Environmental Impacts and Costs of Energy

How much is clean air worth?

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ExternE = "External Costs of Energy"

funded by European Commission DG Research, since 1991

(until 1995 with ORNL/RFF)

>200 scientists in all countries of EU

Series of projects, includ. ExternE Transport, ExternE-Pol, NEEDS (04-08), CASES (06-08) and related projects, e.g. ESPREME, …

Major publications **1995**, **1998**, **2000, 2004**

www.externe.info

Methodology

1) Site specific impact pathway analysis

(for each pollutant: emission→dispersion→impact→cost)

2) Life Cycle Analysis of fuel chain (LCA)

Impact Pathway Analysis

to calculate damage of a pollutant emitted by a source

Impacts are summed over entire region that is affected (Europe) and all damage types that can be quantified:

- health
- loss of agricultural production
- damage to buildings and materials

Result: €/kg of pollutant

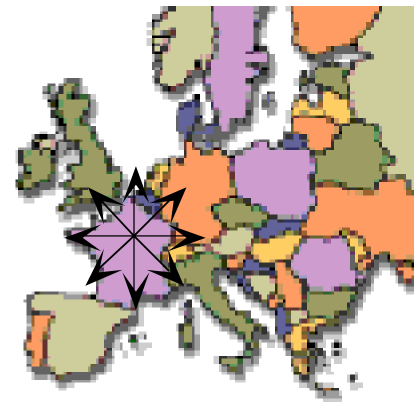
Multiply by kg/kWh to get €/kWh

SOURCE
(site, stack height and technology)

⇒ **emission**
(e.g., kg/yr of PM_{10})

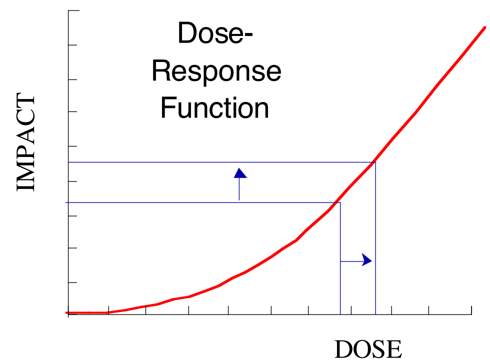
DISPERSION
(atmospheric dispersion & chemistry)

⇒ **increase in concentration at receptor sites**
(e.g., $\mu g/m^3$ of PM_{10} in all affected regions)



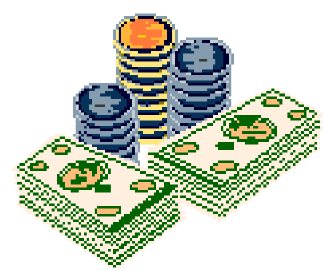
DOSE-RESPONSE FUNCTION

⇒ **impact**
(e.g., hospital admissions due to PM_{10})



MONETARY VALUATION

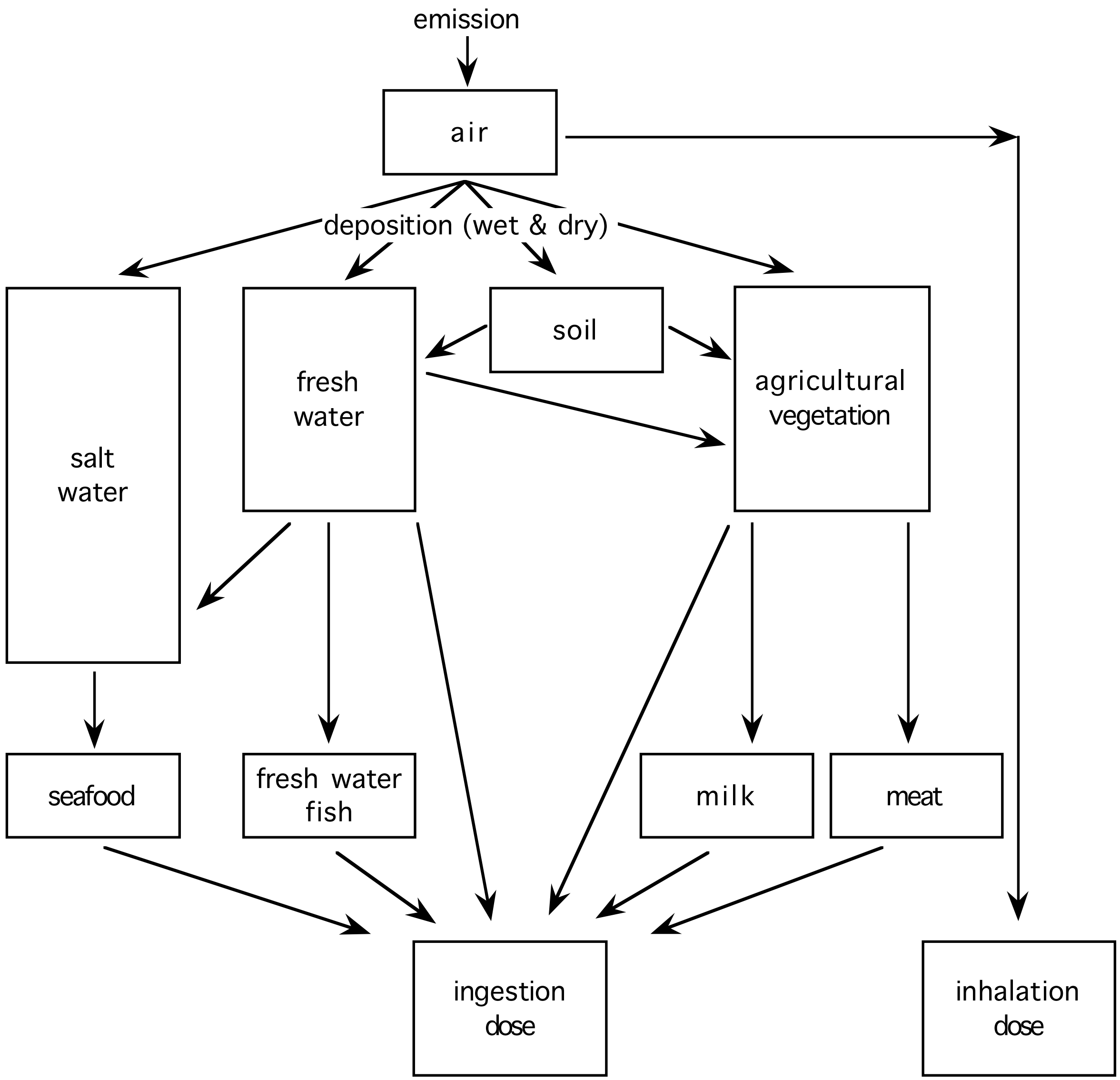
⇒ **cost**
(e.g., cost of hospital admission, includ. WTP to avoid suffering)



Pathways for Dioxins and Toxic Metals

For many persistent pollutants (dioxins, As, Cd, Cr, Hg, Ni, Pb, etc)

ingestion dose is about two orders of magnitude higher than inhalation



Relation
impact pathway analysis ↔ LCA

→ real impacts for each stage (site specific)

Goal: evaluate the entire matrix

Steps of impact pathway analysis → **Stage of fuel chain** ↓	Emission	Dispersion	Exposure-response function	Economic valuation
Fuel extraction				
Fuel transport				
Power plant				
Transmission of electricity				
Management of wastes				

Life cycle assessment: first sum over emissions ↓ Σ then → × multiplication by **"potential impact"** indices

Key Assumptions

Local + regional dispersion models

Linear dose-response functions for health (no threshold):

Mostly $PM_{2.5}$, PM_{10}, O_3

A few for SO_2 and CO

None for NO_2

Sulfates are treated like PM_{10}, Nitrates like $0.5 \times PM_{10}$

also As, Cd, Cr, Hg, Ni and Pb

Mortality in terms of LLE (loss of life expectancy) rather than number of deaths

Monetary valuation based on Willingness-to-pay (**WTP**) to avoid a loss:

Value of a Life Year (VOLY) due to air pollution = **50,000 €**

Cancers 2M€/cancer, based on VSL = 1 M€

(VSL = "Value of Statistical Life" = WTP to avoid risk of an anonymous premature death; *typical values used in EU and USA* ***1-5 M€)***

CO_2 of biological origin

IPCC and many practitioners of LCA do not count biogenic CO_2

⇒Absurd conclusions, e.g. the burning of tropical forests is no worse for global warming than their preservation,

No benefit from adding carbon capture to biofuel power plants,

etc

Correct method:

Count each source and each sink

when and where it occurs

Rabl A, Benoist A, Dron D, Peuportier B, Spadaro JV and Zoughaib A. 2007. "How to account for CO2 emissions from biomass in an LCA". Int J LCA 12 (5) 281.

Impacts and Technologies evaluated

Impacts

1) Global warming (CO_2, CH_4, N_2O)

2) NO_x, SO_2, PM etc (primary & secondary pollutants)

- **Health** (morbidity: ~ 30% of total cost
  mortality: ~65% of total cost, other than global warming)
- **Buildings & materials**
- **Agricultural crops**
- **Global warming**
- **acidification & eutrophication (biodiversity)**

3) Other burdens

- **Amenity** (noise, visual impact, recreation)
- **Accidents**
- **supply security**

Technologies

- **Energy:** coal, lignite, oil, gas, biomass, PV, wind, hydro, nuclear
- **Waste treatment:** landfill and incineration
- **Transport:** cars, trucks, bus, rail, ship, *(planes)*

Loss of Life Expectancy (LE) due to Air Pollution

In EU and USA typical concentrations of $PM_{2.5}$ around 20 - 30 $\mu g/m^3 \Rightarrow$ LE loss 8 months

Reasonable ***policy goal*** *during coming decades:*

reduction by about 50%

LE ***gain*** *about* ***4 months***

To put this in perspective with other public health risks:

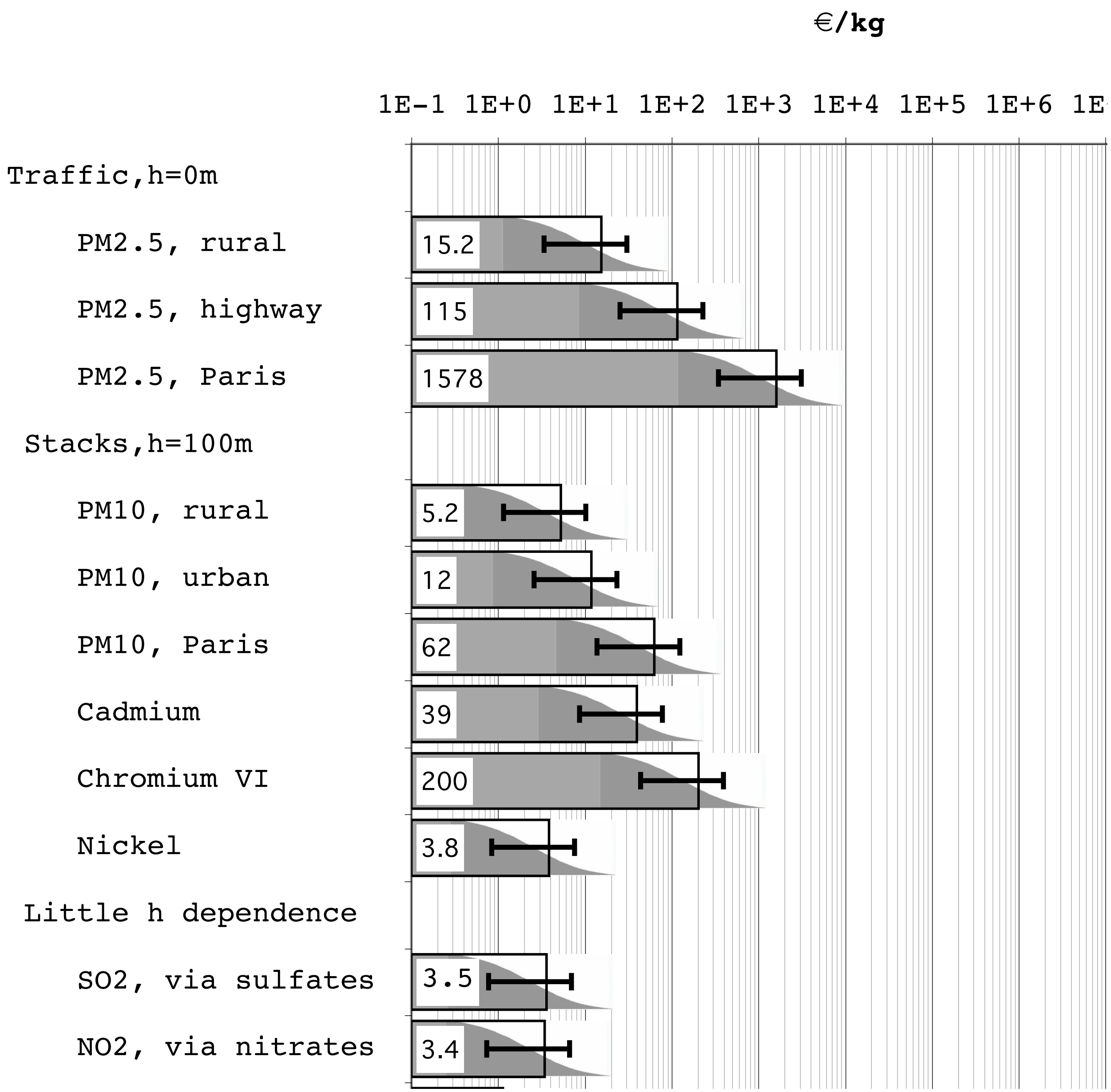
Smokers lose about 5 to 8 years on average

Rule of thumb:

each cigarette reduces LE by about the duration of the smoke

Air pollution (in EU and USA) equivalent to about 4 cigarettes/day

Damage Cost per kg of Pollutant,
(typical values for Central Europe)
and uncertainty (error bars and probability distribution)



Somewhat different numbers in different publications, but within uncertainty bounds *(progress in the science of impact assessment)*

Damage Cost of CO_2

Various estimates for $2xCO_2$
loss on the order of **1 to 2 % of gross world product**

Cost per ton CO_2
depends on **discount rate** and other controversial assumptions
especially **"value of life"** in developing countries (where most of the damage will occur)

For low discount rates mainstream estimates are around **10 €/t_{CO2}**
Report by Stern et al [2006]: ~ **85 €/t_{CO2}**
Study by Dept. of Envir. UK [2005]: ~25 €/t_{CO2}

Valuations by ExternE
ExternE 1998:
18-46 €/t_{CO2} ("restricted range", geometric mean 29 €/t_{CO2})
ExternE 2000: 2.4 €/t_{CO2}
ExternE 2004: **19 €/t_{CO2}**

Simplified Analysis: the Uniform World Model (UWM)

$$\mathbf{D_{uni} = p\ \rho\ s_{CR}/k = \text{damage cost €/kg}}$$

- p = unit cost (price) of endpoint
- ρ= average population density within 500 to 1000 km
- s_{CR} = slope of concentration-response function
- k = depletion velocity (wet+dry deposition, transformation or decay)

Also for secondary pollutants (if k includes transformation rate)

Exact for uniform distribution *of sources or of receptors*, by conservation of matter

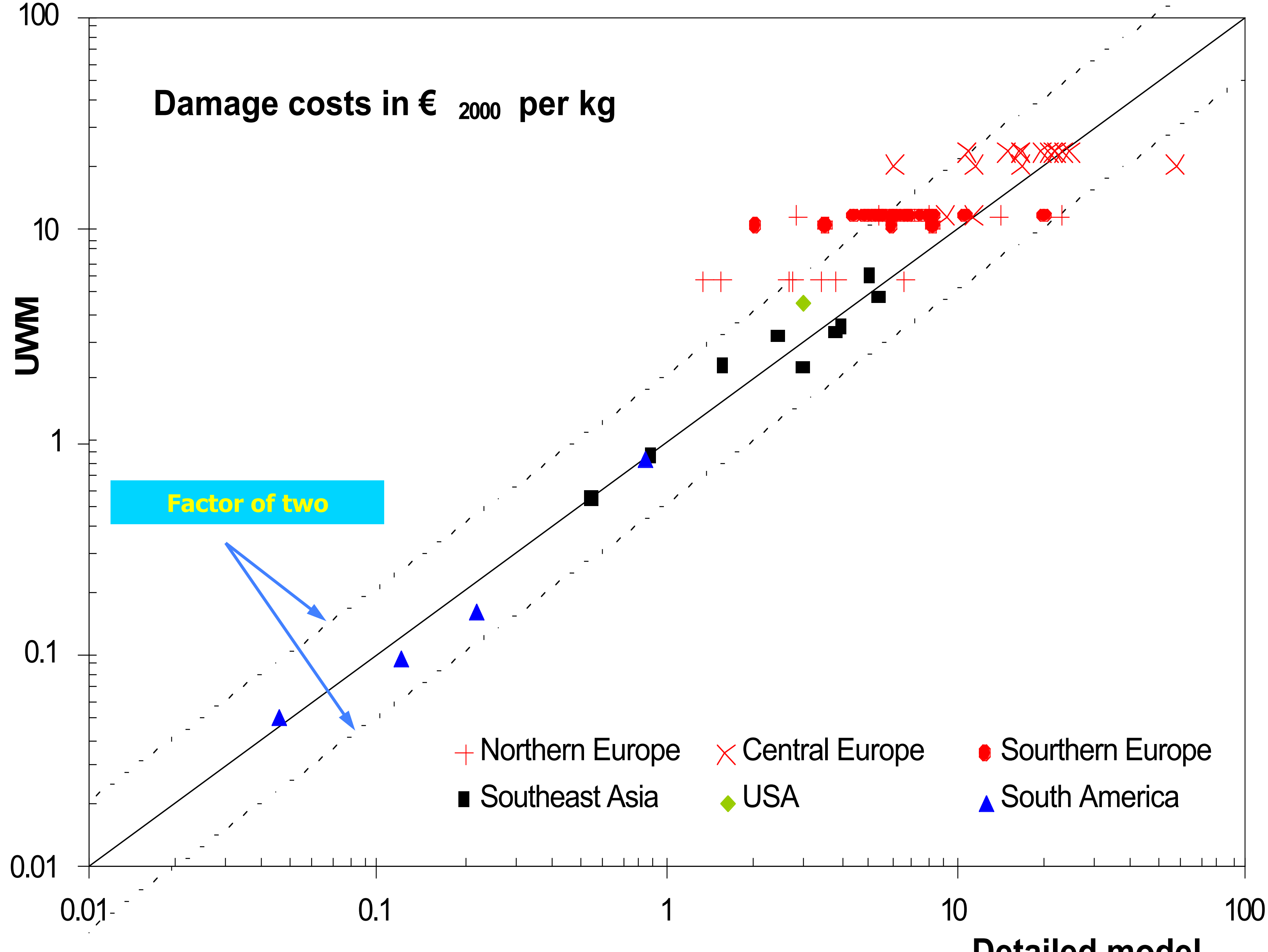
Good within a factor of about 2 for stacks height >50 m

Correction factors for site and stack height:

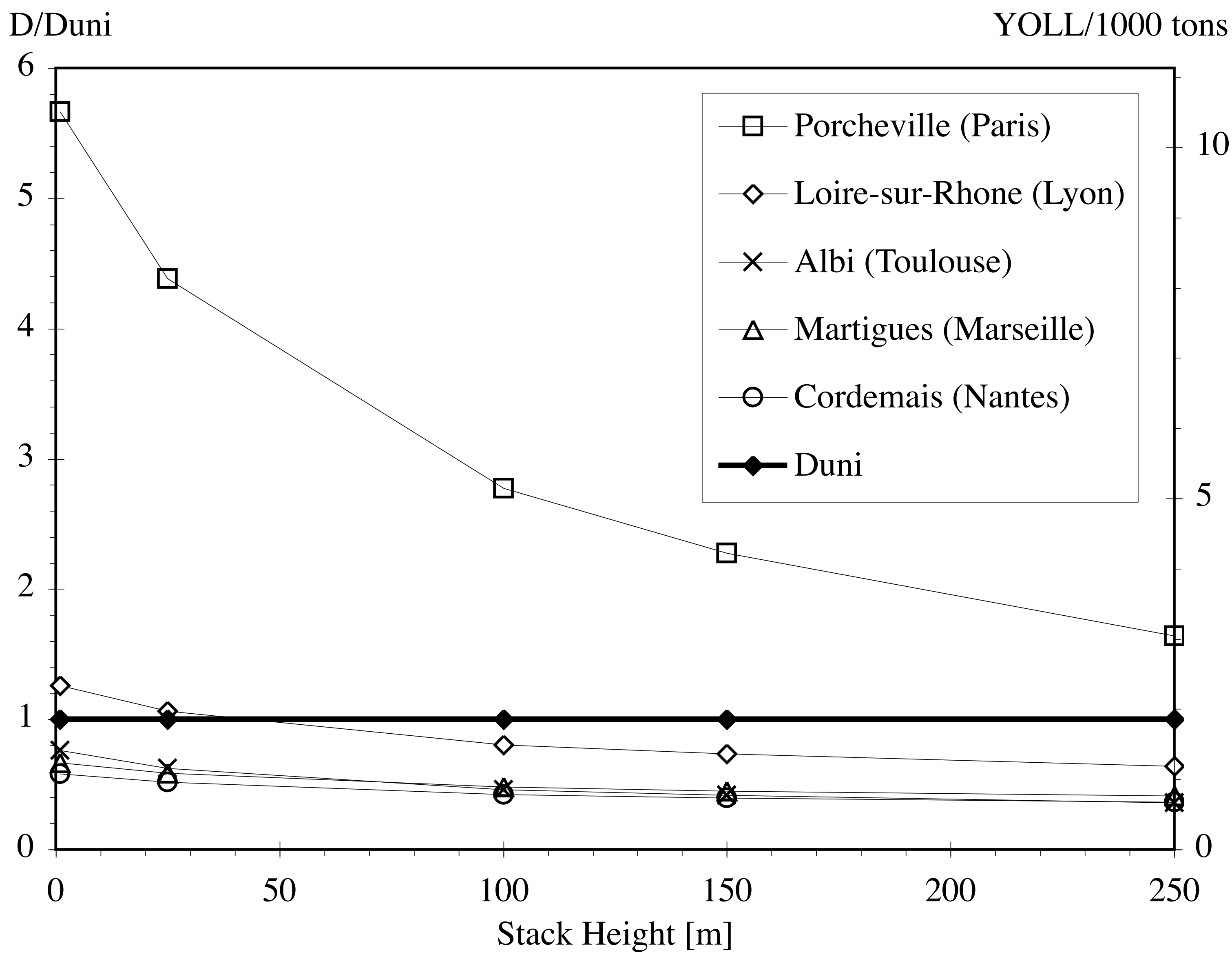
- no variation for globally dispersing pollutants such as CO_2;
- weak variation for As, Pb and dioxins because non-inhalation pathways dominate: ≈0.7 to 1.5;
- weak variation for secondary pollutants: ≈0.5 to 2.0;
- strong variation for primary pollutants: ≈0.5 to 5 for site, ≈0.6 to 3 for stack conditions (up to 15 for ground level emissions in big city).

UWM and more detailed simple models included in **RiskPoll software** [free from www.arirabl.org]. Use **EcoSense** for "exact"

Comparison UWM ↔ detailed model. World



Site Dependence: Comparison UWM ↔ detailed model



For SO_2.

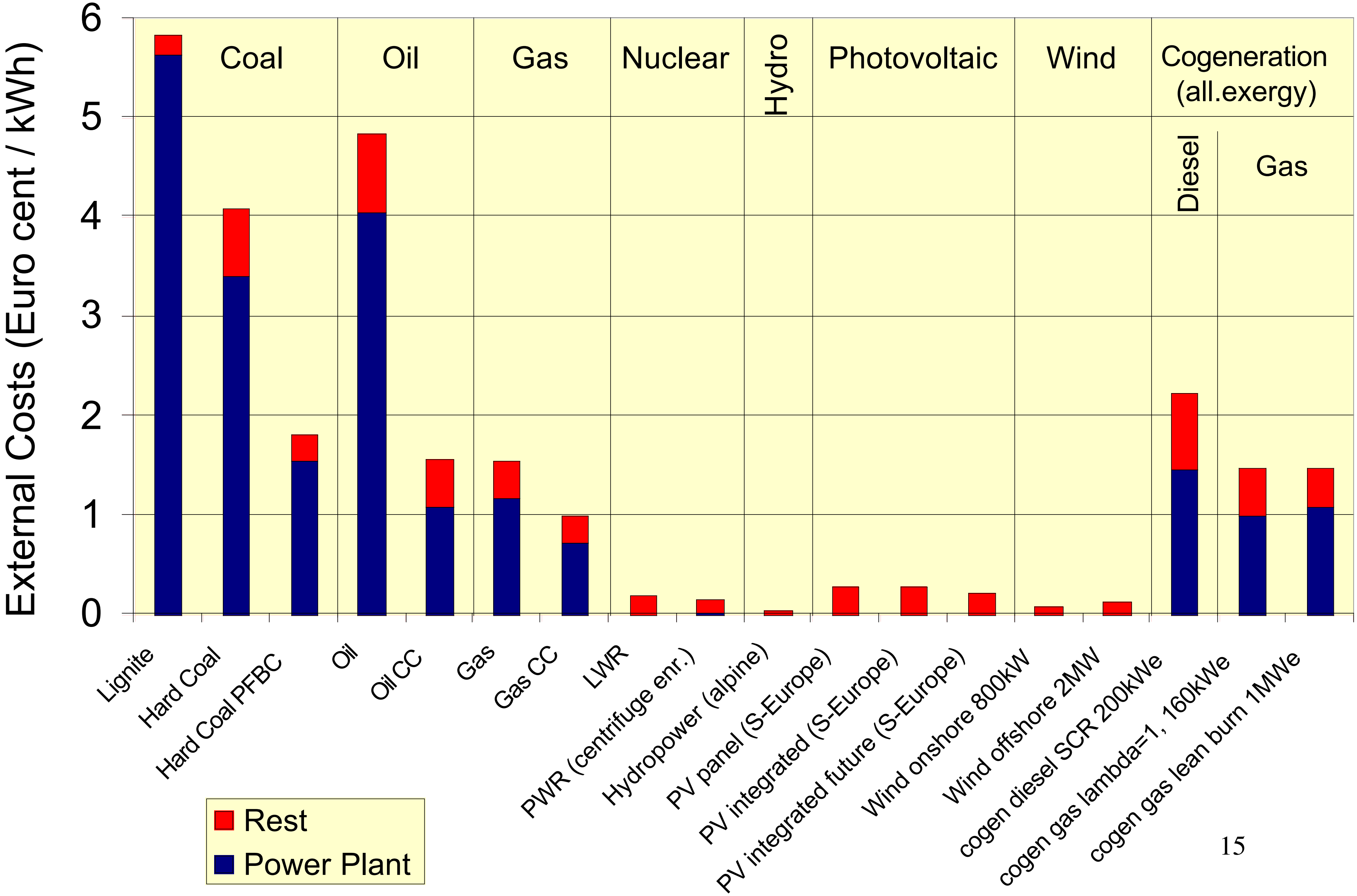
YOLL = years of life lost

Results for Power Plants

Typical numbers for Central Europe [ExternE 2004]. Average price France ~7cents/kWh

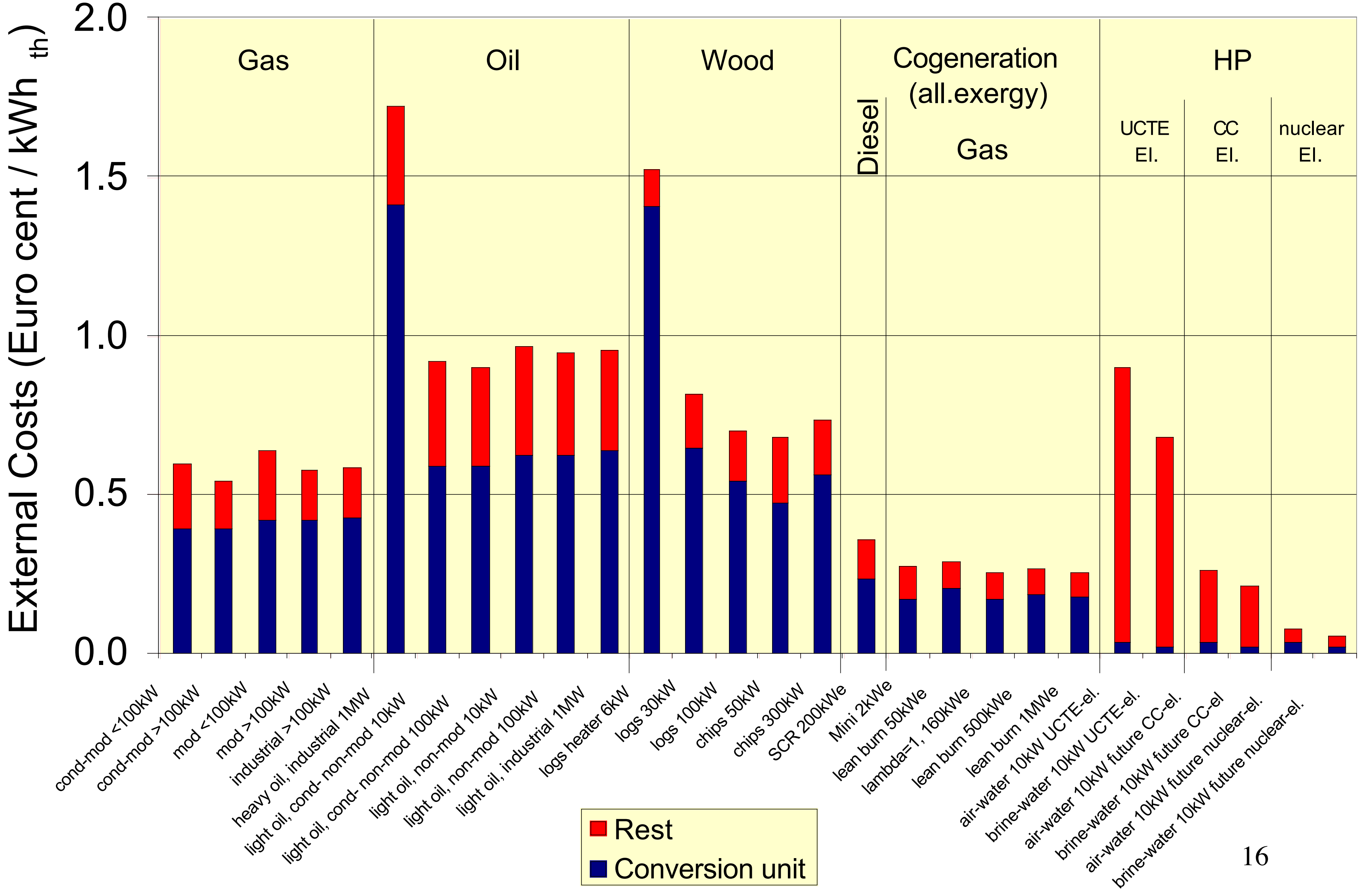
Results for Electricity

*Damage costs of current and advanced systems, **power plant + rest of energy chain***



Results for Heating Systems

Damage costs of current and advanced systems, ***boiler + rest of energy chain***



comparison Incineration ↔ Landfill
Variation with energy recovery assumptions

For energy recovery: E=electricity, H=heat, g=gas, o=oil, c=coal

Private cost
Landfill
~50€/t$_{waste}$

Cf: private cost ~50€/t

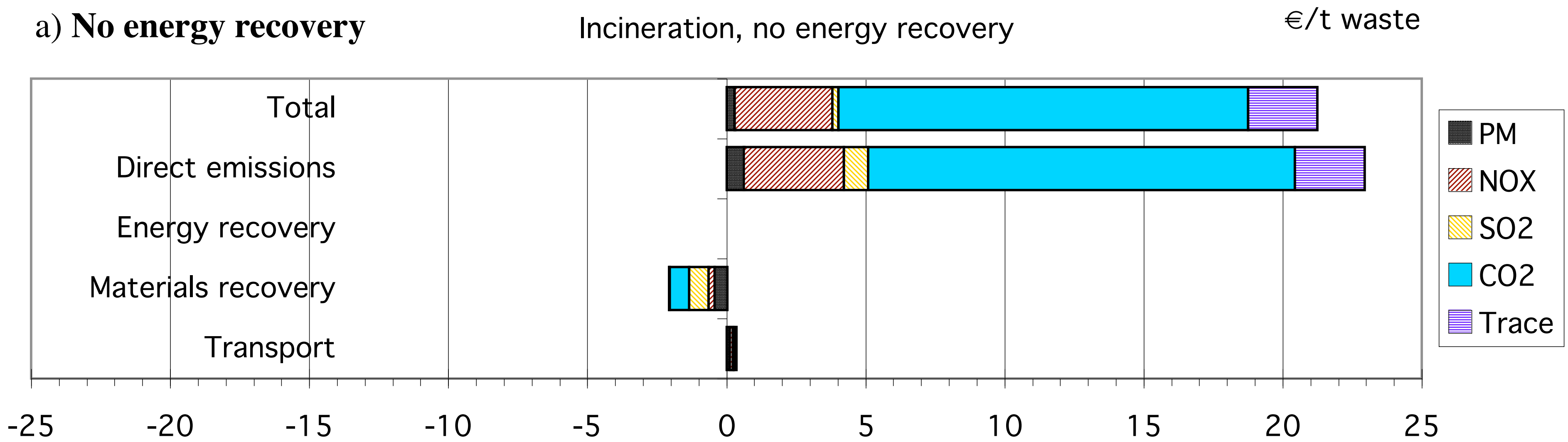
Private cost
incinerator
~100€/t$_{waste}$

But costs are not the only criterion!

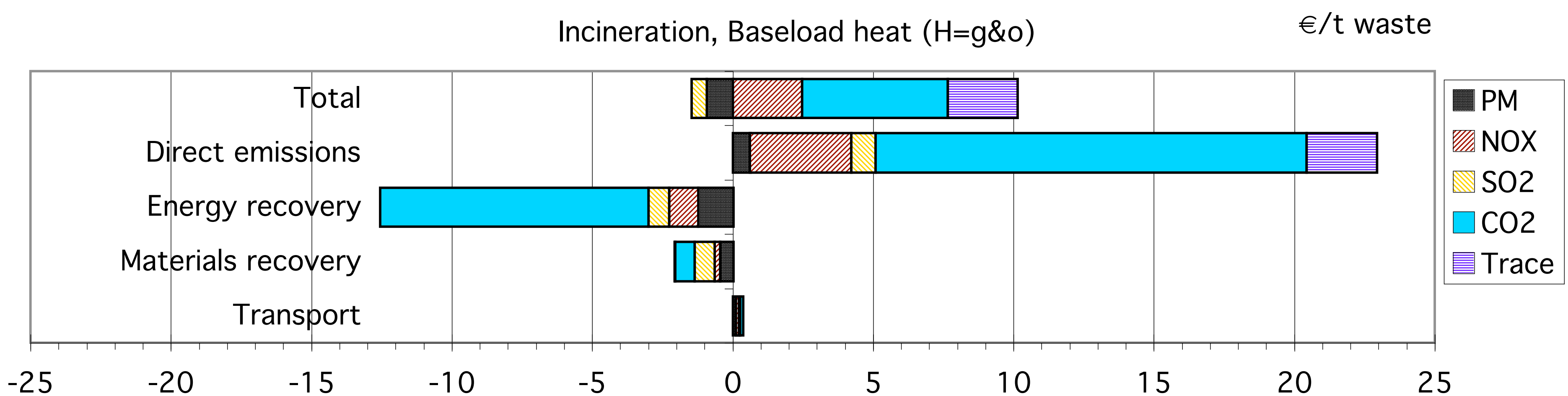
Incineration, some detailed results

- If electricity displaces nuclear (France), like no energy recovery.
- Transport based on hypothetical 100 km.

a) **No energy recovery**



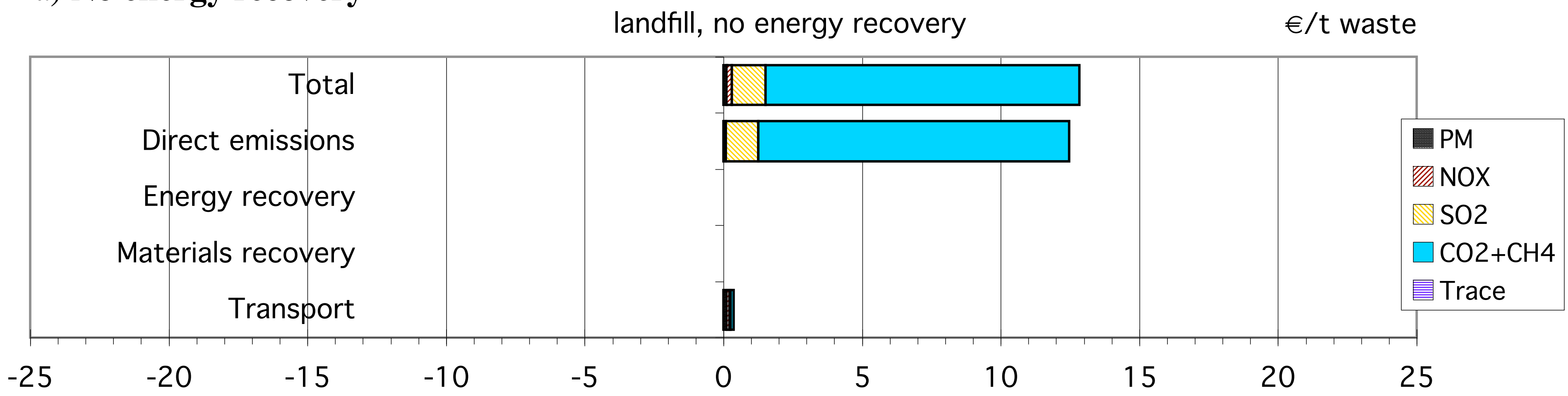
b) **Energy recovery to replace gas and oil**



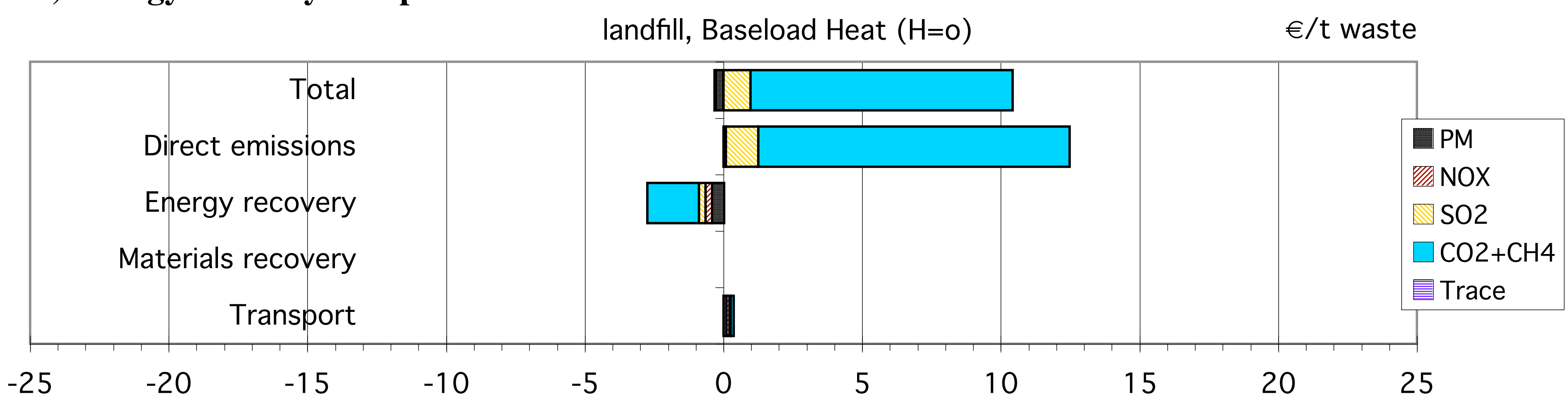
Landfill, some detailed results

- If electricity displaces nuclear (France), like no energy recovery.
- Transport based on hypothetical 100 km.

a) **No energy recovery**



b) **Energy recovery to replace oil**



Electric vehicle (EV)

Funk K & A Rabl 1999. "Electric versus conventional vehicles: Social Costs and Benefits in France". Transportation Research Part D: Transport and Environment, Vol.4(6), 397-411.

Paris = most favorable site for EV because large city (10 million with suburbs) and nuclear electricity

Compare 3 versions of Peugeot 106 (gasoline, diesel and electric),

LCA, including production of vehicle and battery (NiCd)

Assume utilization 25 km/day gasoline, 45 km/day diesel, for 10 yr.

Compare €/km (life cycle cost)

for individual (**private cost**, including taxes but excluding pollution) and

for society (**social cost**, excluding taxes but including pollution)

EV not justified by environmental benefit,

unless battery cost and performance improve

remains valid with new results of ExternE and lower emissions of new vehicles:

diesel with particle filter has very low damage cost

Hybrid vehicle, €/km in USA

Recent study for Toyota, by A. Rabl & J.V. Spadaro [2004]

Compare Toyota Camry, Corolla, RAV4 and Prius, and Honda Civic and Insight, all models of 2004

Hybrid versions: Prius and Insight (only hybrid), RAV4, Civic

LCA inventories based on studies by MIT and by Delucchi of UC Davis

For **well-to-wheel** analysis use **GREET model** of Argonne National Lab

LCA stages:

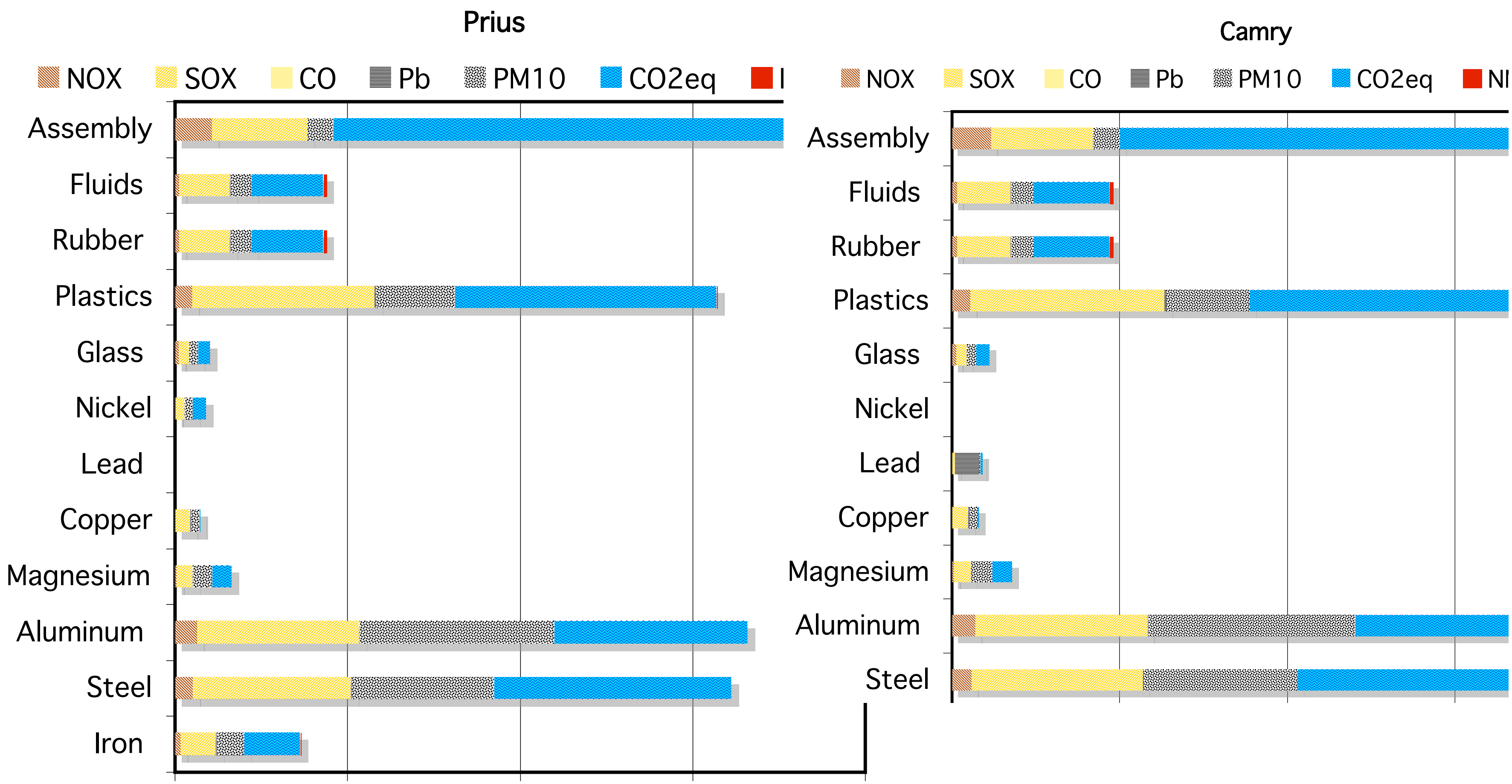
- Production of the materials needed for the vehicle
- Assembly of the materials
- Fuel feedstock
- Fuel supply
- Utilization of the vehicle
- Disposal of the vehicle at the end of its life

  (the only significant impacts of disposal are included by accounting for recycling in the production of the materials)

Damage costs of ExternE [2004] but adjusted for lower population density in USA

Hybrid vehicle, vehicle production $/car

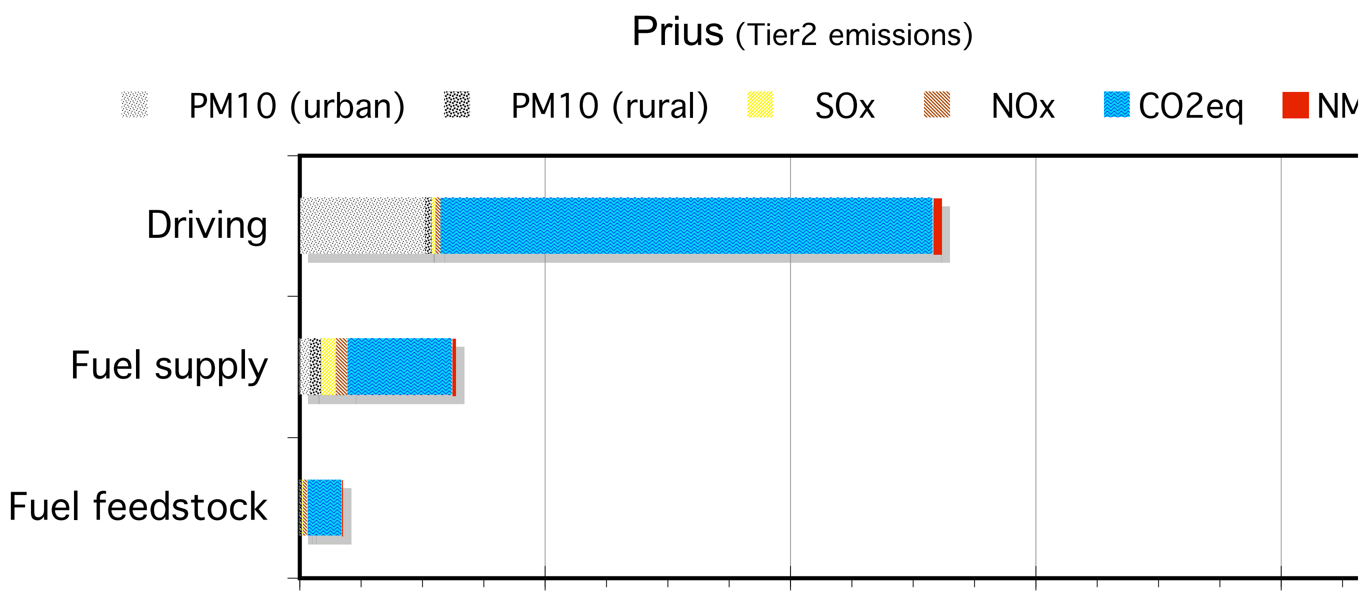
Comparison hybrid and conventional cars

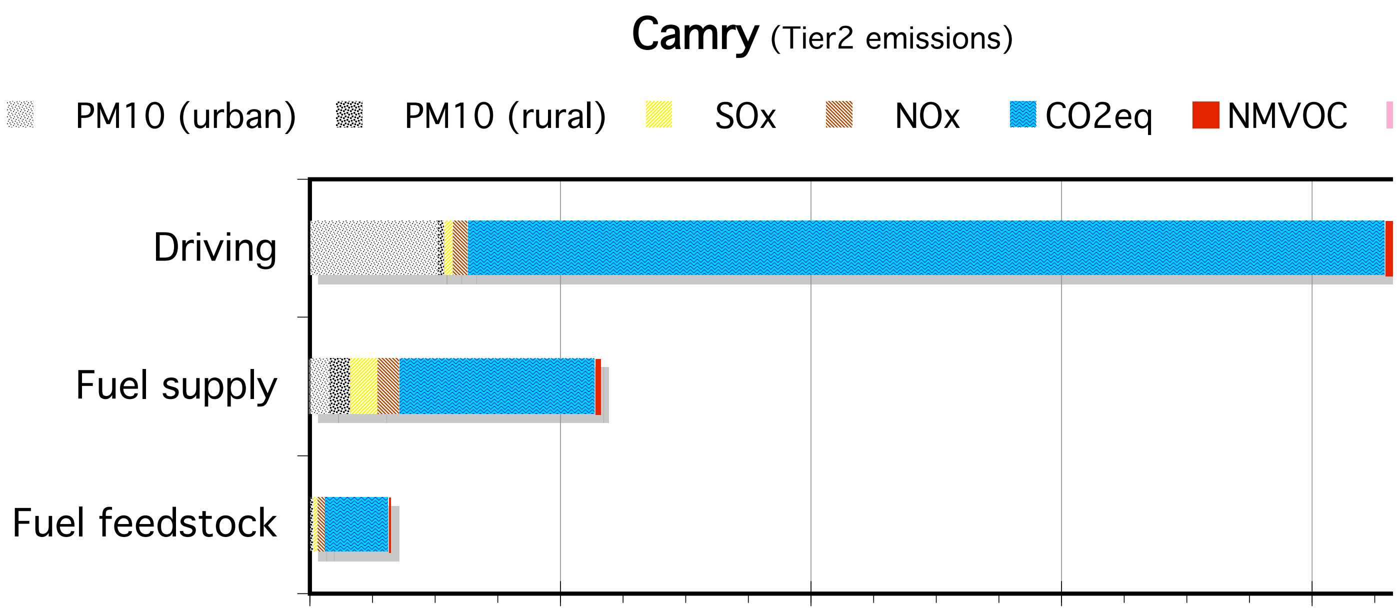


Total about $180/car, no significant difference hybrid ↔ conventional

Hybrid vehicle, well-to-wheel ¢/mile

Comparison hybrid and conventional cars

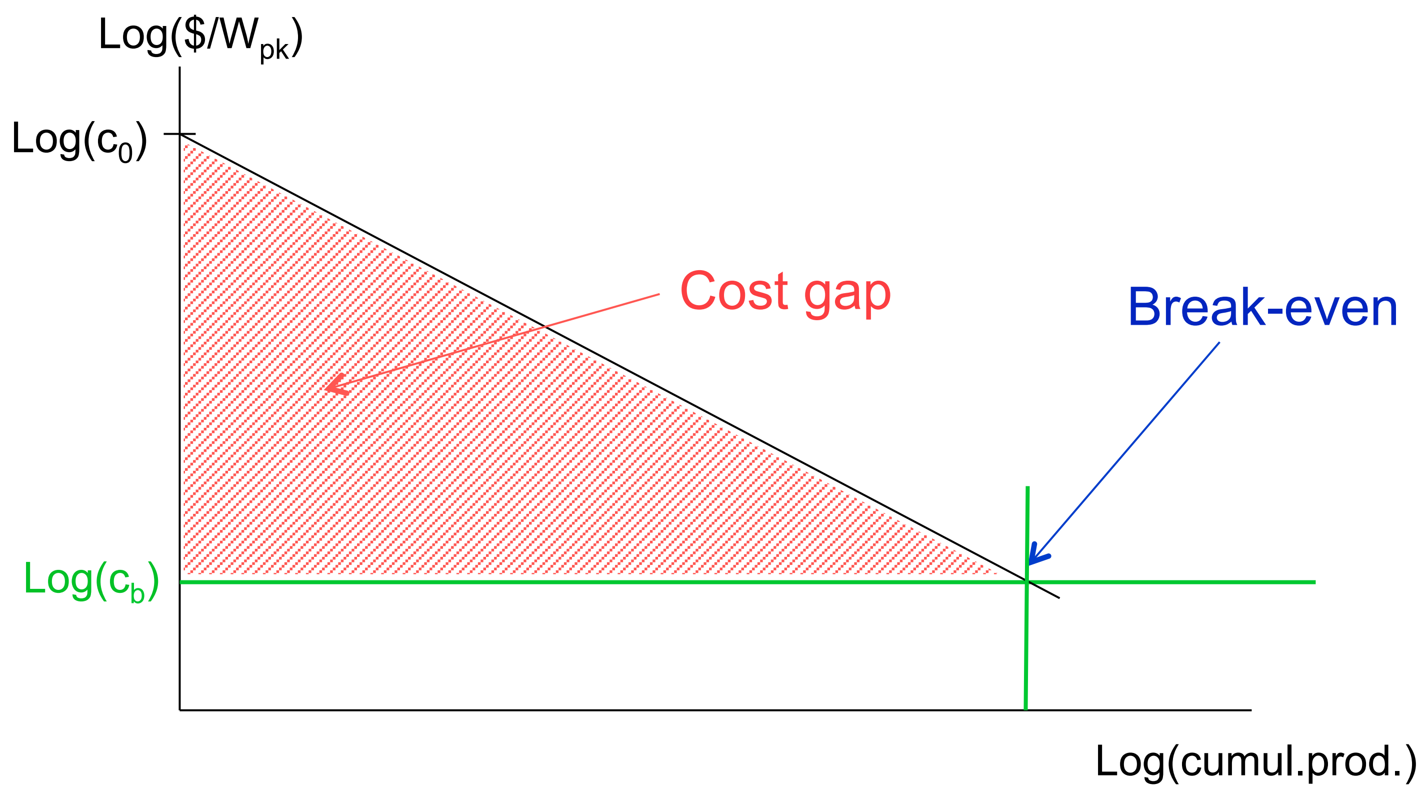




Can Avoided Damage Justify Cost of Developing PV?

Cost required to reach break-even (where PV becomes competitive) and **cost gap** (**=cost of reaching break-even - production cost at break-even**), as function of **progress ratio** (***learning curve***).

Assumptions: current cumulative production n_0 = 1 GW_p, current unit cost c_0 = 5 $/$W_p$, break-even unit cost c_b = 1.0 $/$W_p$.



Ref.: "Prospects for PV: a learning curve analysis". B van der Zwaan & A Rabl, Solar Energy, Vol. 74(1), 19-31 (2003).

Can Avoided Damage Justify Cost of Developing PV?, cont' d

cost gap (**=cost of reaching break-even - production cost at break-even**),
as function of **progress ratio** (***learning curve***) and **avoided damage**.

Assumptions: current cumulative production $n_0 = 1$ GW$_p$, current unit cost $c_0 = 5$ \$/W$_p$, break-even unit cost $c_b = 1.0$ \$/W$_p$.

Only costs up to break-even are included
Real benefits much larger because they continue after break-even

Progress ratio, pr	0.7	0.75	**0.8**	0.85	0.9
Break-even cumulative production, n_b (GW$_p$)	23	48	**148**	957	39700
Break-even cumulative production, as % of 3300 GW, the present world capacity	0.7%	1.5%	**4.5%**	29.0%	1200%
Cost of reaching break-even, C_b (\$ billion)	37	74	**211**	1240	46800
Cost of producing $n_b – n_0$, if unit cost were already at break-even, $(n_b–n_0)\ c_b$ (\$ billion)	22	47	**147**	956	39700
Cost gap, C_b - $(n_b–n_0)\ c_b$ (\$ billion)	15	27	**64**	288	7110
Cost gap (% of cost of reaching break-even)	41%	36%	**30%**	23%	15%
Avoided damage of $n_b–n_0$ (at 0.25 \$/W$_p$, in \$ billion)	5	12	**37**	239	9920
Avoided damage (% of cost gap)	37%	44%	**58%**	83%	140%

Even the benefits up to break-even pay for much/most of the cost gap

Conclusions

Damage costs are significant, especially for fossil fuels

Due to **PM, NO_x, SO_2 & O_3,** and **global warming**

Applications

Energy policy: e.g. nuclear, gas or coal? Subsidies for renewables?

Transport policy: e.g. how large is benefit of reducing traffic in cities?

Waste treatment: incineration or land fill?

How much recycling of what?

Regulations: optimal emission limits for power plants, vehicles, factories, agriculture, …

Optimal level of **pollution taxes**

Optimal level of **tradable permits**

Significant premium for clean energy!