# Integrated Assessment of Technologies for Electricity Generation Vergleichende Bewertung von Stromerzeugungssystemen

**Rainer Friedrich**

**Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart**

**75. Jahrestagung der DPG, 14. März 2010**

# Decisions are needed about:

- *Investments (electricity utilities)*
- *Development aims (power plant manufacturers)*
- *Subsidies, allocation of research funds, steering tax (public authorities)*
- *Environmental regulations (public authorities)*

***Electricity generation with different technologies causes different***

- ***costs;***
- ***‚back-up'-costs;***
- ***demand for emission certificates;***

**private costs**

- ***health risks (during normal operation and accidents);***
- ***climate change due to greenhouse gases;***
- ***damage to ecosystems, reduction of biodiversity;***
- ***damage to materials, redution of crop yield;***
- ***Economic risks due to unsecure supply (oil, gas, solar thermal)***

**external effects**

***All these effects should be considered when making decisions.***

# External Costs

**= external effects expressed in monetary units**

# Social Costs

**= total costs associated with the generation of 1 kWh electricity with a certain supply security**

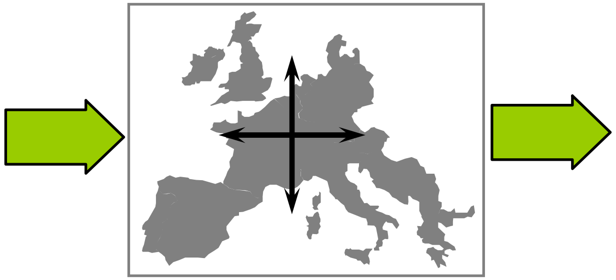
**= sum of private and external costs**

# Private Costs

- private costs = all costs per kWh borne by the electricity producer, but without taxes (VAT) and subsidies
- includes investment, operation and maintenance, fuel, supplies and services, dismantling, waste disposal
- Includes back-up costs (provision of reserve capacity), estimated by comparing scenarios of energy systems with and without the assessed technology with the same supply security
- estimation/projection of costs for plants built 2025 and some educated guesses for 2050

**Pollutant Emissions**

**Transport and Chemical Transformation**



Calculation is made twice: with and without project!

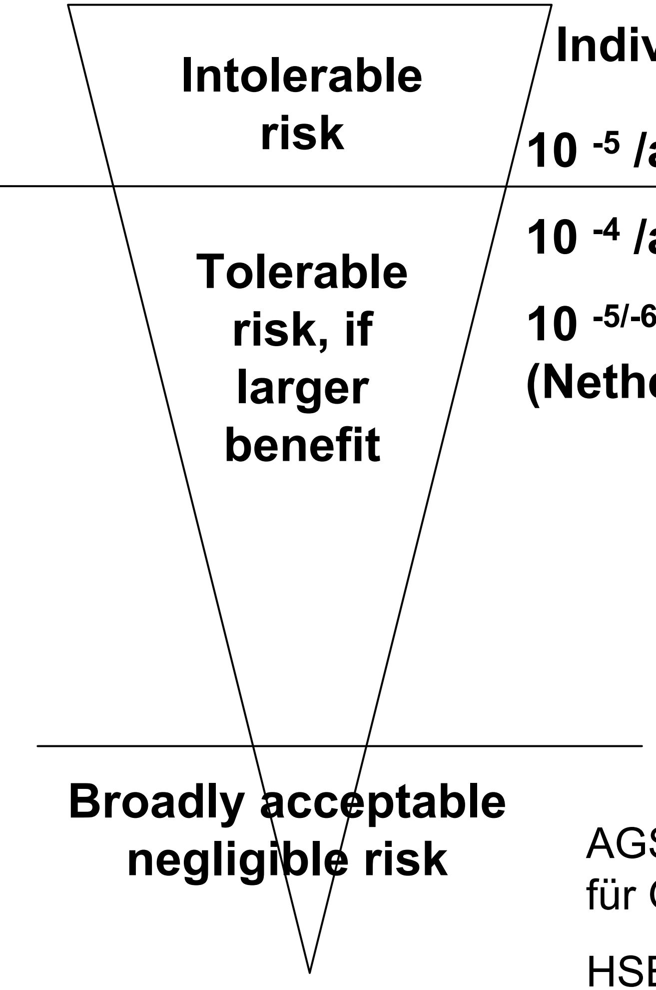
**Differences of Physical Impacts**

**For an assessment, pressures (e.g. emissions) have to be converted into impacts**

# Some examplary impact functions for $PM_{2.5}$

| Health effect | Relative Risk | Age Group | Population | Impact Function |
|---|---|---|---|---|
| **PM2.5** | | | | |
| Mortality (all cause) | 6% (95% CI: 2%, 11%) change per 1 µg/m3 PM2.5 | Adults 30 years and older | General Population | 235 years of life lost per µg/m3 increase in PM2.5 per 100,000 people aged >30 |
| Work loss days (WLDs) | 4.6% (95% CI: 3.9%, 5.3%) increase per 10 µg/m3 PM2.5 | 15-64 Years | General Population | 20,700 (95% CI: 17,600, 23,800) additional work lost days per 10 µg/m3 increase in PM2.5 per 100,000 people aged 15-64 in the general population per year |
| Minor Restricted Activity Days (MRADs) | 7.4% (95% CI: 6.0%, 8.8%) change per 10 µg/m3 PM2.5 | 18-64 Years | General Population | 57,700 (95% CI: 46,800, 68,600) additional MRADs per 10 µg/m3 increase in PM2.5 per 100,000 adults aged 18-64 (general population) per year |
| Restricted activity days (RADs) | 4.75% (95% CI: 4.17%, 5.33%) change per 10 µg/m3 PM2.5 | 18-64 Years | General Population | 90,200 (95% CI: 79,200, 101,300) additional RADs per 10 µg/m3 increase in PM2.5 per 100,000 adults aged 18-64 (general population) per year |

# Assessment of Impacts




**Individual risks:**

**$10^{-5}$ /a (HSE UK);**

**$10^{-4}$ /a (AGS)**

**$10^{-5/-6}$ /a (Netherlands)**

AGS = Ausschuss für Gefahrstoffe,

HSE = Health and Safety Executive

**Step 1: Inacceptable intolerable risks have to be avoided by all means (e.g. via thresholds, bans).**

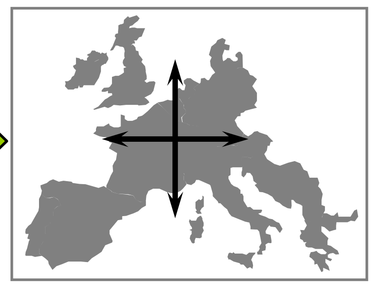
**Lower risks (with a frequency of less then $10^{-5}$ /a ) seem to be acceptable, if they are compensated by a benefit (can be observed in our decisions/behaviour) - see however discussion of Damocles risks later**

**Step 2: The assessment of tolerable risks is based on the measured preference of the affected well informed population.**

# The Impact Pathway Approach

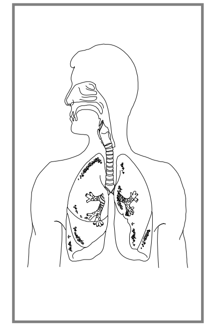
**Pollutant Emissions**

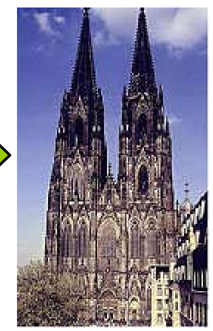
**Transport and Chemical Transformation**



Calculation is made twice: with and without project!

**Differences of Physical Impacts**





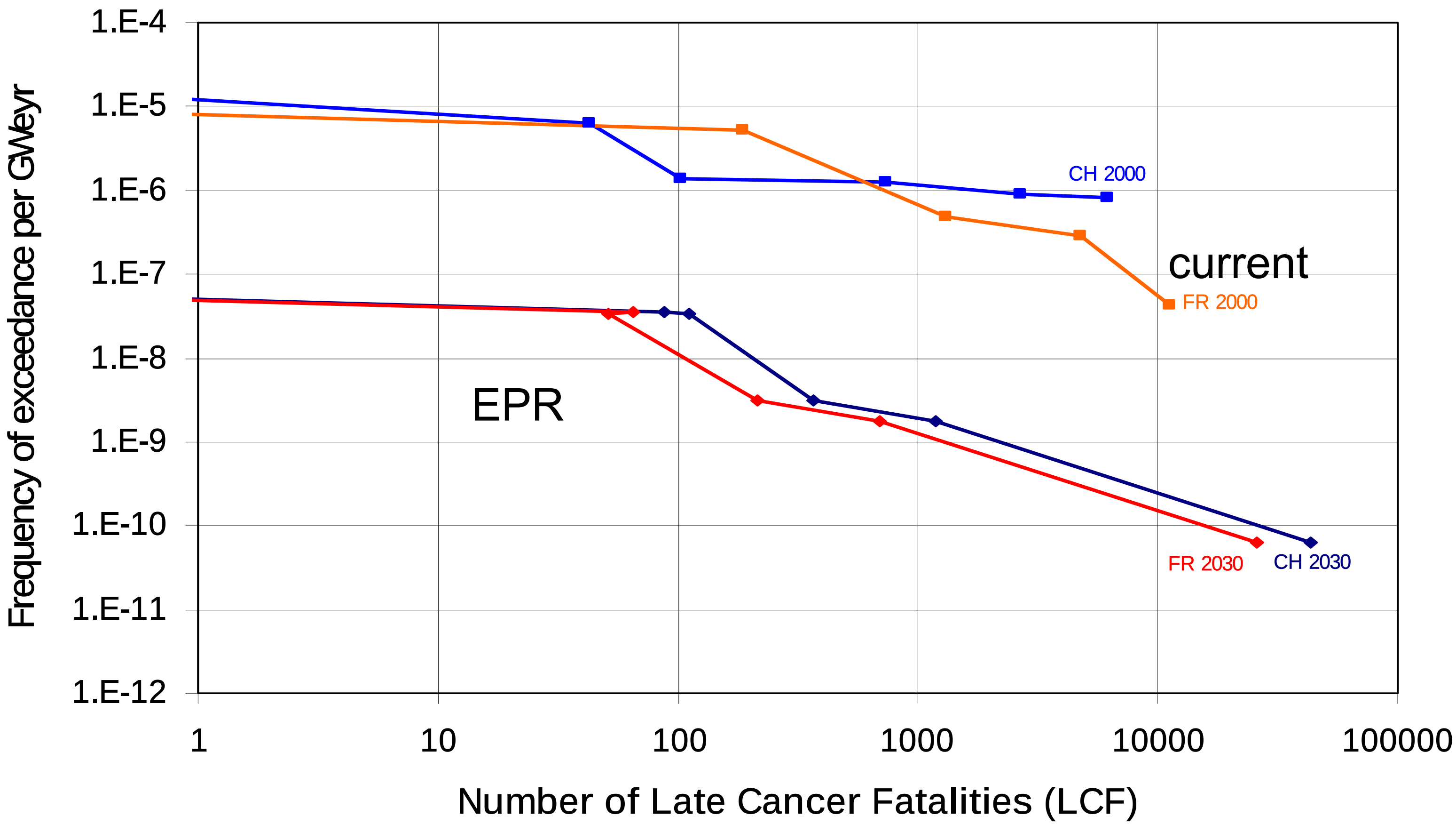
**monetary valuation**

# Monetary values of health endpoints (EUR 2010)

| Health End-Point | Low | Central | High | per case |
|---|---|---|---|---|
| Increased mortality risk - VSLacute | 1,121,433 | 1,121,433 | 5,607,164 | Euro |
| Life expectancy reduction - Value of Life Years chronic | 40,500 | 59,810 | 213,820 | Euro |
| Sleep disturbance | 400 | 1,045 | 1,320 | Euro/year |
| Hypertension | 740 | 800 | 930 | Euro/year |
| Acute myocardial infarction | 2,200 | 4,470 | 31,660 | Euro |
| Lung cancer | 69,080 | 719,212 | 4,187,879 | Euro |
| Leukaemia | 2,045,493 | 3,974,358 | 7,114,370 | Euro |
| Neuro-development disorders | 4,486 | 14,952 | 32,895 | Euro |
| Skin cancer | 10,953 | 13,906 | 26,765 | Euro |
| Osteoporosis | 2,990 | 5,682 | 8,074 | Euro |
| Renal dysfunction | 22,788 | 30,406 | 40,977 | Euro |
| Anaemia | 748 | 748 | 748 | Euro |

# Possibilities for the assessment of accidents of nuclear power plants

**F-N Curves: Latent Cancer Fatalities (LCF) for current nuclear power plants and EPR (European Pressurized Reactor); source: Hirschberg, PSI**




Source: Hirschberg et al., 2008

# Possibilities for the assessment of accidents of nuclear power plants, approach 1: assessment based on estimation of risk as defined in engineering sciences:

- **Risk = frequency * damage = expectation value of damage**

a) Frequency in F-N curve used shows a frequency for a core-melt of $10^{-5}$ /(year and plant) as a result of probabilistic safety studies (one core-melt per 230 years for 440 reactors worldwide)

b) To account for unforeseen events (as in Fukushima), frequency is increased by a factor of 10 (one core-melt per 23 years for 440 reactors), thus frequency for large release (similar Tschernobyl) increased to $10^{-6}$ /(year and plant)

c) Rough estimation of damage ca 1 to 10 * $10^{12}$ € per large release

d) Risk = Expection value of damage per plant (1200 $MW_{el}$) and kWh thus (1 to 10* $10^{12}$ € )* ($10^{-6}$ /a) / (9,4 * $10^{9}$ kWh/a) = 0,001 – 0,0001 €/kWh

# Possibilities for the assessment of accidents of nuclear power plants, approach 1: assessment based on estimation of the technically defined risk:

- **Risk = 0,001 – 0,0001 €/kWh for current plants**
- **Risk = 0,00001 – 0,000001 €/kWh for new plants (EPR), as they have a frequency for accidents that is more than two orders of magnitude lower than for current plants according to the probabilistic safety analysis**
- Using this result the overall external costs for nuclear energy per kWh are about **0,002 €/kWh**, i.e. in the same order of magnitude than for renewables, but private costs and thus social costs are smaller than for all renewables.

→ Using this approach for decisions leads to an optimal reduction of the expectation value of damages

- **However…**

# Possibilities for the assessment of accidents of nuclear power plants, approach 2: Damocles risk assessment

- **A very high damage (and/or a very scaring event) with low probability, i.e. a Damocles risk, is often assessed as worse than the same risk with a much lower damage (and thus higher frequency).**
- **The occurrence of such high damage/scaring events should – according to the opinion of 'risk-averse' persons -, be avoided at any costs.**
- **Methods to deal with Damocles risks in other countries:**

  **Switzerland: factor 100 proposed (would increase external costs of current plants to considerable 0,1 -0,01 € per kWh, but not affect the low social costs of new EPR plants)**

  **The Netherlands: tolerable risk $10^{-3}$ /N² (N = number of deaths), would lead to ban of nuclear plants.**
- **Currently there is no accepted quantitative methodology in Germany for assessing Damocles risks for Germany. Thus the decision on whether a Damocles risk is tolerable or not has to be made based on qualitative considerations.**
- **As e.g. German law forbids building new nuclear power plants, their risks are seen as not tolerable in Germany (however different opinion in some other countries). Thus new nuclear power plants are not included in the analysis, that follows.**
- **Obviously using this approach leads to a reduction of the possible occurrence of Damocles events, but to higher expectation values for health risks (e.g. by coal or gas plants) and to higher negative economic and thus social impacts.**

# Values for Assessing Greenhouse Gas Emissions

| [Euro 2010 per tonne CO2 eq] | 2010 | 2015 | 2025 | 2035 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| MDC_NoEW | 9 | 11 | 14 | 15 | 17 | 22 |
| **Kyoto+** | **26** | **30** | **36** | **42** | **74** | **87** |
| **2° max** | **36** | **46** | **73** | **119** | **194** | **250** |

**Kyoto/20%+ : avoidance costs, leads to fulfillment of the Kyoto aim 2010, 20% GHG reduction 2020 in EU and further considerable reduction after 2020**

**Max 2° : avoidance costs, leads to a temperature increase of max 2° compared to pre-industrial times (with 50% probability)**

**MDC_NoEQ: quantifiable marginal damage costs without equity weighting, estimated with the FUND model**

# Which External Costs Are Included ?

- Environmental externalities: the release of a substance (PM2.5, PM10, NO2, SO2, NH3, VOC, CO, dioxins and furanes, cadmium, mercury, lead, BaP) or energy (noise, radiation) into environmental media (air, indoor air, soil, water), that causes - after transport and transformation - considerable (not negligible) harm to ecosystems, humans, crops or materials.
- Land use change (typical conditions)
- Global warming impacts from emissions of greenhouse gases: damage costs and avoidance cost approach used.
- Accidents: Public and partly occupational risks caused by accidents (use of expectation value).
- LCA impacts also included.

# Which Effects Are Not Included in the Following Results?

**As they are not considered as externalities:**

- **Effects on employment**
- **Depletion of non-renewable resources (oil, gas, silicon, copper, …)**
- **Research and development (sunk costs)**
- **Income distribution**
- **Local damage to natural and seminatural biotopes (however addressed and fully or at least partly compensated within the Environmental Impact Assessment)**

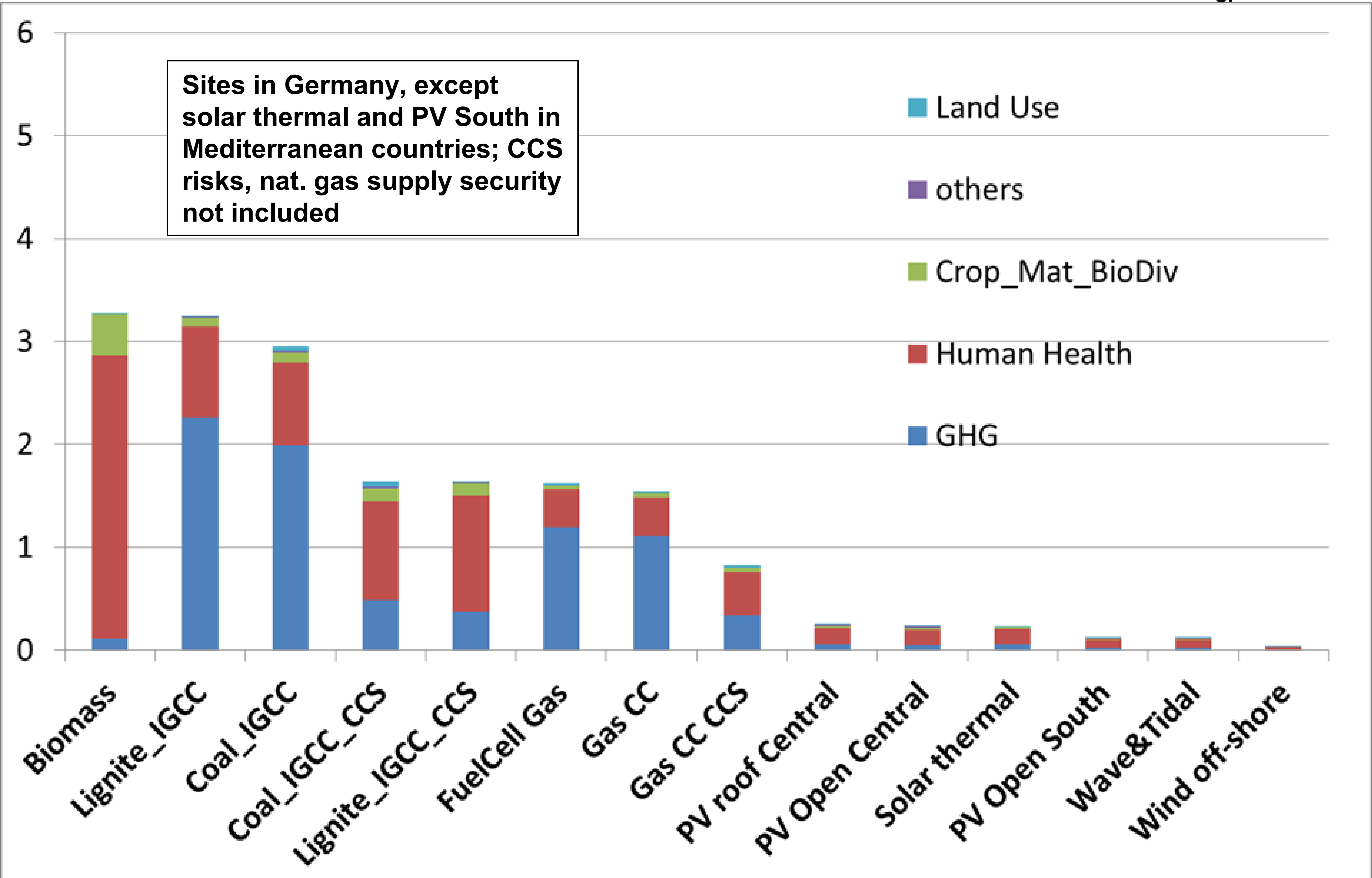
# Which Effects Are Not Included ?

**as agreed methods or reliable information are not available, though impacts on the result may be large :**

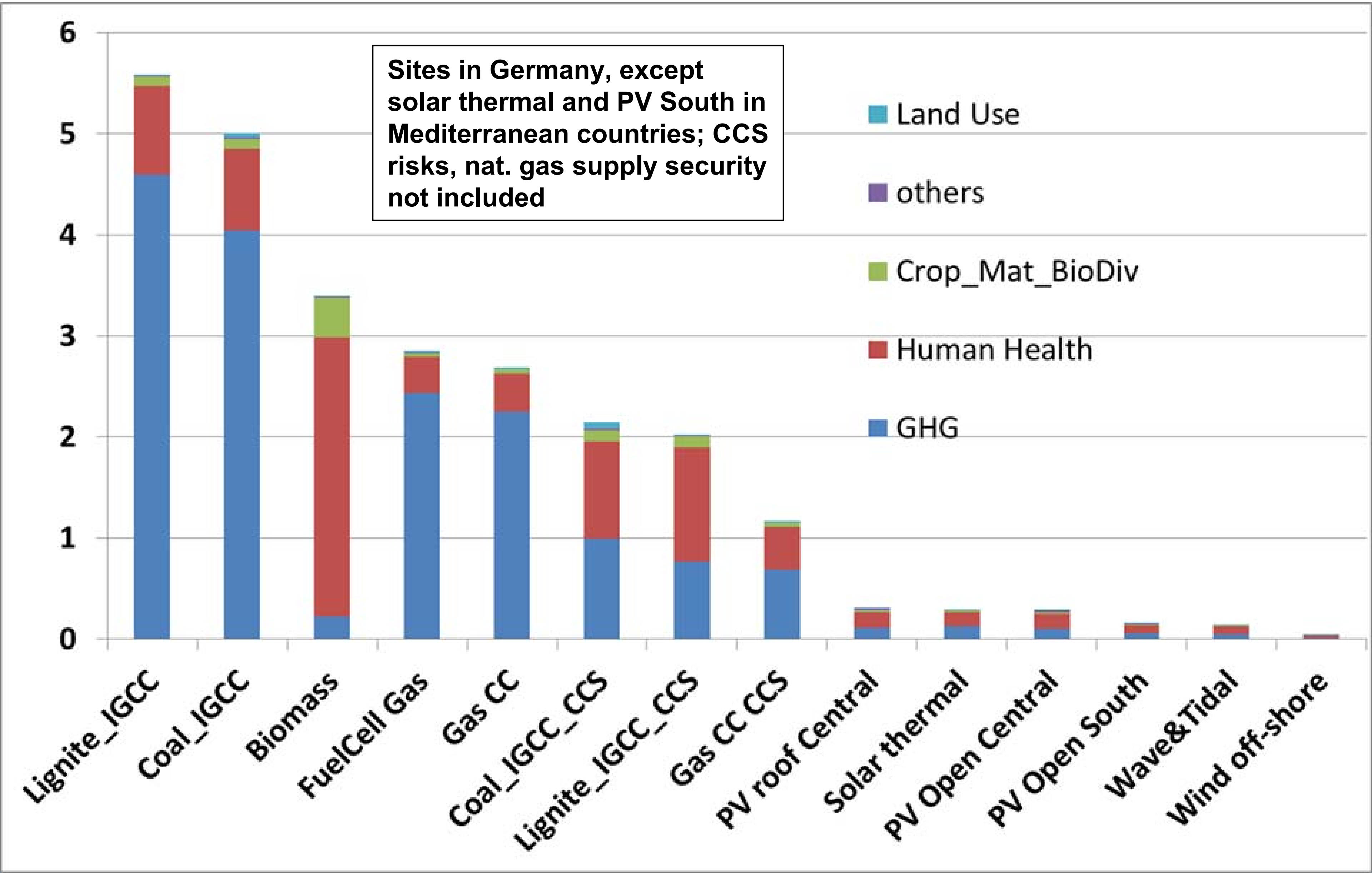
- **Visual annoyance - large spatial and temporal variability, thus benefit transfer not possible**
- **Risk of carbon storage – no quantitative information yet available**
- **Security of supply for natural gas - methodology not available**

The following slides show estimated external and social costs (with uncertainty range) ranked according to central values of external/social costs for 2025 and 2050 and two climate scenarios: moderate = Kyoto+, high ambition = 2 max

# External Costs 2025 Scenario Kyoto+ 36€/tCO2eq , in €-cent/kWh$_{el}$

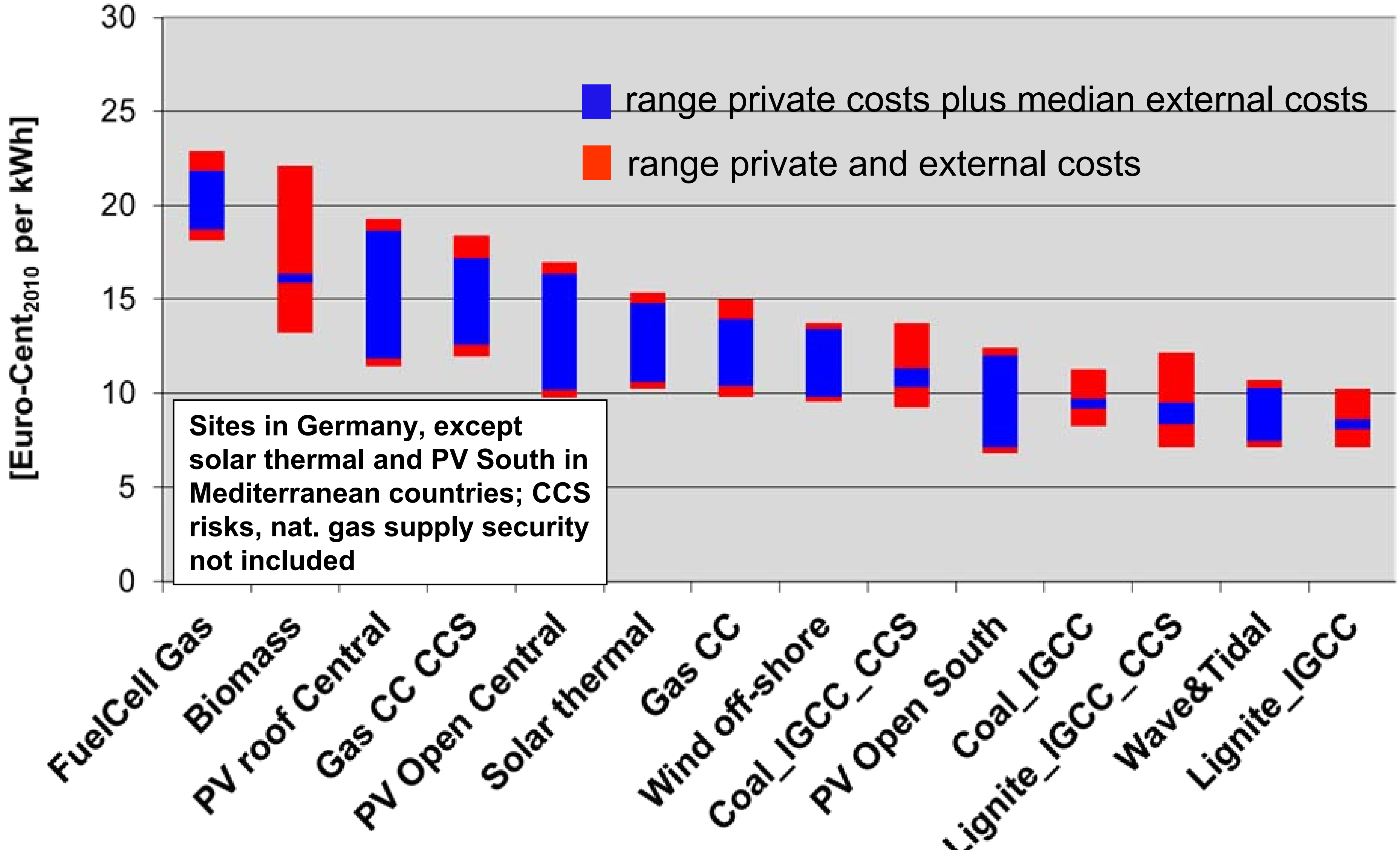


# External Costs 2025 Scenario 2° max, ca. 73€/tCO2eq, **in €-cent/$kWh_{el}$**



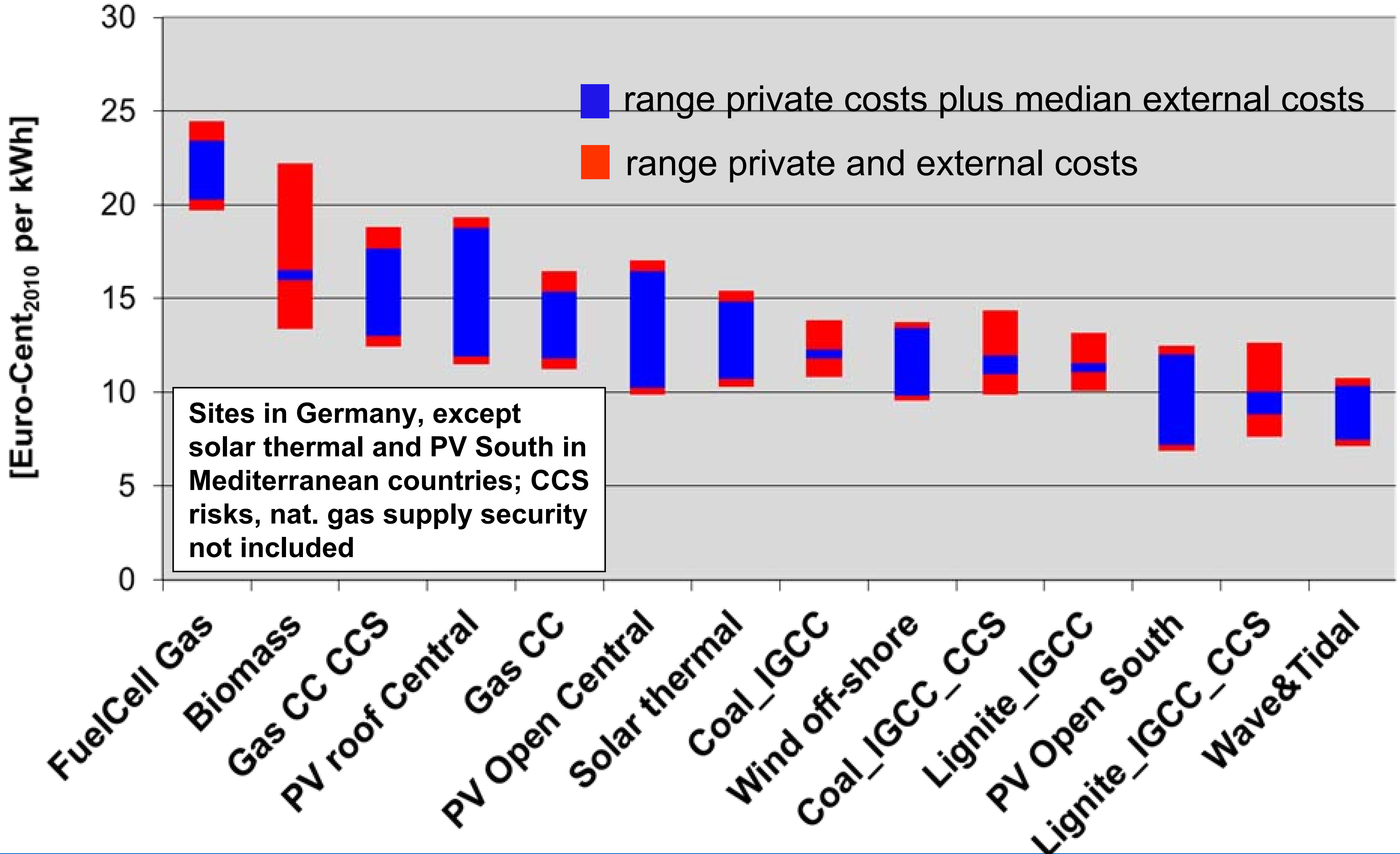
# Social Costs 2025

Scenario Kyoto+: 36€$_{2010}$/tCO2eq



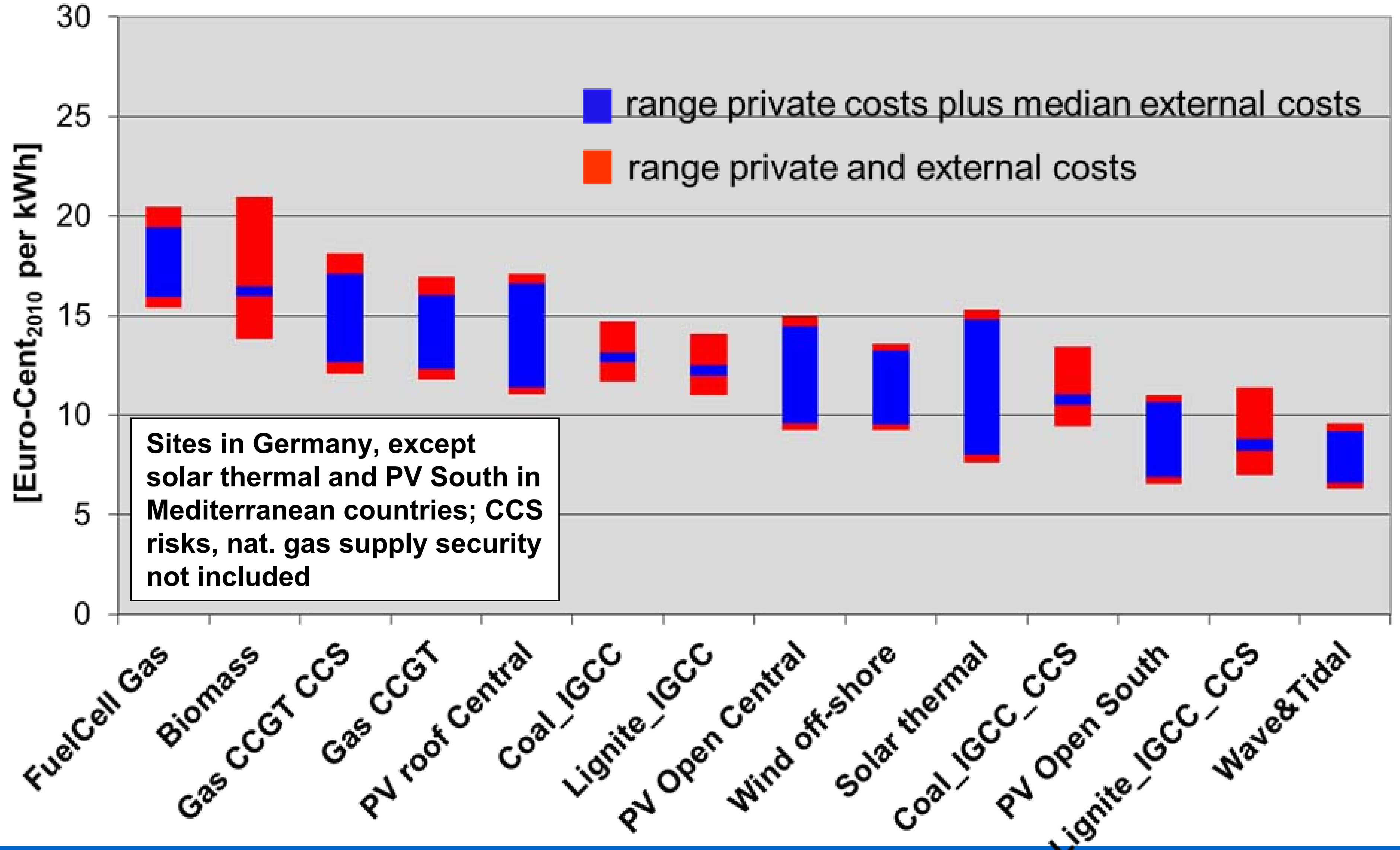
# Social Costs 2025

Scenario 2° max: 73€/tCO2eq



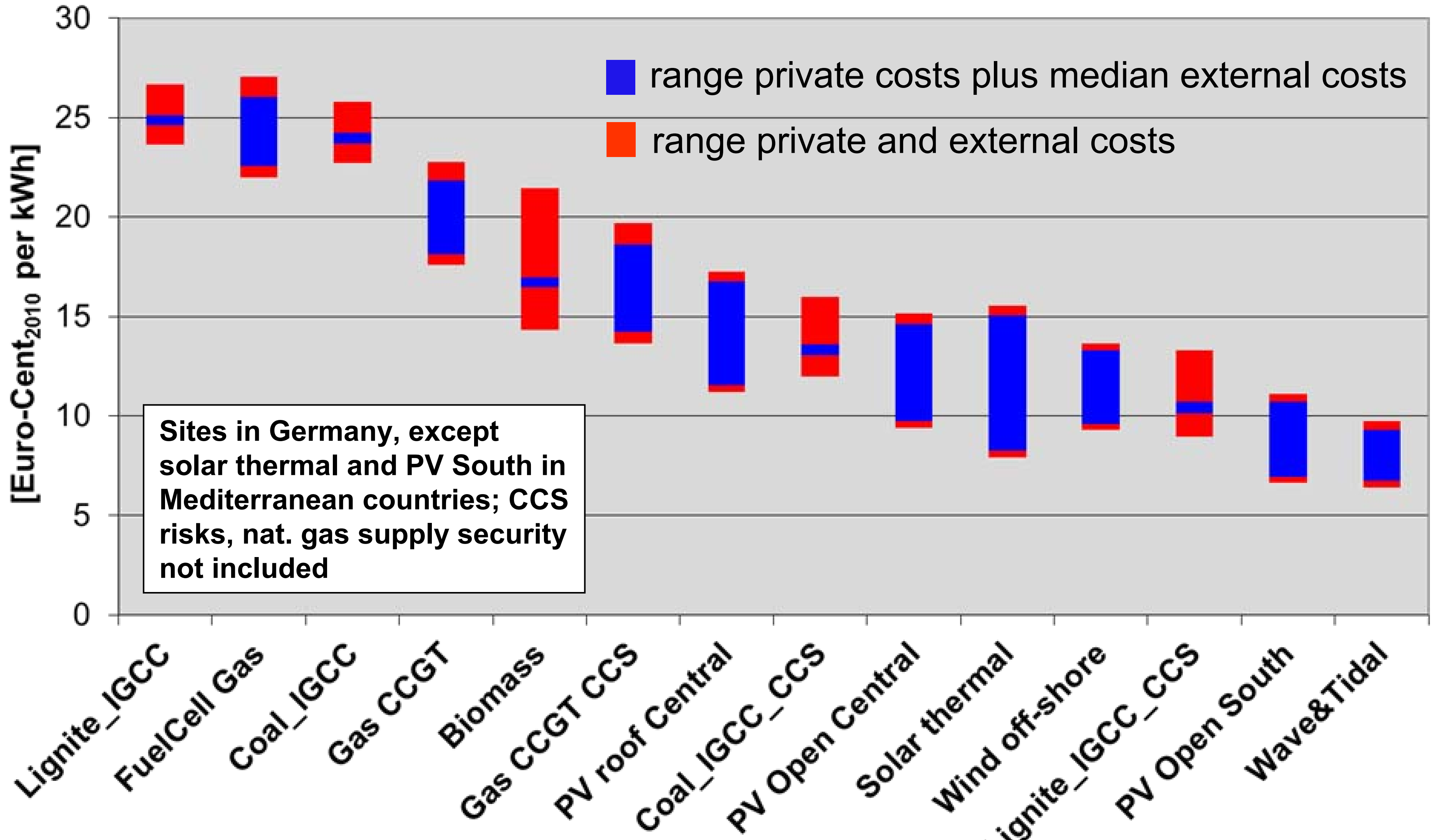
# Social Costs 2050

Scenario Kyoto+: 87 $€_{2010}$/tCO2eq



# Social Costs 2050

Scenario 2° max: 250 €/tCO2eq



# Conclusions I

- **Wind, run-off water, possibly also wave and tidal energy are electricity generating options with lower external and social costs. However, wind and water have a limited potential, wind and wave need back-up capacity or storage.**
- **Lignite where available and coal burnt in IGCC (integrated gasification combined cycle) plants will thus continue to play a certain role, – with CCS, if**
  - **CCS turns out to have low environmental and technical risks,**
  - **the costs for transport and storage are not much higher than anticipated,**
  - **the level of ambition for climate protection is high.**

# Conclusions II

- Natural gas will only play a role replacing coal, if the price for gas (and oil) is expected to stay moderate, then however without CCS. In the short run, i.e. before CCS is available, gas might be used as a transition technology.
- Biomass has relatively high external and social costs. The use of residual biomass in large combustion plants might be a favourable option.
- Electricity production with solar plants (PV) in Germany tend to have higher private and social costs at least until 2030. Solar thermal systems and /or PV plants (depending on technological progress) in Mediterranean countries would be the next best option with high potential – especially, if the climate protection goals are very ambitious and CCS turns out to be a less efficient or safe option or has a limited potential.

- **More information: www.externe.info ; www.needs-project.org; www.integrated-assessment.eu**