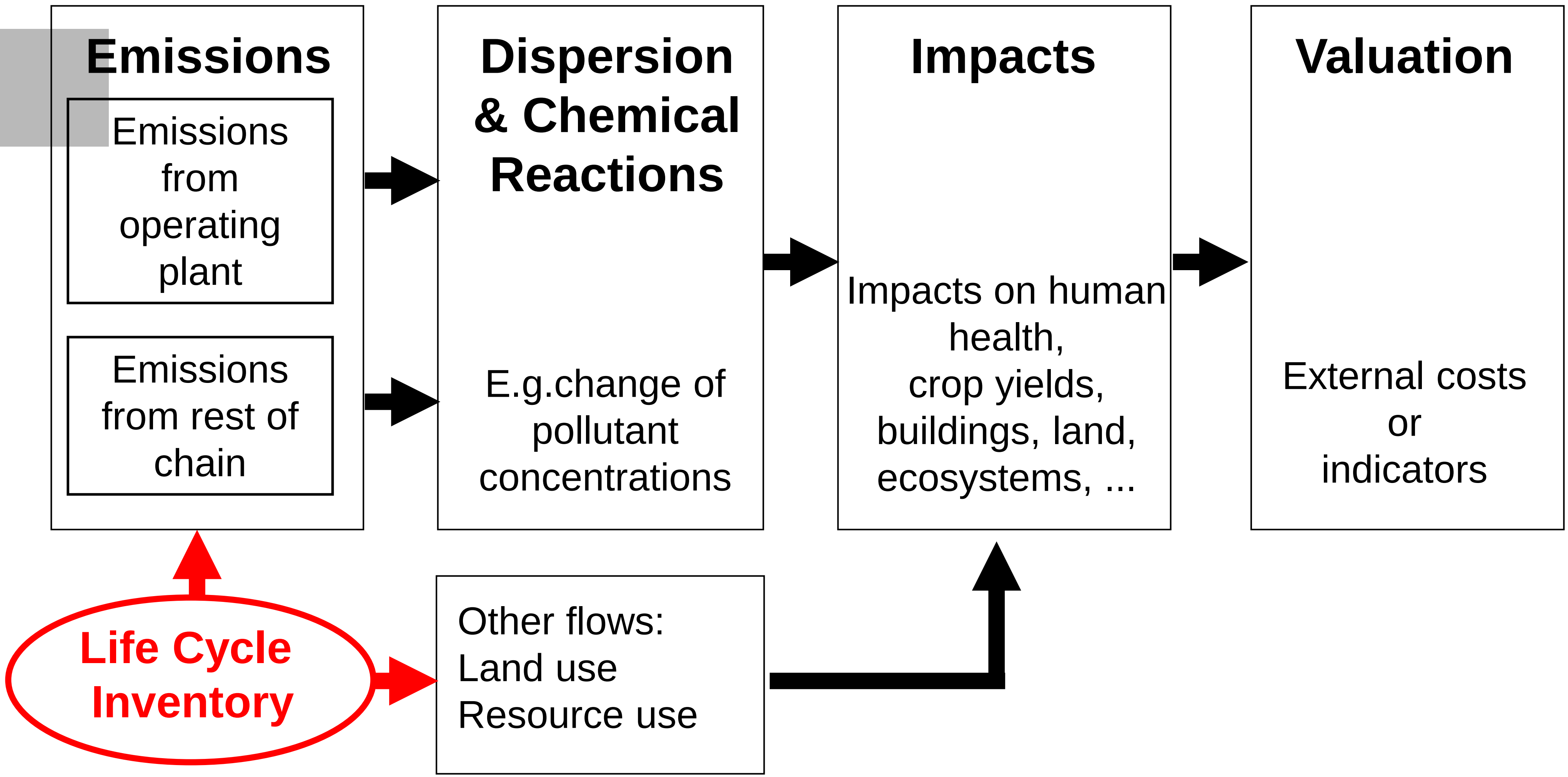
Receptor	Impact Category	Pollutant	f_{er}
ADULTS			
	Restricted activity days	PM_{10},	0.025
		Nitrates,	0.025
		Sulfates	0.042
	Chronic bronchitis	PM_{10},	2.5E-5
		Nitrates,	2.5E-5
		Sulfates	3.9E-5
ENTIRE POPULATION			
	Acute mortality (YOLL)	SO_2	5.4E-6
	Chronic mortality (YOLL)	PM_{10},	1.57E-4
		Nitrates,	1.57E-4
	YOLL: Years of Life Lost	$PM_{2.5}$,	2.60E-4
		Sulfates	2.60E-4

f_{er}, has units of [cases/(yr-person-µg/m^3)] for morbidity, and [YOLL/(yr-person-µg/m^3)] for mortality

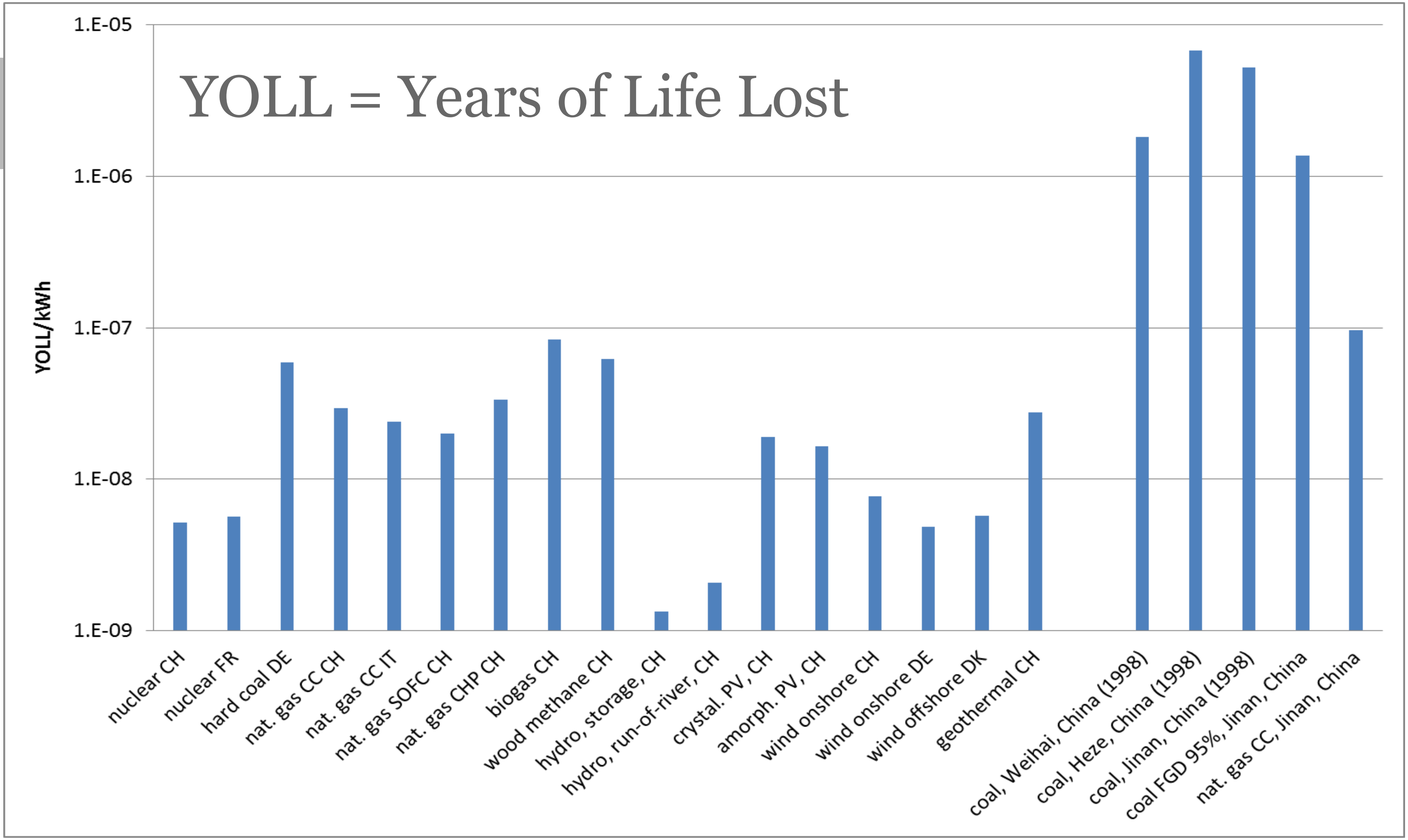
Life Cycle Analysis - LCA (nuclear energy chain)



The impact pathway approach (including LCA)

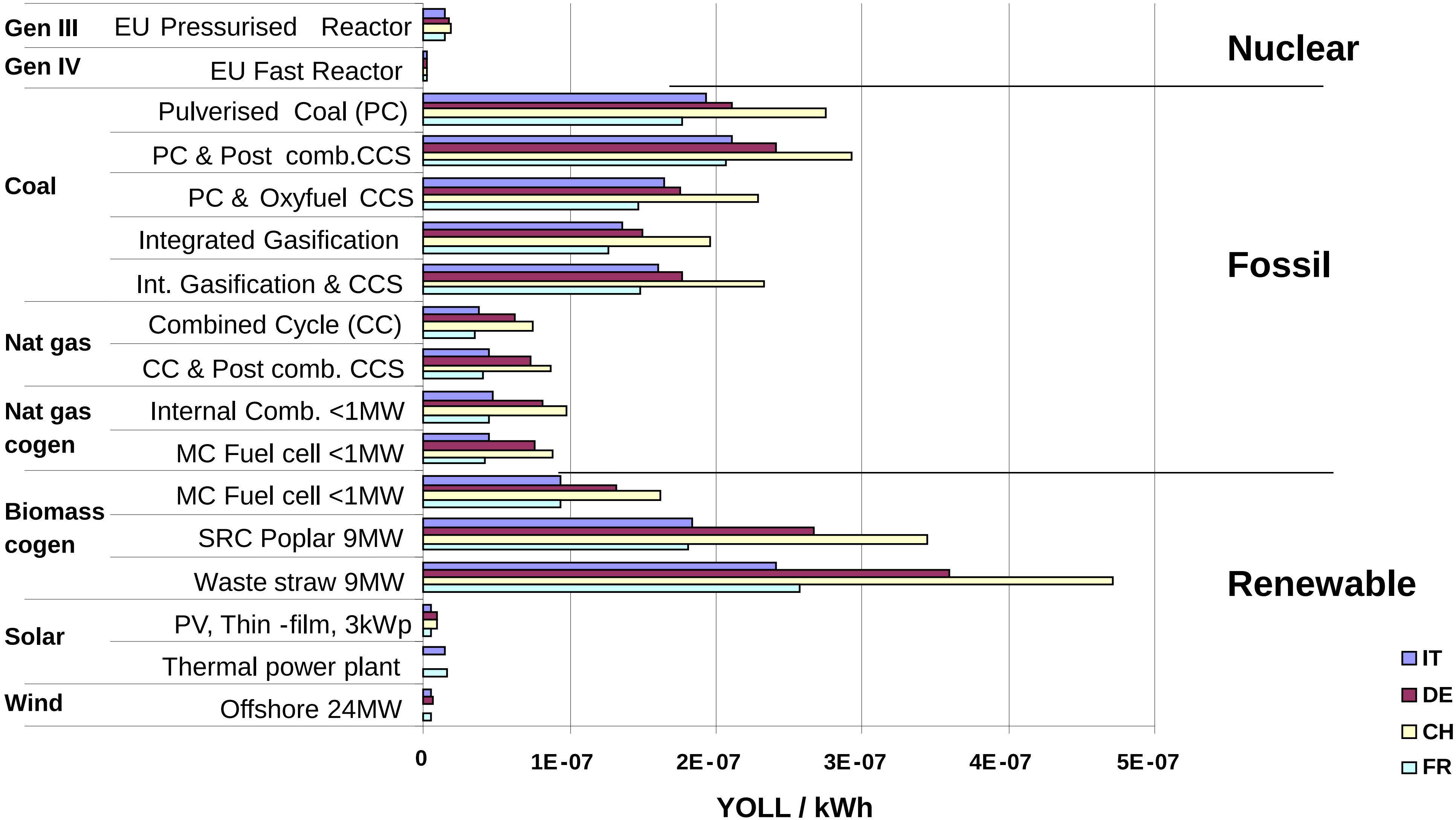


Mortality Based on Impact Pathway Approach



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

Social: Years of Life Lost - YOLL (2050)



Source: Friedrich & Preiss, 2008

SEVERE ACCIDENT RISKS

Overview of Accidents in the Energy Sector

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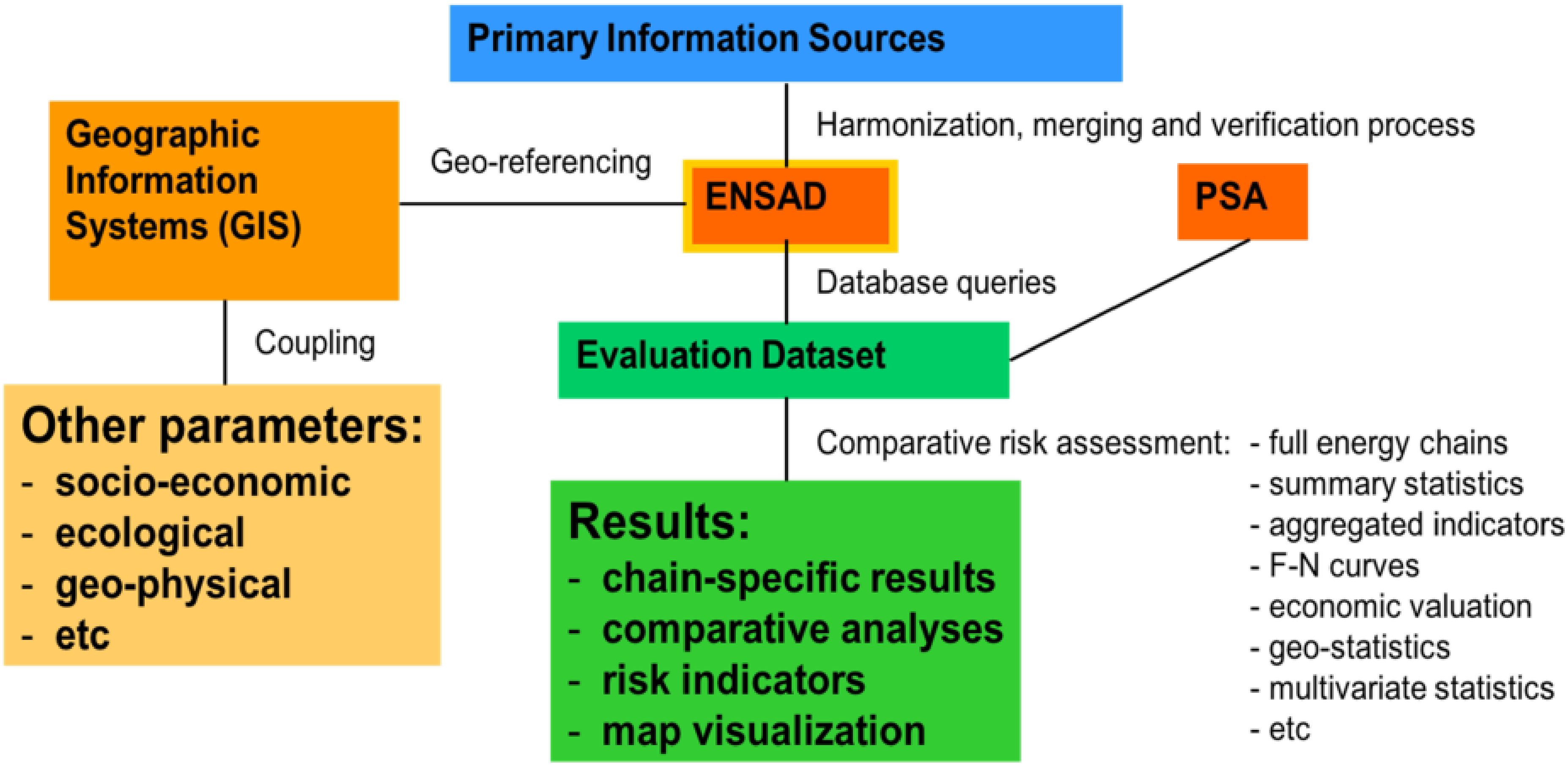
Severe Accident Definitions

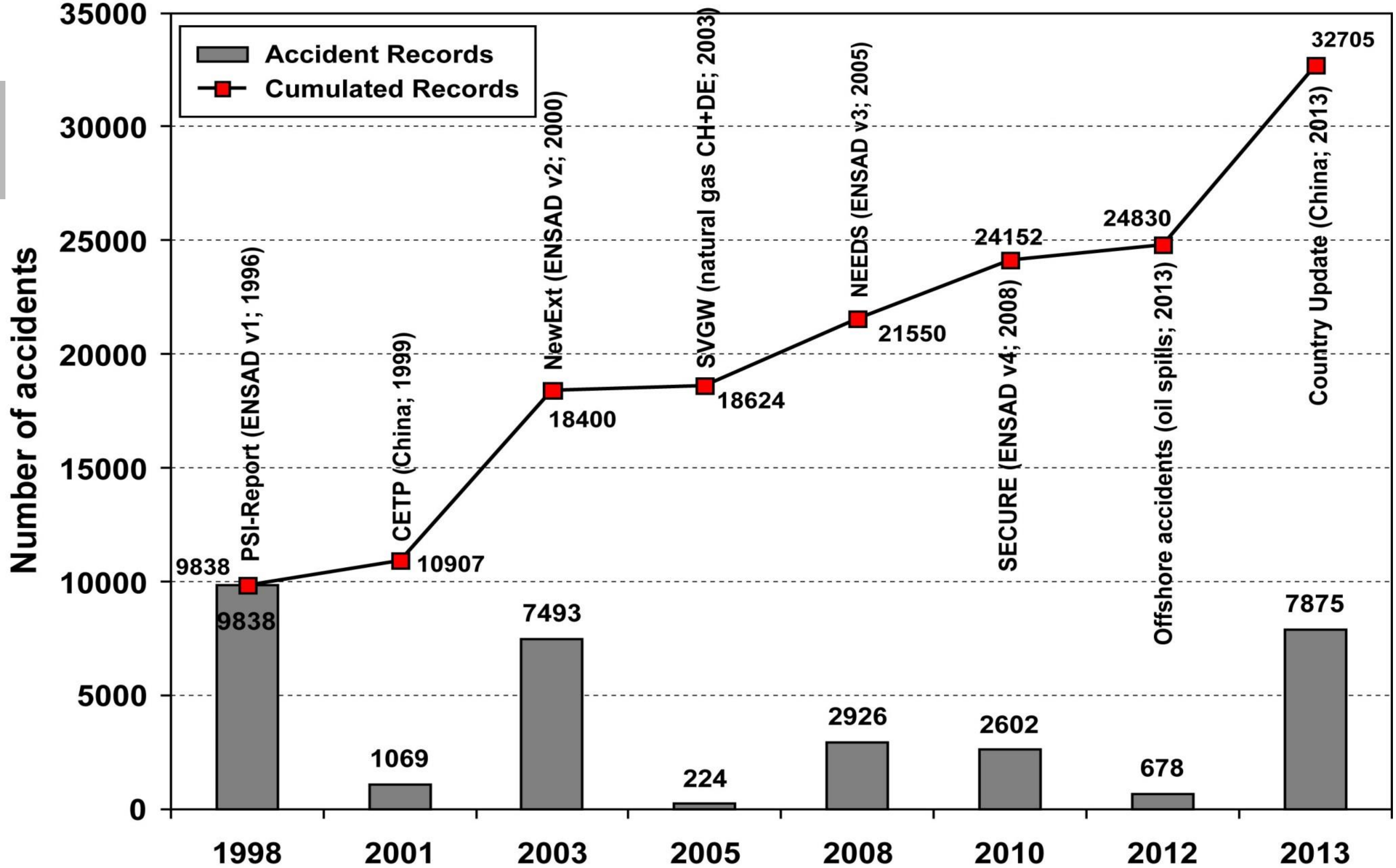
Consequence indicator	ENSAD	Sigma	EM-DAT	NatCat	WOAD
Fatalities	≥ 5	≥ 20 (dead or missing)	≥ 10	> 20	≥ 1
Injured persons	≥ 10	≥ 50	aff.	-	-
Evacuees	≥ 200	≥ 2000 (homeless)	aff.	-	-
Extensive ban on consumption of food	yes	-	-	-	-
Release of hydrocarbons	≥ 10000 t	-	-	-	≥ 1000 t
Enforced clean up of 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)

Severe Accidents: Methodological Framework



Major Steps in ENSAD Development



Burgherr & Hirschberg, 2013

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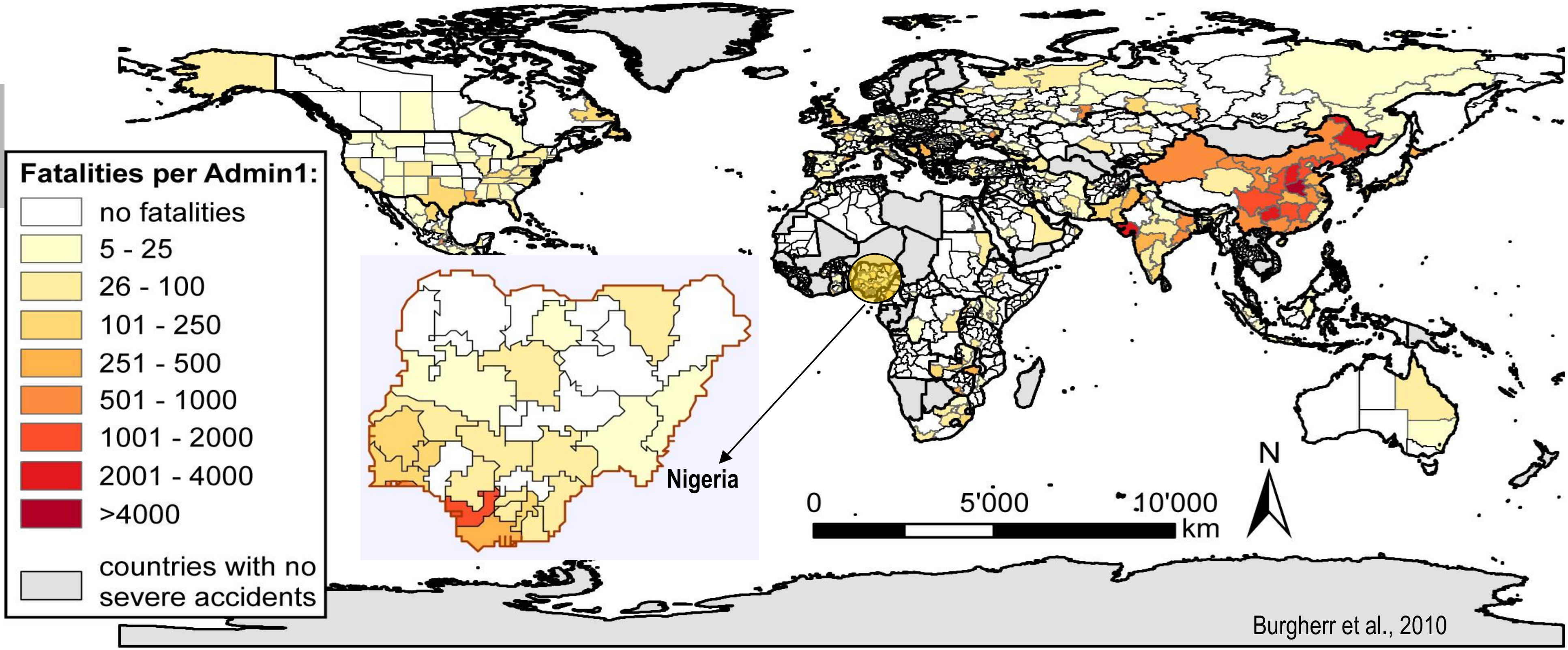
Geographic Distribution of Severe Accidents



- **Top 10 countries** accounted for **83% of all fatalities**; countries with 100 to 1000 cumulated fatalities contributed another 15.1%, and remaining countries summed up to only 1.9%.
- **China**: 53343 fatalities; 25772 in coal mine accidents (mostly Shanxi, Henan, Guizhou, Heilongjiang and Hunan); 26000 in Banqiao/Shimantan dam failure (Henan).
- **Nigeria**: oil chain accounts for over 98% of fatalities; Delta, Lagos, Rivers, Osun and Abia states.
- **USA**: most fatalities in the Gulf of Mexico area (e.g. LA, TX), where O&G activities are concentrated.

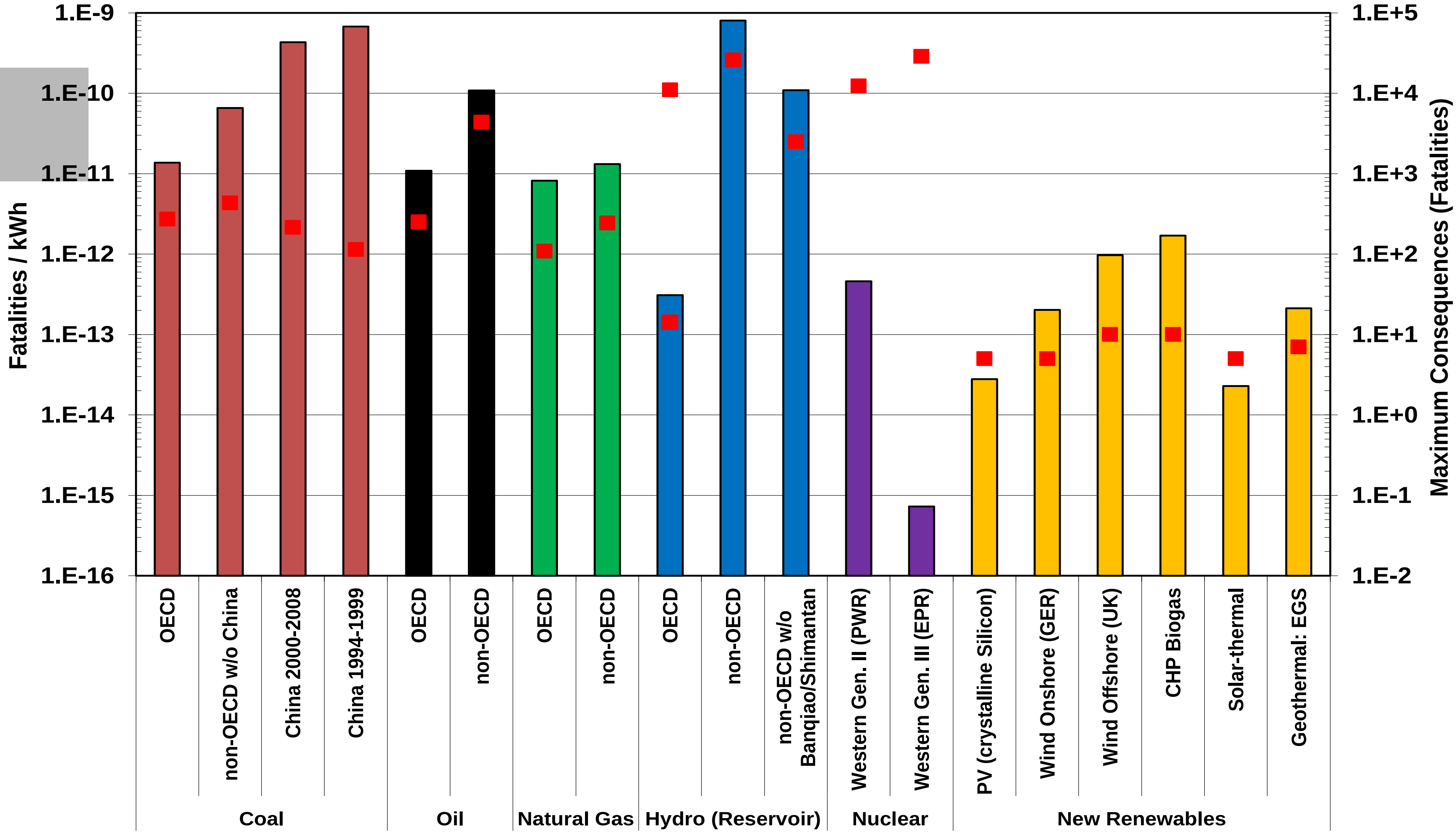
Contributions of stages in the various energy chains

	Coal	Oil	Natural Gas	Hydropower	Nuclear
Exploration and production/ processing	Explosions and fires in coal mines	Well blowouts, accidents on drilling platforms at sea.	Well blowouts, accidents on drilling plat-forms at sea.		
Transportation		Tanker accidents at sea	Pipeline accidents		
Processing/ storage		Process acci-dents in refineries and tank farms			
Regional/ local division		Overturning and collisions of tank trucks	Pipeline accidents		
Powerplant or heat production			Process accidents	Overflow or failure of storage dams	Core meltdown with large release of radio-activity
Waste treat-ment/disposal					

0–5%	5–15%	15–30%	30–60%	60–100%

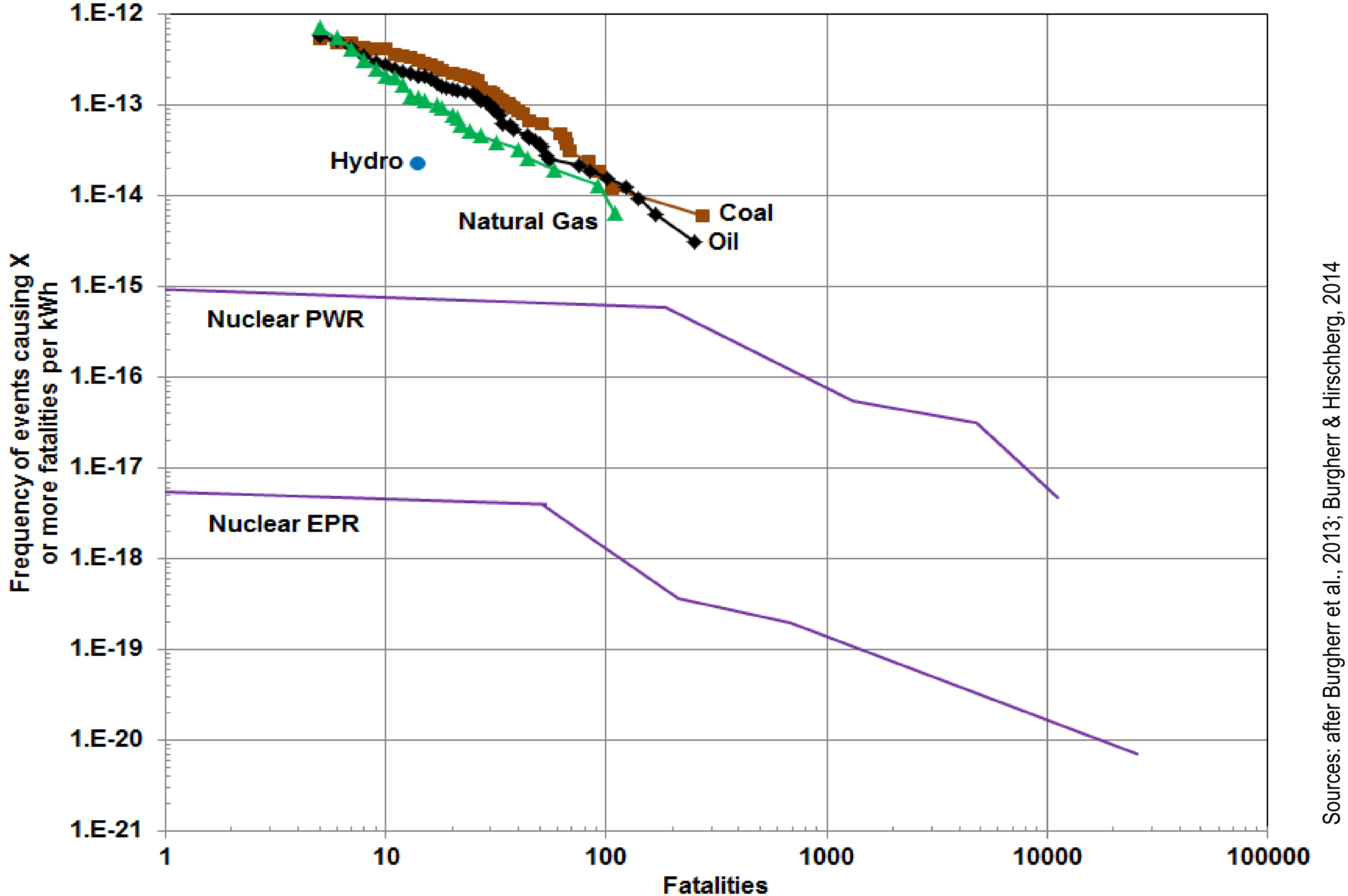
Relative share of accidental fatalities in the stages of various energy chains

Severe accident fatality rates and maximum consequences

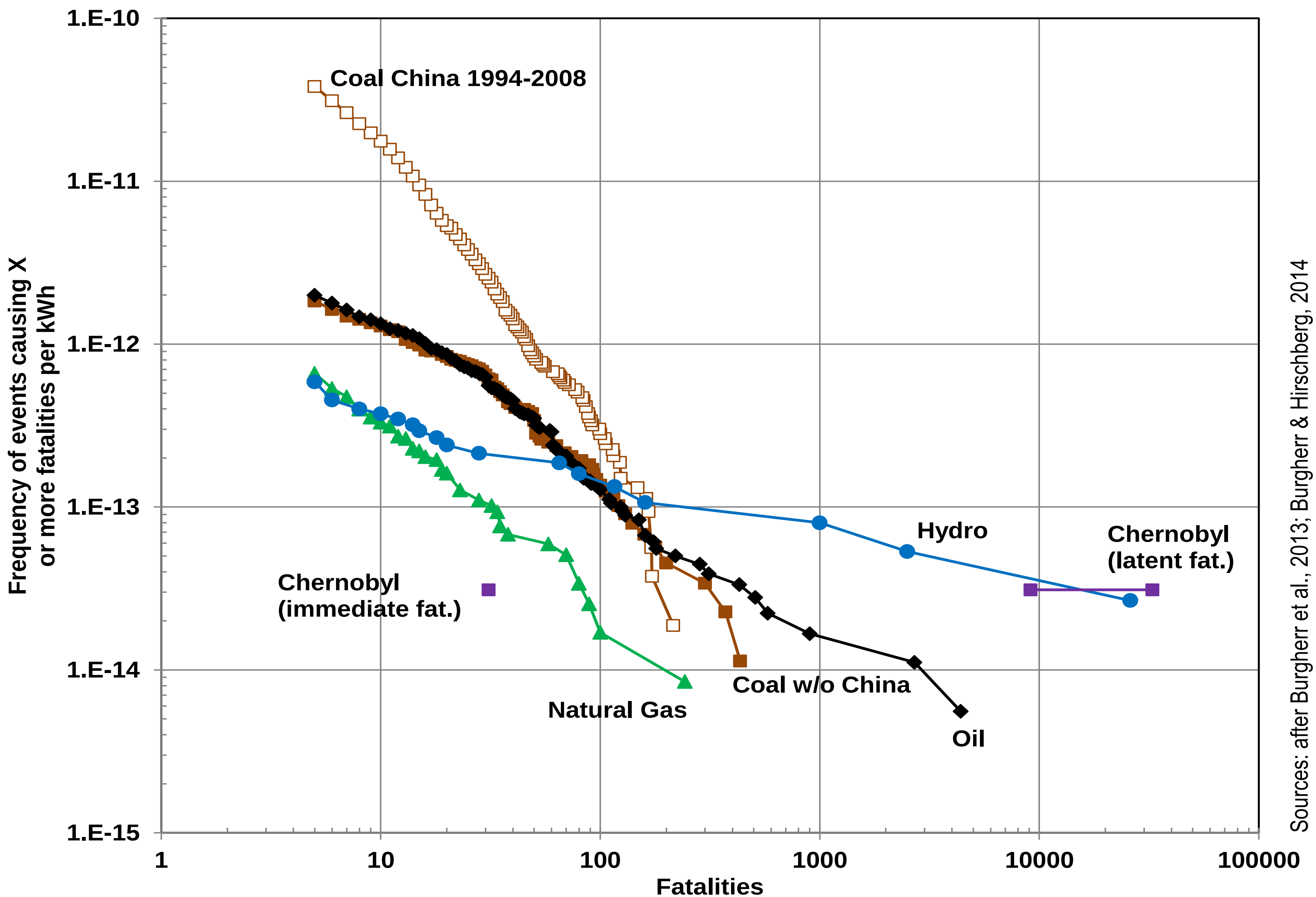


Sources: after Burgherr, 2011; Burgherr et al., 2013; Burgherr et al., 2014; Burgherr & Hirschberg, 2014

Frequency-Consequence Curves: OECD



Frequency-Consequence Curves: non-OECD



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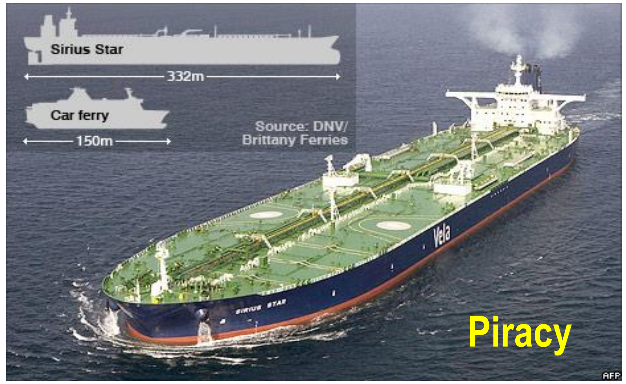
TERRORIST THREAT

Intentional Attacks on Energy Infrastructure



Terrorist Threat: Methodology

Terrorism risk

=

Probability that an attack is planned	x	Probability that it can be implemented	x	Consequences

Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

Methodology

Terrorism risk

=

Probability that an attack is planned

x

Probability that it can be implemented

x

Consequences

Probability that an attack is planned:

Historic evidence of attack on similar target

x

Evidence of terrorist groups targeting a specific country

Probability that it can be implemented:

Detailed analysis of potential attack
-Time
-Resources
-Know-How
-Countermeasures
-…

Consequences:

Physical analysis of consequences
-Immediate fatalities
-Latent fatalities
-Land contamination
-…

Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

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Implementation of risk assessment

Probability that an attack is planned

- Initiator
- Groups

Probability that it can be implemented

- Supplies
- Weapons
- Means of delivery
- Detection
- Countermeasures
- Implementation

Consequences

- Consequences

1. Quantify probability for every sub-issue
2. Define uncertainty distribution for sub issues

Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

Implementation of risk assessment

Initiator
Groups
Supplies
Weapons
Means of delivery
Detection
Countermeasures
Implementation
Consequences

What is the probability that necessary supplies can be obtained?

- Budget
- Weapons
- Know-How
- Support
- Communication equipment
- Transport

Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

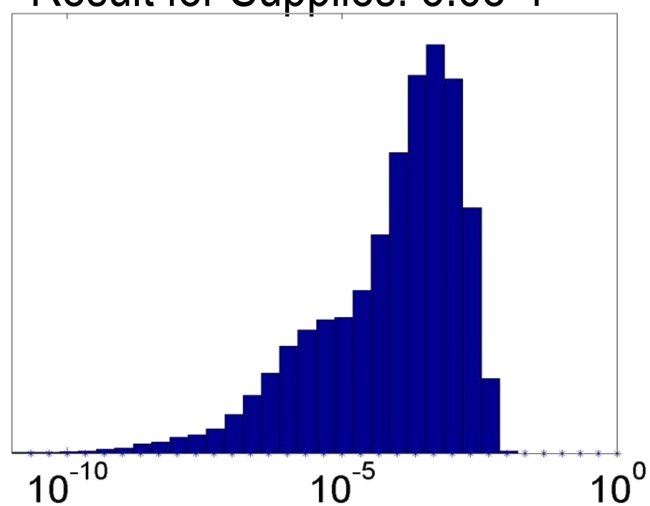
Implementation of risk assessment

- Initiator
- Groups
- **Supplies**
- Weapons
- Means of delivery
- Detection
- Countermeasures
- Implementation
- Consequences

What is the probability that these supplies can be obtained?

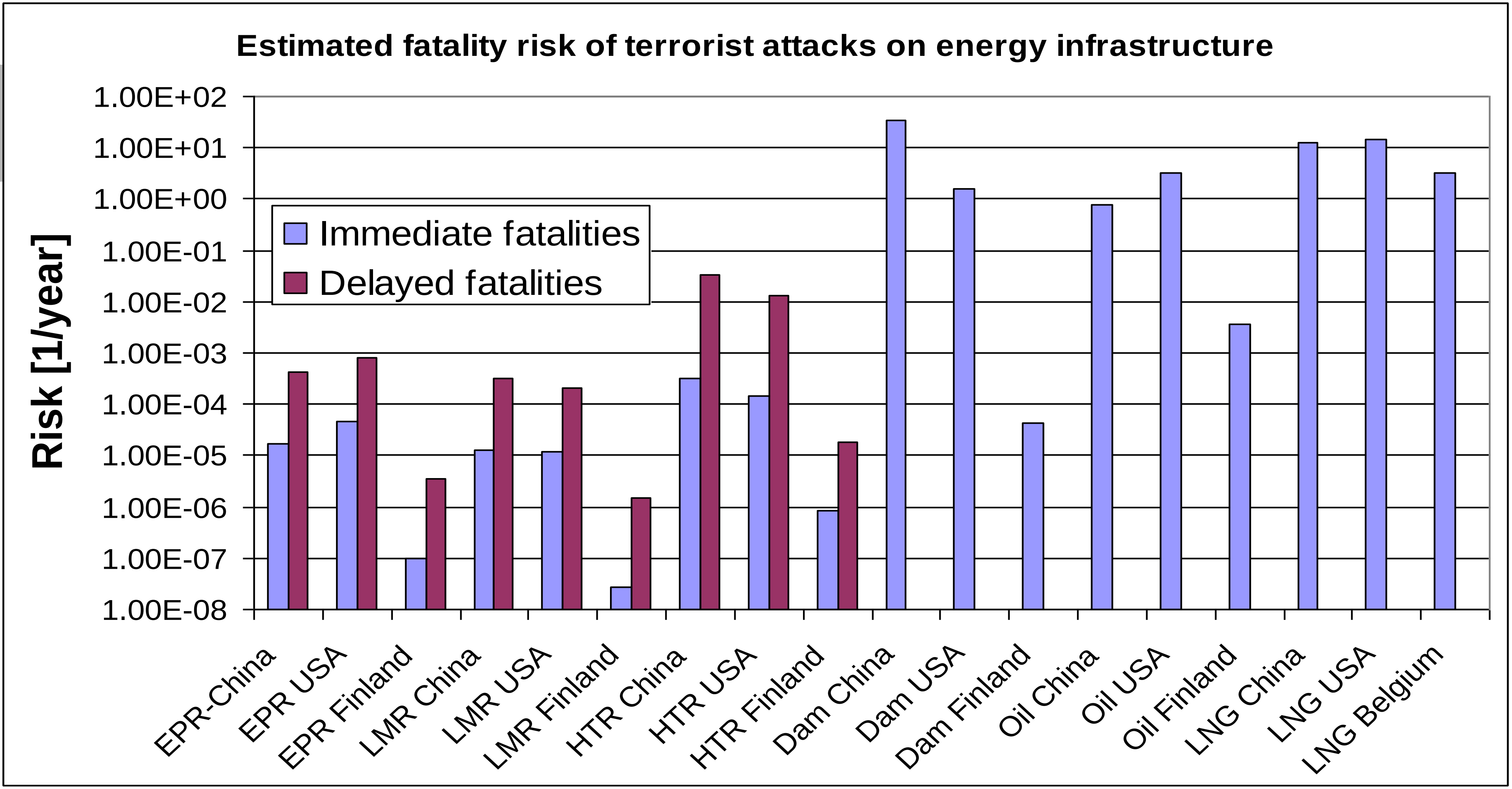
	Point value	Uncertainty class
- Budget	0.1	unlikely (0-0.2)
- Weapons	0.1	unlikely (0-0.2)
- Know-How	0.9	likely (0.8-1)
- Support	1	
- Communication equipment	0.25	not very likely (0-0.5)
- Transport	0.25	not very likely (0-0.5)

Result for Supplies: 5.6e-4



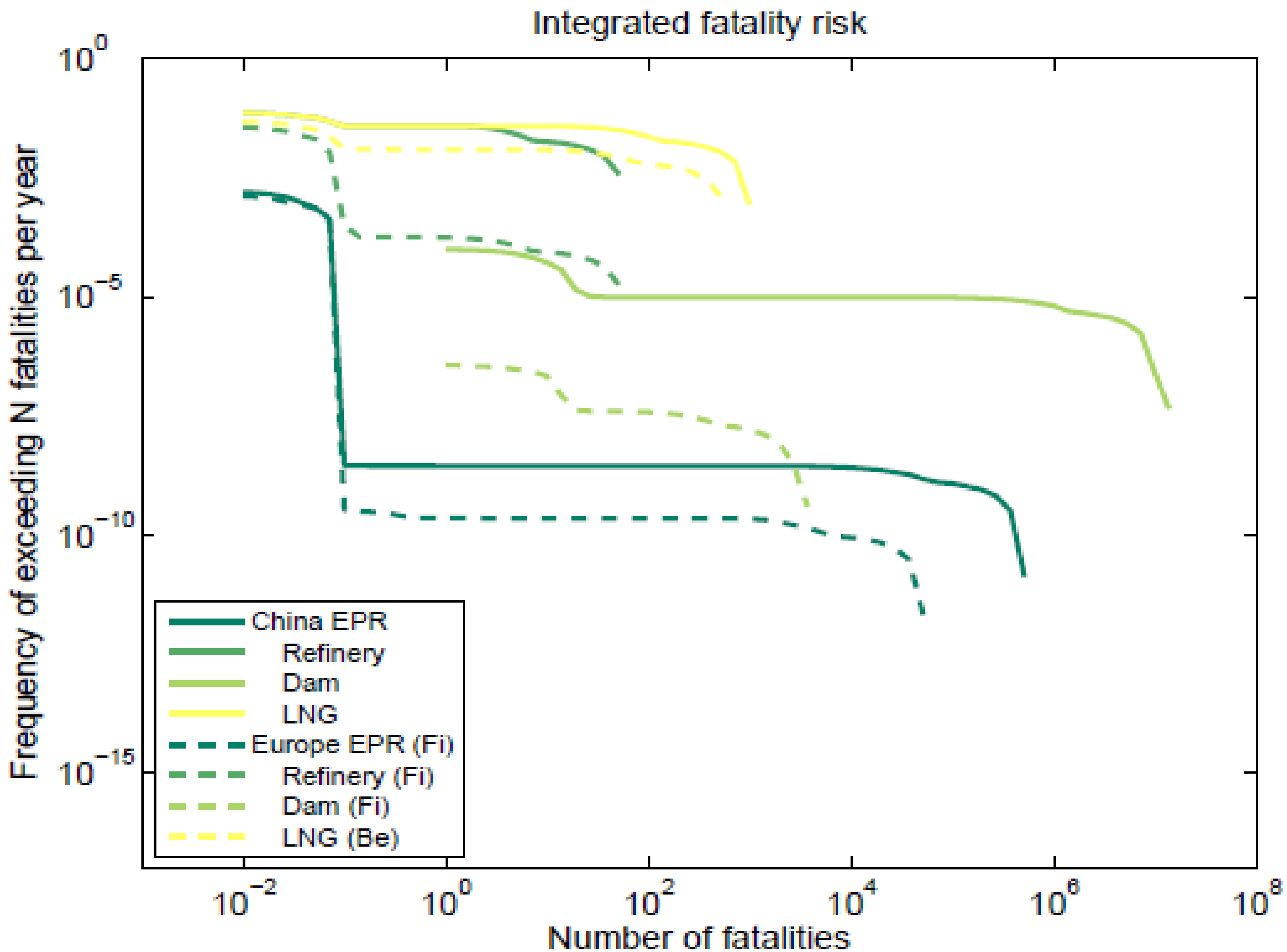
Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

Risk of fatalities due to hypothetical terrorist attacks



Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

Frequency-consequence curves for hypo



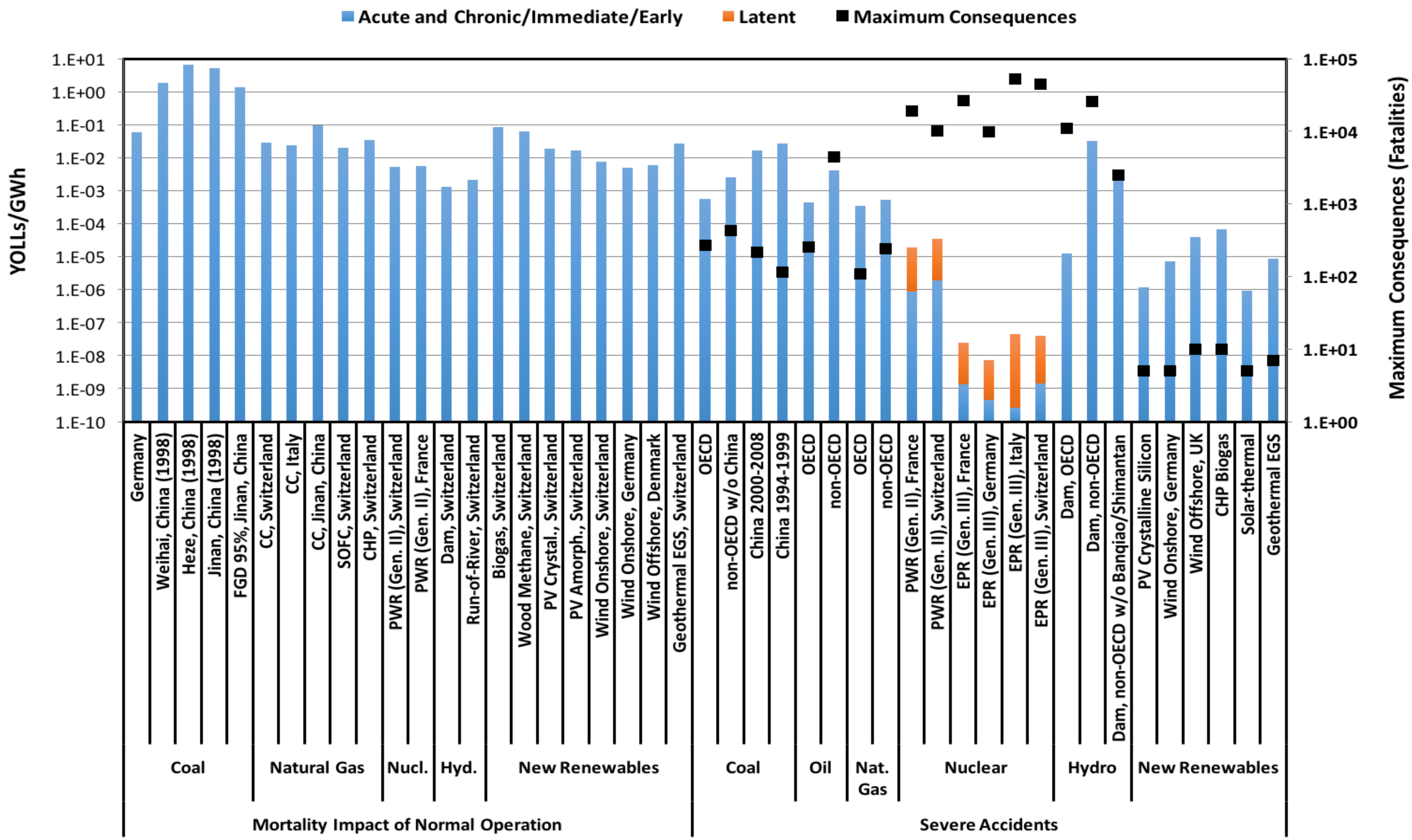
Source: Eckle, Cazzoli, Burgherr & Hirschberg, 2010

HEALTH RISK COMPARISONS

Stefan Hirschberg, Laboratory for Energy Systems Analysis, Energy Divisions

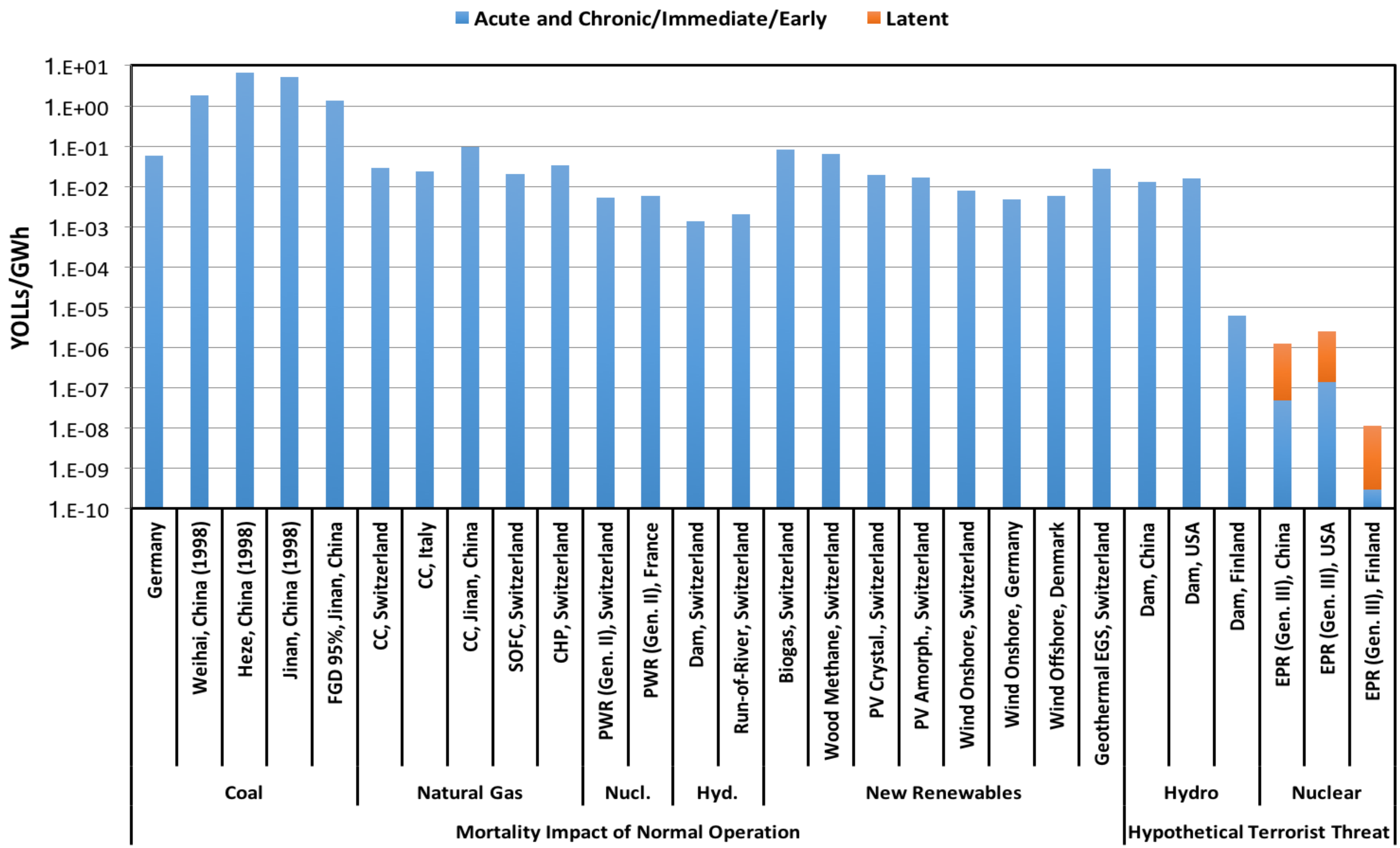
Example: Comparison between Mortality Impacts of Normal Operation and Severe Accidents

YOLL = Year of Life Lost



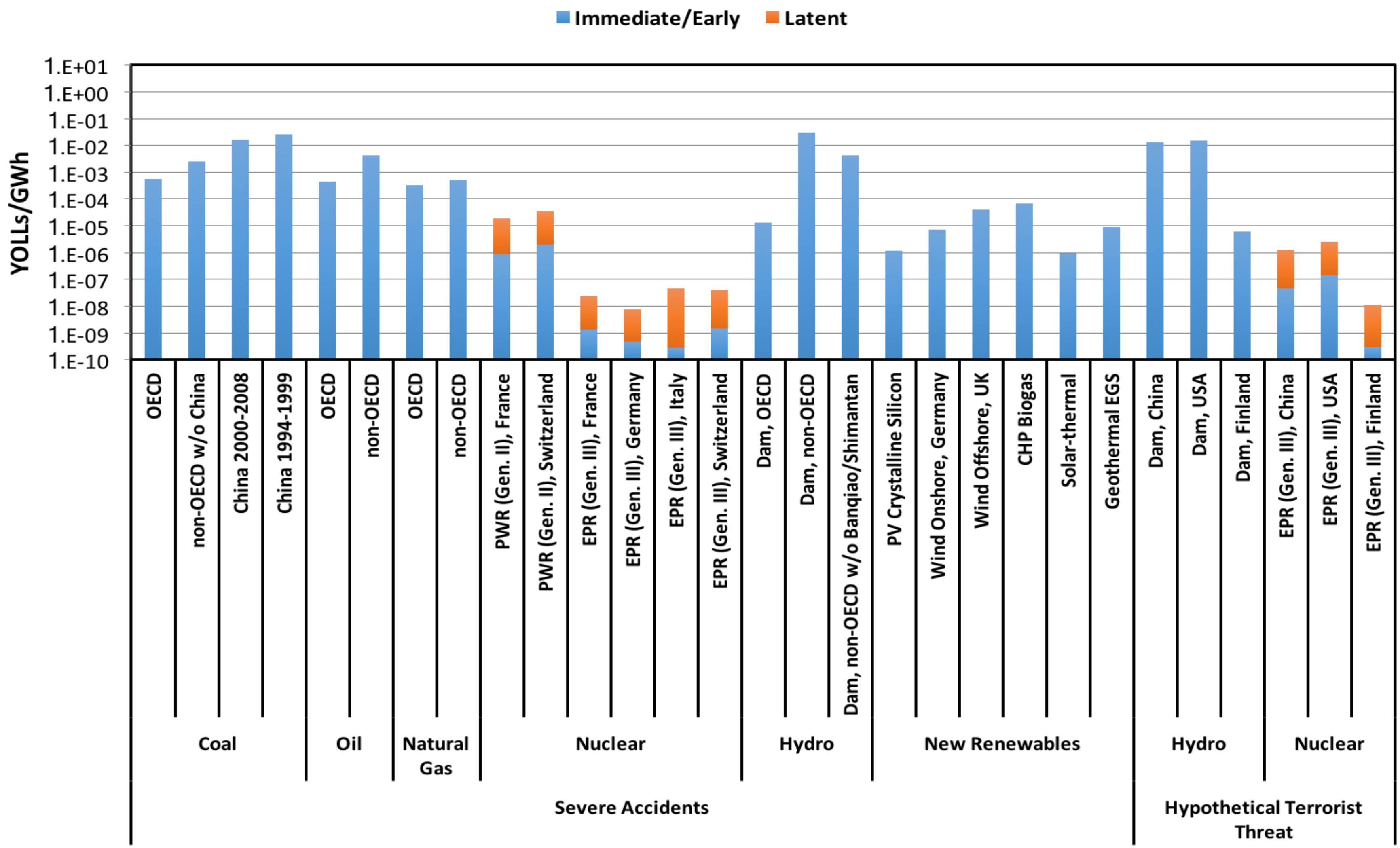
Source: Hirschberg et al., 2016

Example: Comparison between Mortality Impact of Normal Operation and Hypothetical Terrorist Threat



Source: Hirschberg et al., 2016

Example: Comparison between Severe Accidents and Hypothetical Terrorist Threat



Source: Hirschberg et al., 2016

Conclusions

- **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
  - ✓ Dominance of health impacts from normal operation
  - ✓ 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.

Conclusions (cont.)

- **Severe accidents risks:**
  - ✓Lowest fatality rates apply to hydro and nuclear with high safety standards in OECD countries.
  - ✓In both cases events with very low frequency can lead to quite extreme consequences.
  - ✓Energy-related accident risks in OECD and EU 27 countries are substantially smaller than in non-OECD countries.
- **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.
  - ✓Historic preference of terrorists for fatalities implies lower risk for energy infrastructure compared to soft targets.
- **Limitations:**
  - ✓Choice of reference technologies and geographical coverage
  - ✓Treatments of health impacts of climate change, morbidity and uncertainties
  - ✓Solar PV and geothermal accident risks
  - ✓Cyber risks
  - ✓Implementation of terrorist risk assessment

Thank you for your attention!

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