

Sustainable Energy Transformation Technologies, SH2706

Lecture No 21

Title:

Principles of Life-Cycle and Economic Assessment for ETS

Henryk Anglart

Nuclear Engineering Division

Department of Physics, School of Engineering Sciences

KTH

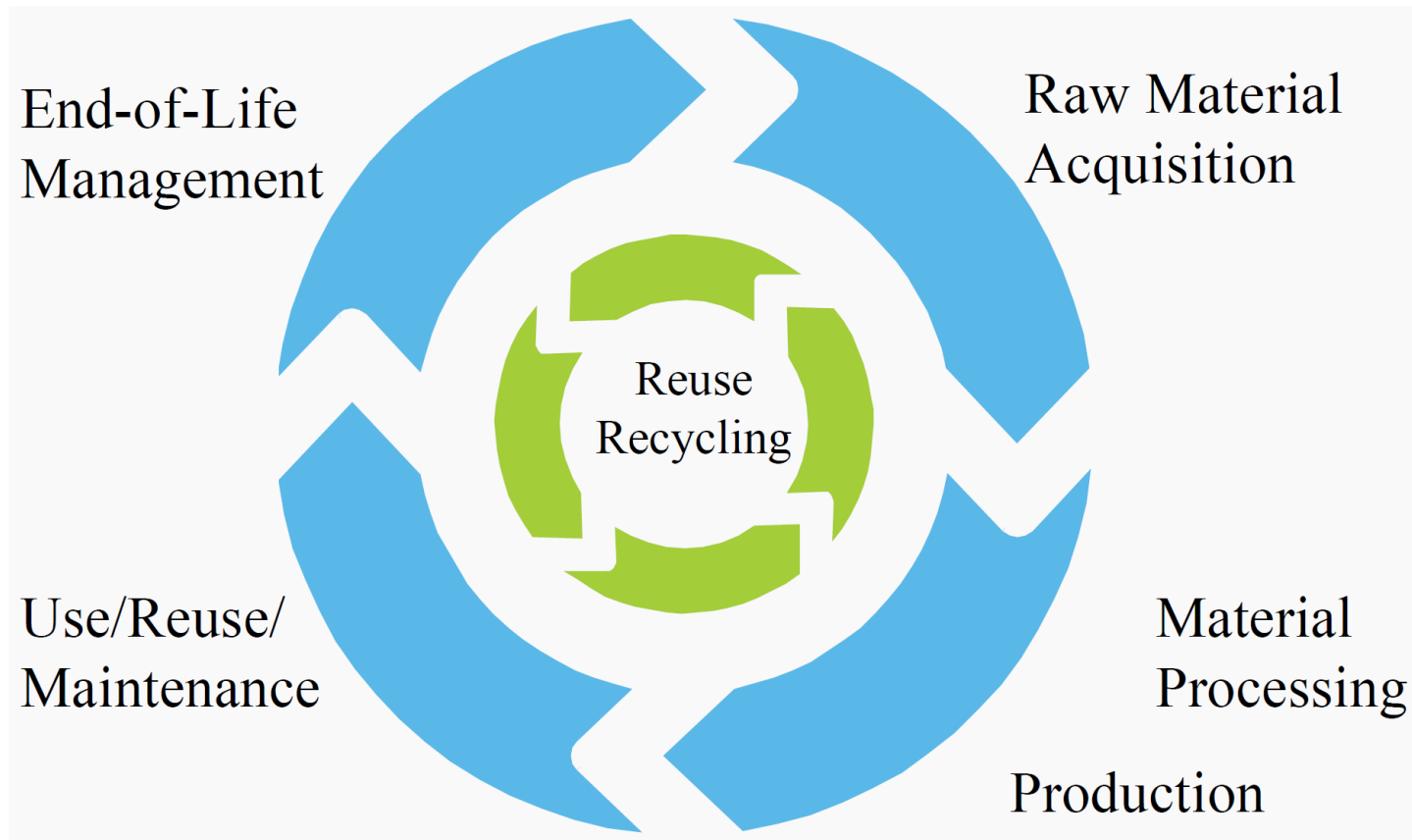
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Life-Cycle Assessment - Outline

- Brief description of life cycle assessment (LCA) methodology
- International standard ISO-14040
- Life cycle impact assessment
- Results of LCA application to energy transformation systems
- Case study – power density and land use

Life Cycle Assessment

LCA is an industrial environmental management approach to look holistically at products, processes and activities



Life Cycle Assessment

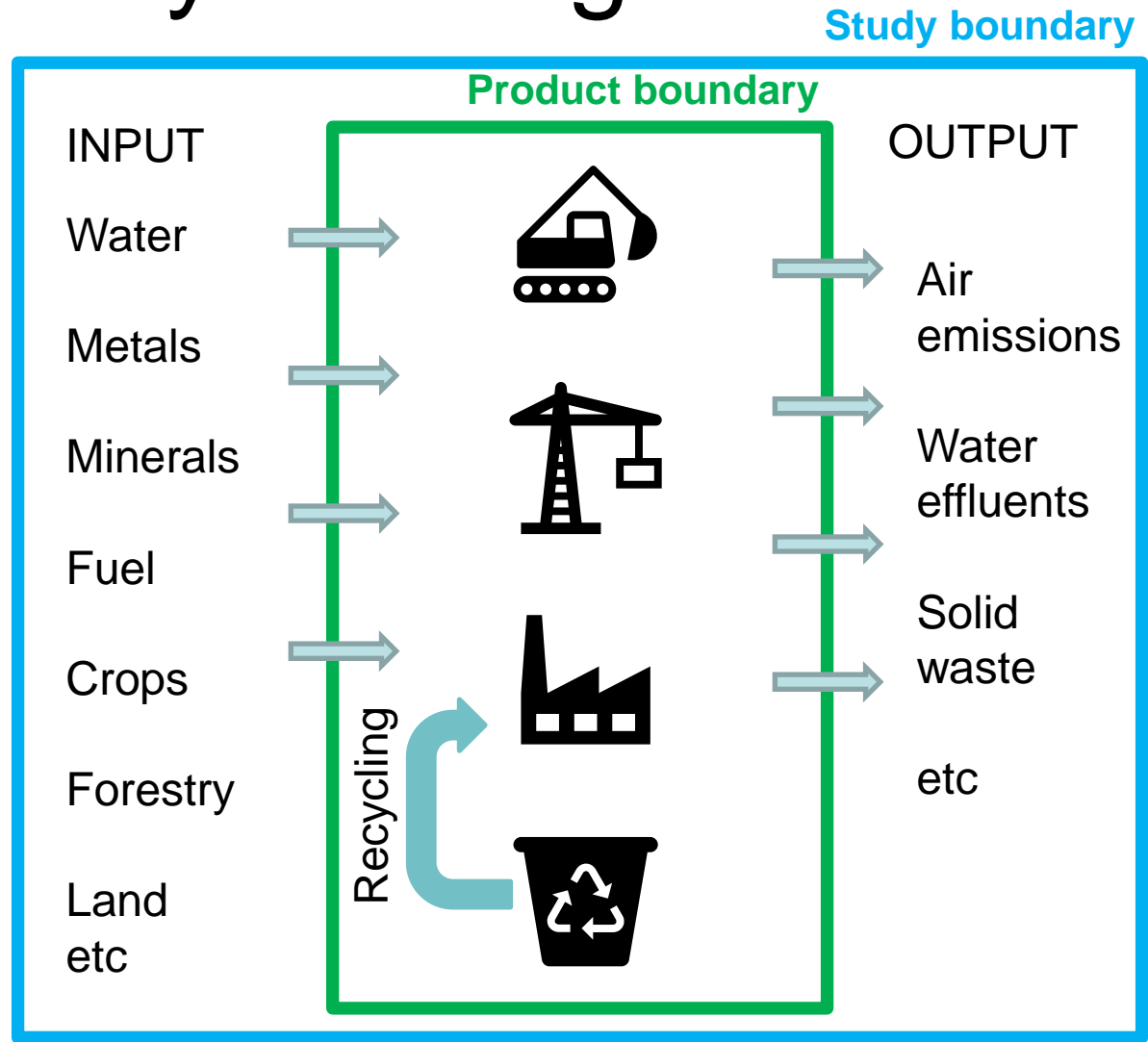
- LCA is also known as **life-cycle analysis** or **cradle-to-grave analysis**
- LCA can help to optimize a process including its interaction with the environment
- In particular it can provide
 - identification of energy and material inputs and environmental releases
 - evaluation of potential impacts associated with identified inputs and releases
 - interpretation of the results to help making a more informed decision

Goals and Purposes of LCA

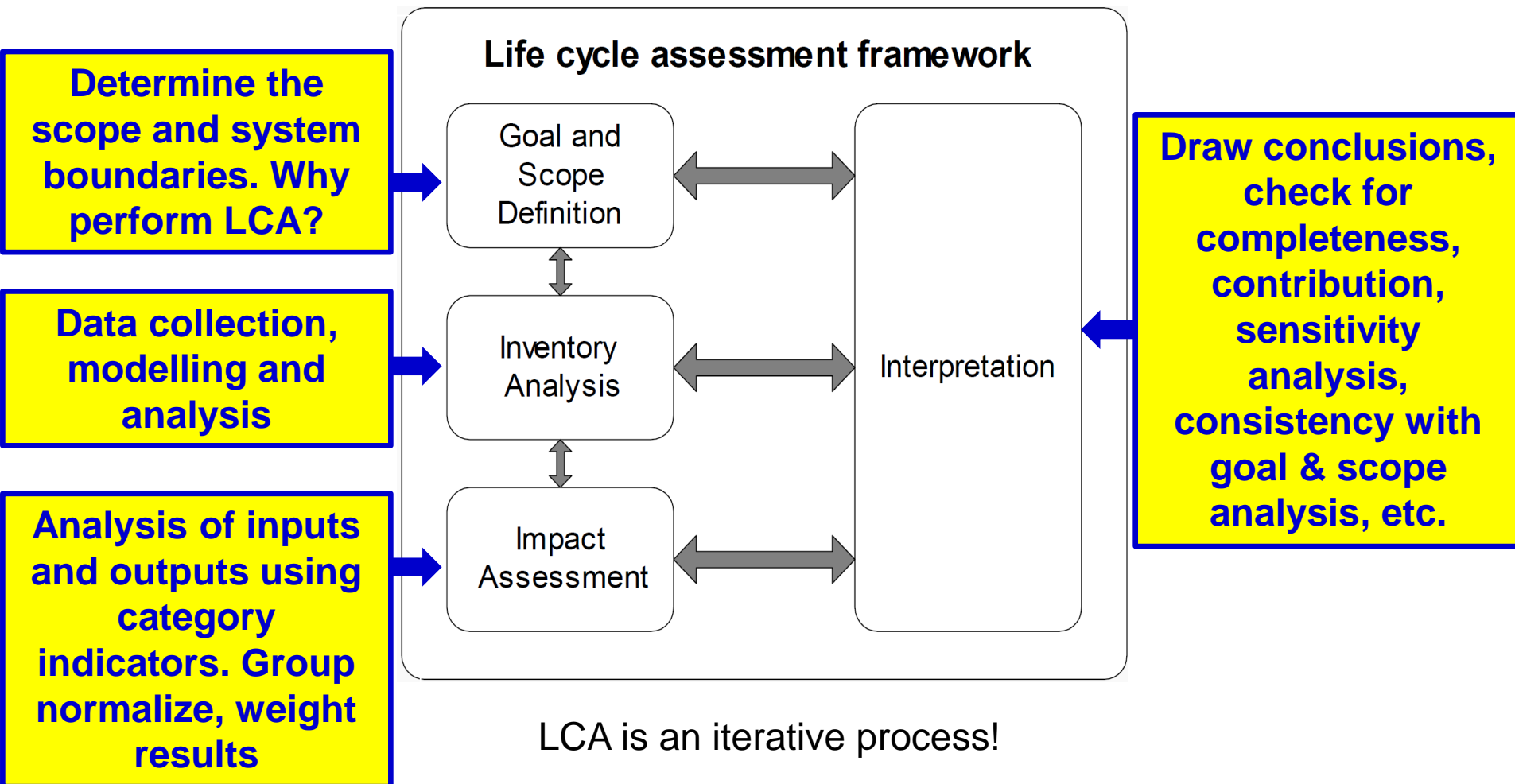
- To compare the full range of environmental effects assignable to products and services
 - identifying inputs and outputs of material flows
 - assessing how these materials affect the environment
 - using this information to improve processes, support policy and decisions
- Term **life-cycle** means a **holistic** assessment, including:
 - raw-material production
 - manufacture and distribution
 - use
 - disposal

Life Cycle Stages

- Raw material acquisition
- Material processing
- Production
- Use and Maintenance
- End-of-life



ISO 14040/14044



LCA of Electricity Generation Technologies

- A comprehensive LCA of electricity generation technologies was performed by R. Turconi *et al.* (2013):
 - “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renewable and Sustainable Energy Reviews* 28 (2013) 555-565
 - The full paper is provided in Canvas
 - In what follows, main results of the study are cited.

LCA case studies included

- The cited work of Turconi et al. is a review which is covering 33 LCA publications including 167 case studies of all main electricity generation technologies, representing 98% of electricity in 2008
- The following technologies are included:
 - hard coal
 - lignite
 - natural gas
 - oil
 - nuclear power
 - hydropower
 - solar PV, wind and biomass

Objective and Scope

- The objective of the study was to provide a systematic overview of important emissions from electricity generation technology based on a critical review of relevant LCA studies in the literature
- Emission factors for GHG, NO_x and SO₂ were selected as key indicators for environmental performance during electricity generation
- These emissions were evaluated by:
 - highlighting important technological differences
 - identifying critical methodological choices between studies
 - providing examples illustrating quantitative importance of the above aspects

LCA Methodological Framework

- The current regulatory framework for LCA is defined by ISO 14040 and ISO 14044
- LCA is carried out by iteration of four phases:
 - (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, (4) interpretation
- Current ISO standards provide guidelines, but allow freedom for interpretation key methodological issues
- Consequently, subjective choices may lead to results incompatible with other studies with identical scope

Data Acquisition Approaches

- Data acquisition itself might significantly affect the results
- Two approaches are used:
 - process chain analysis (PCA), which is a bottom-up approach that uses engineering data and process-specific information preferably obtained directly from the plants
 - this is time consuming but more precise, if no cut-offs are applied
 - input-output analysis (IOA), which is a top-down approach based on monetary data for individual economic sector
 - IOA provides results that are less case-dependent and less precise as compared to PCA
- In general IOA estimates larger impacts than PCA because system boundaries are extended and no process cut-offs are applied

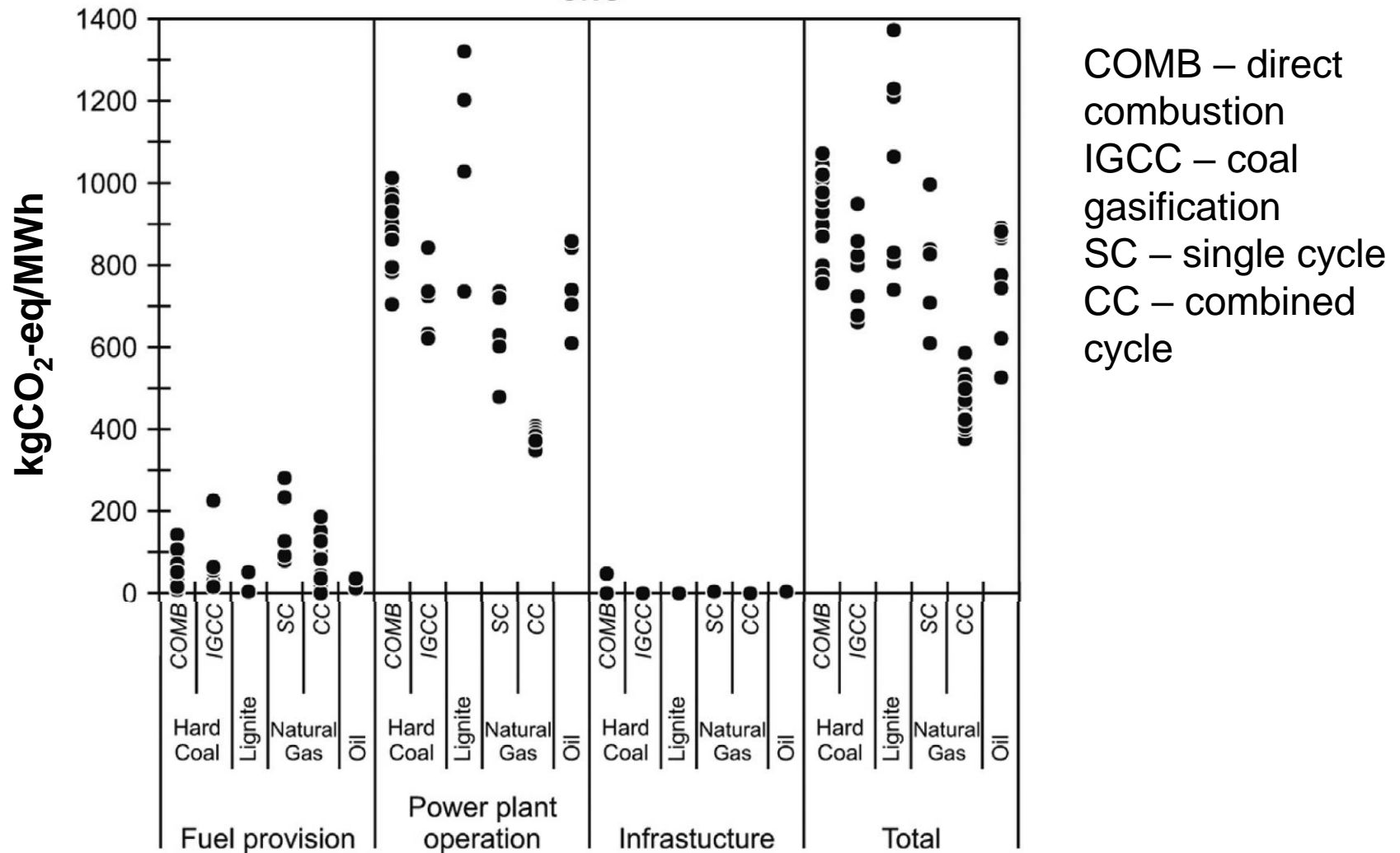
Emissions Included

- Emissions of GHG, NO_x and SO₂ were selected based on their importance
 - energy sector contributes with 19% of NO_x, 56% of SO₂ and 40% of GHG emissions
 - NO_x and SO₂ (along with NH₃) are responsible for acidification
 - NO_x (along with NH₃) is responsible for eutrophication
- NH₃ is primarily emitted from animal waste in agriculture, NO_x and SO₂ emissions provide a reasonable approximation for contributions to acidification and eutrophication

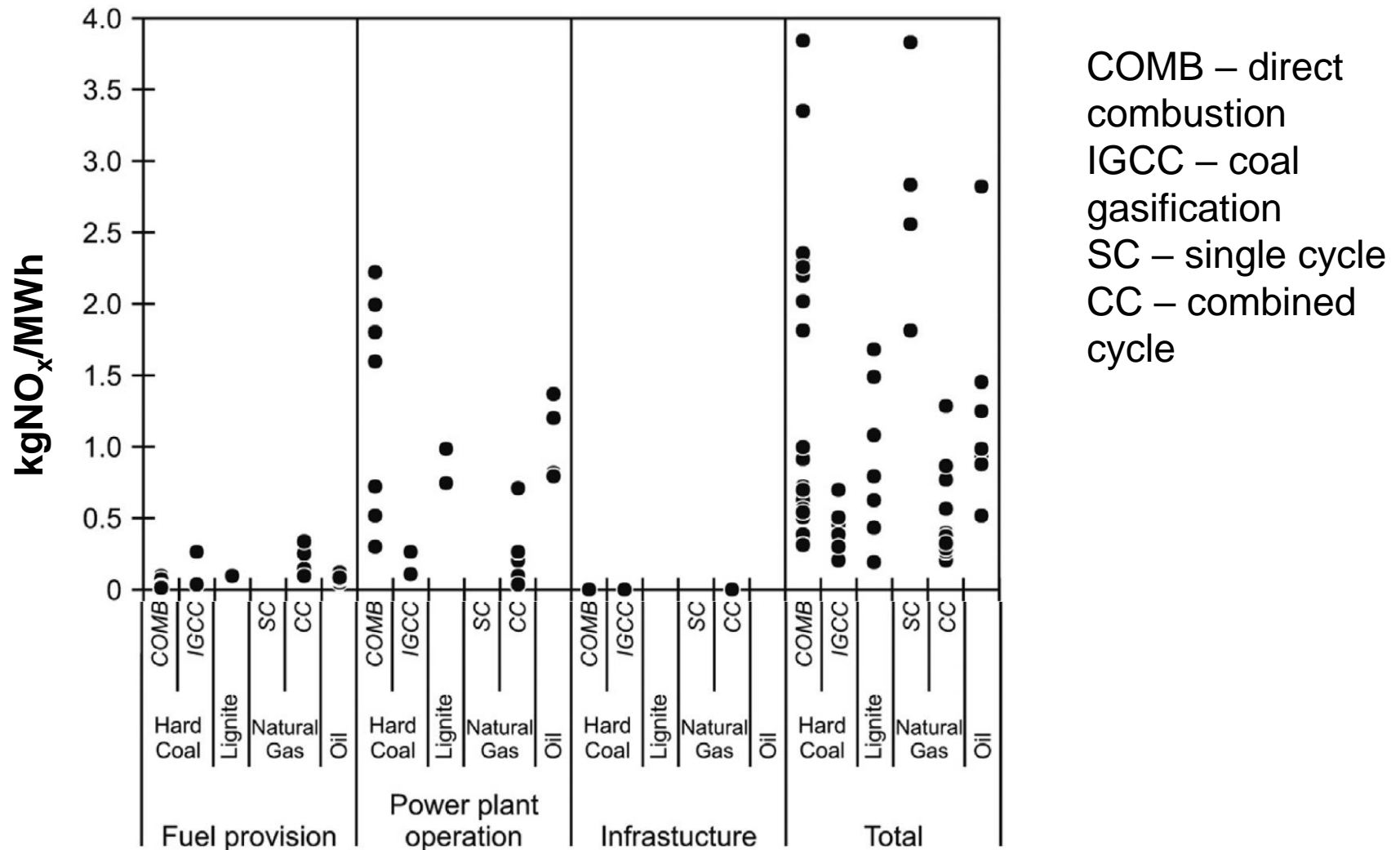
Presented Results of the Study

- The results are presented by energy technology
- For each technology, GHG (labelled CO₂-eq), NO_x and SO₂ emissions were evaluated for the following three life cycle phases:
 - fuel provision (from the extraction of the fuel to the gate of the plant)
 - plant operation (operation and maintenance, including residue disposal)
 - infrastructure (commissioning and decommissioning)

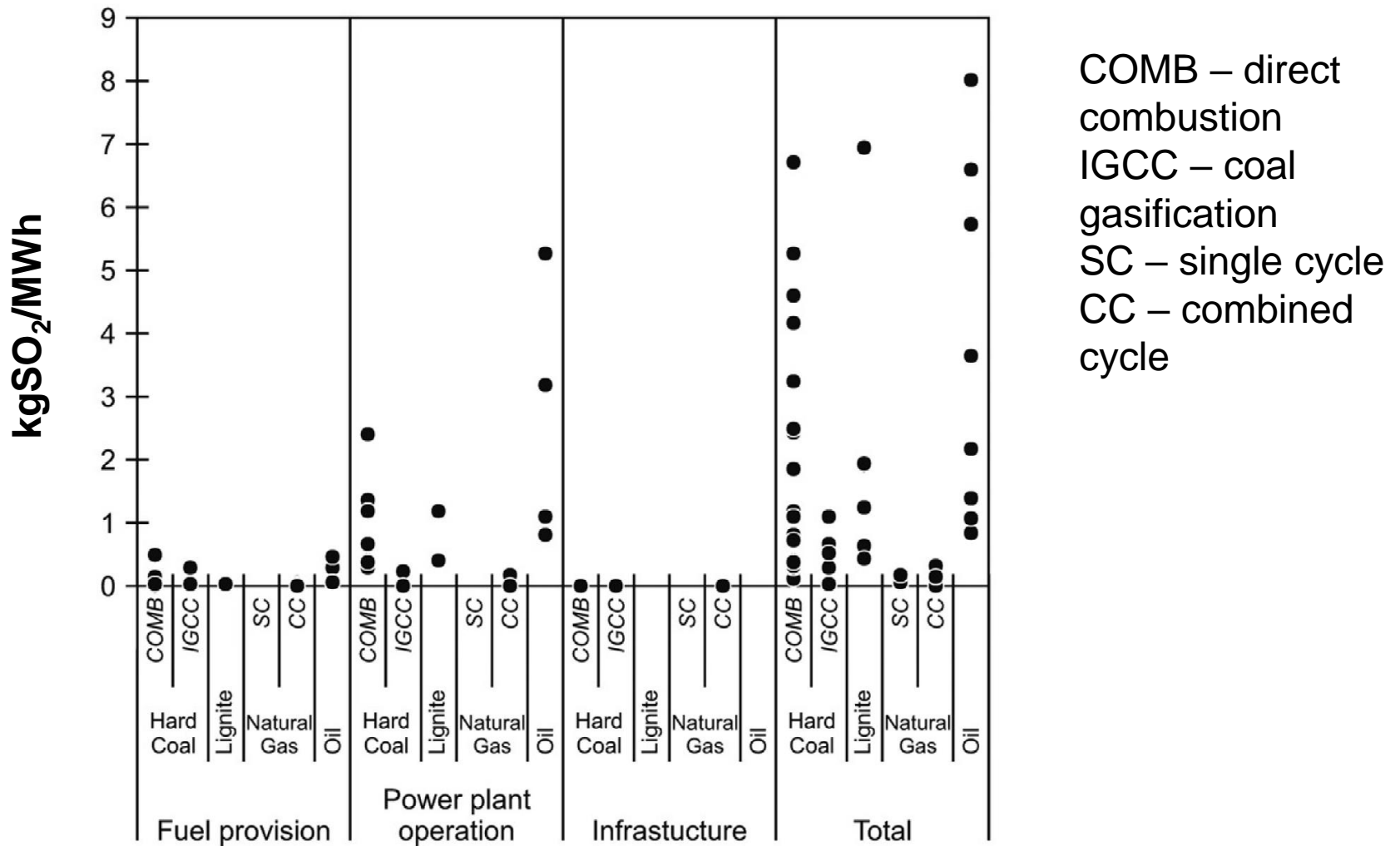
GHG Emissions from Fossil Fuels



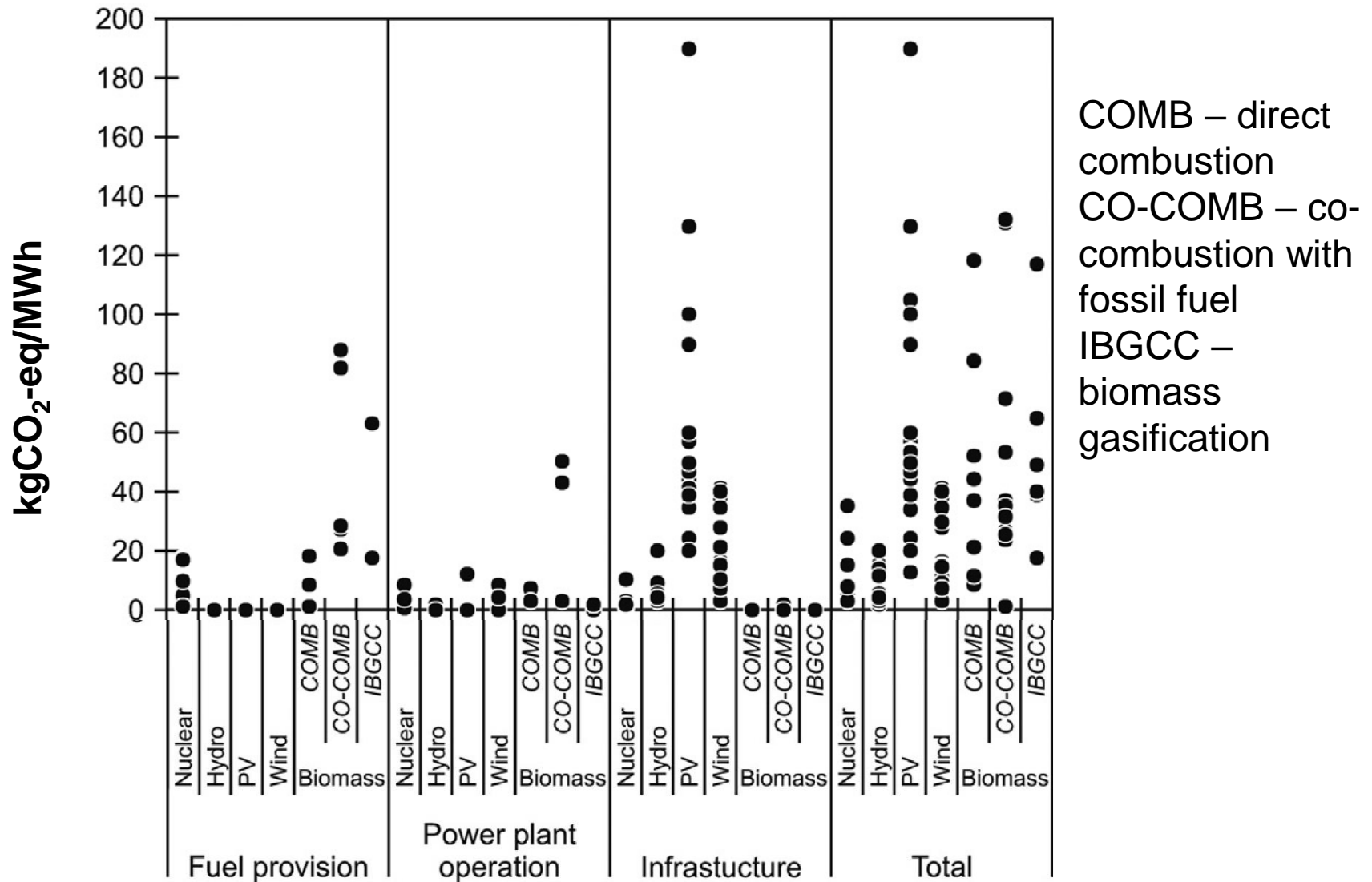
NO_x Emissions from Fossil Fuels



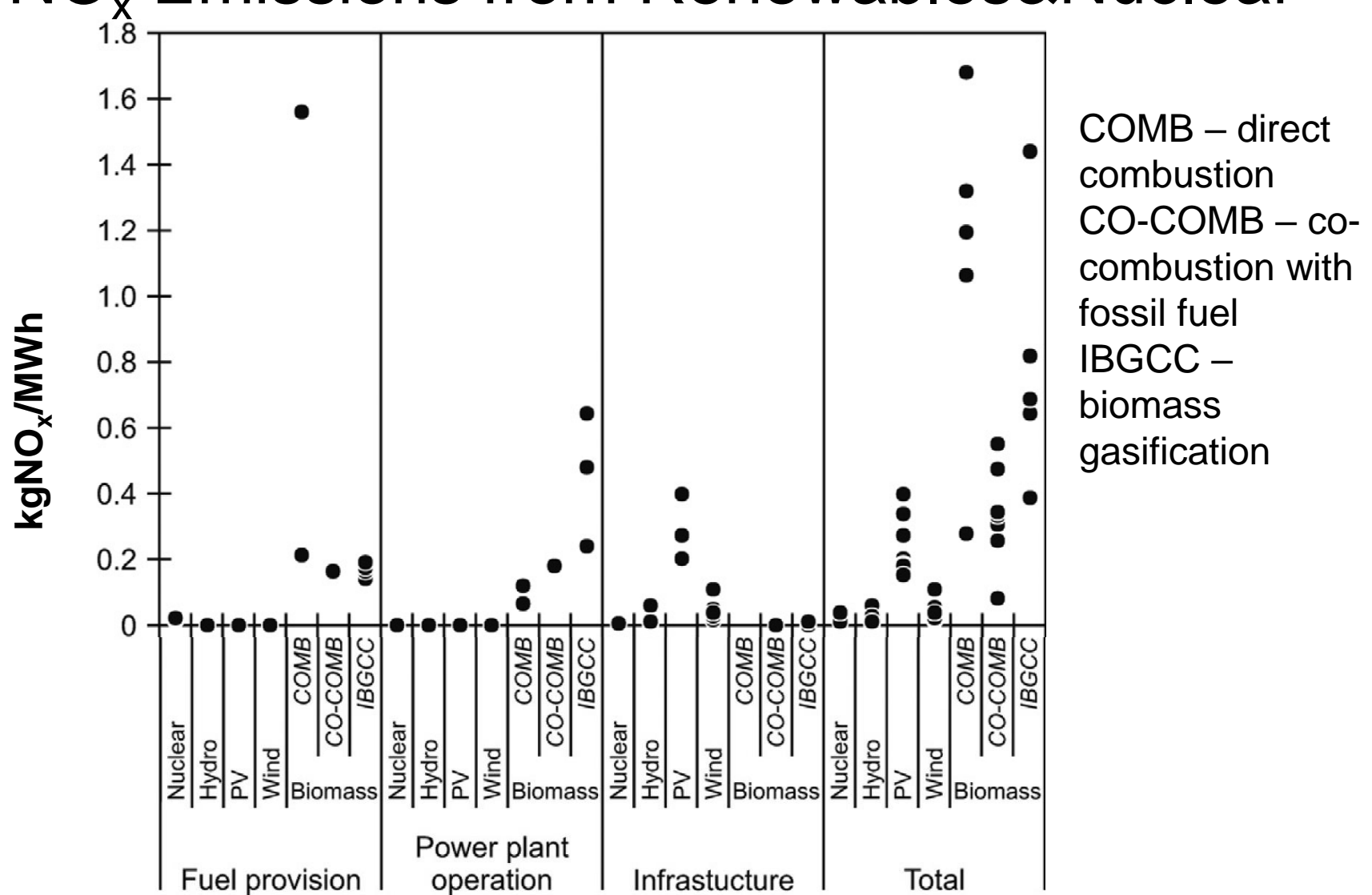
SO₂ Emissions from Fossil Fuels



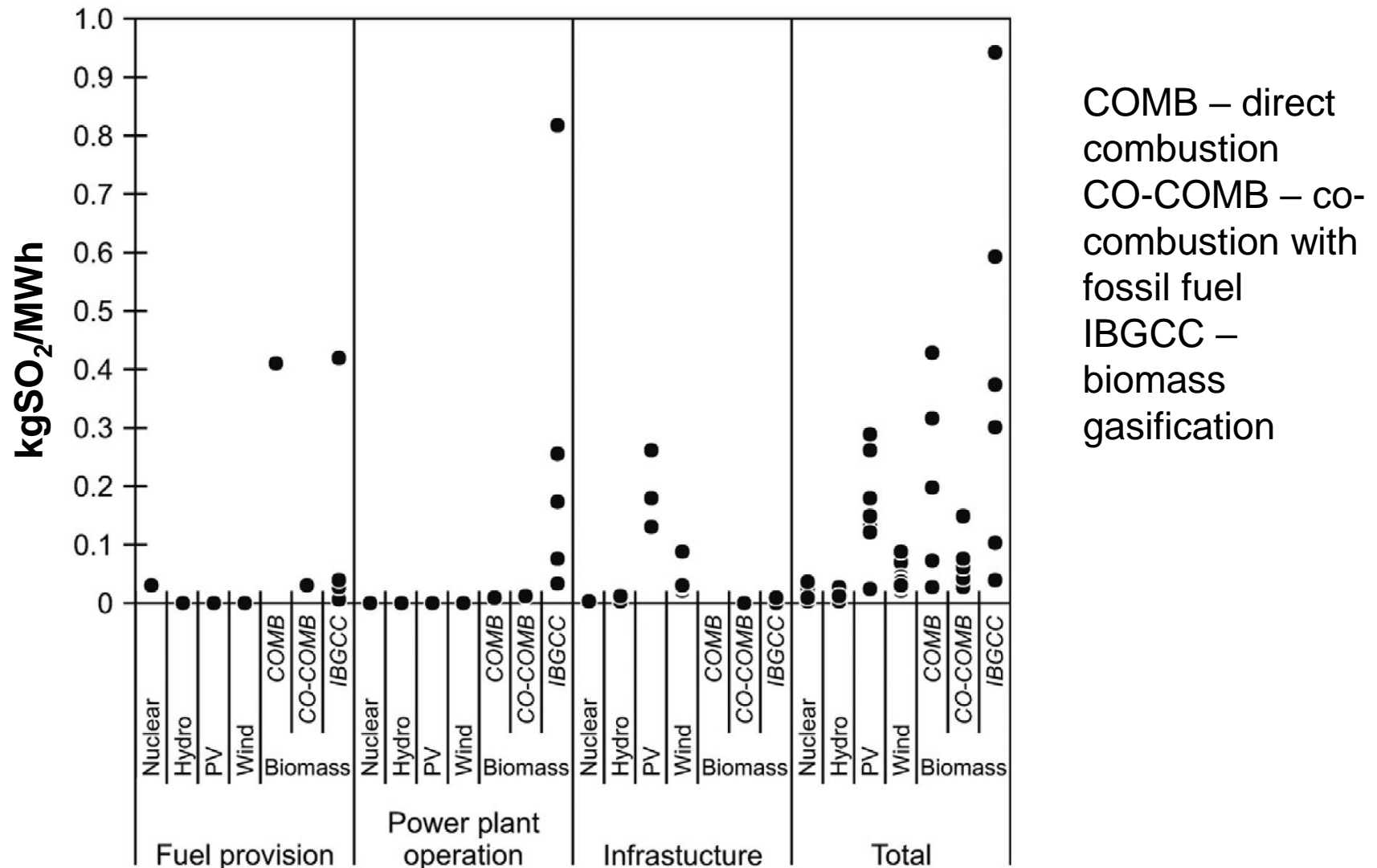
GHG Emissions from Renewables&Nuclear



NO_x Emissions from Renewables&Nuclear



SO₂ Emissions from Renewables&Nuclear



Summary for Hard Coal

- 36 studies included
- Most of the emissions are related to the plant operation
- Direct emission was the main contribution to GHG
 - emissions for direct combustion (DC) is $750 \div 1050$ kgCO₂-eq/MWh
 - emissions for coal gasification (IGCC) is $660 \div 800$ kgCO₂-eq/MWh mainly due to higher efficiency (up to 52%)
- Data for NO_x and SO₂ emissions from direct combustion showed significant variability ($2 \div 4$ kgNO_x/MWh and $2 \div 7$ kgSO₂/MWh for old plants; $0.3 \div 1$ kgNO_x/MWh and $0.1 \div 1$ kgSO₂/MWh for modern plants)
 - mainly due to flue gas cleaning (FGC) systems and energy efficiency being two most important factors

Summary for Lignite

- 7 studies were included
- Emissions from lignite provision are much lower than those from hard coal
 - since lignite power plants are often placed close to the mines
- Lower amount of methane were emitted during mining compared to hard coal
- Emissions due to infrastructure are shown to be small
- Life cycle GHG emissions varied due to low energy content of lignite and lower energy efficiency
- Emissions were in a range 800÷1300 kgCO₂-eq/MWh
- Similar to hard coal, NO_x and SO₂ showed significant variations

Summary for Natural Gas

- Two technologies based on natural gas were considered
 - a single cycle (SC) turbine with low energy efficiency (26÷35%)
 - combined cycle (CC) turbine with high energy efficiency (up to 60%)
- This distinction is made because SC provides peak electricity and CC delivers baseload power
- Direct GHG emissions from CC plants were rather consistent among different studies: 350÷410 kgCO₂-eq/MWh
- Fuel provision represented up to 30% of GHG emissions
- SC plants had higher emissions: 610÷850 kgCO₂-eq/MWh

Summary for Oil

- 10 studies were included
- GHG and NO_x emissions were mainly related to plant operation
- In base load operation energy efficiency is high ($\leq 58\%$) and the corresponding GHG emission is 530 kg/CO₂-eq/MWh
- Peak-load power has lower efficiency (30-40%) and the GHG emissions increase to 750-900 kg/CO₂-eq/MWh
- Emissions of NO_x varied (0.5-1.5 kgNO_x/MWh) mainly due to FGC (Flue Gas Cleaning) systems

Summary for Nuclear

- 10 studies were included
- Emissions of GHG varied significantly (3.1-35 kgCO₂-eq/MWh)
 - different technologies for uranium enrichment were assumed
 - gas diffusion method uses 40 times more electricity than the gas centrifuge method
 - further assumption of fossil fuel electricity for the enrichment process greatly increases the emissions
- When using IOA, emission factors were estimated as 10-20 times greater than those calculated using PCA
- NO_x and SO₂ emissions are only due to energy consumption during uranium extraction and enrichment

IOA – Input-Output Analysis; PCA – Process-Chain Analysis

Summary on Hydropower

- Two hydropower solutions are included:
 - with dams and basin, allowing for matching peaks in electricity demand
 - run-of-river plants, which depend on the amount water flow and cannot be controlled
- 12 studies included (5 dam-reservoirs and 7 run-of-river)
- Life cycle GHG emissions were $2\div5$ kgCO₂-eq/MWh for run-of-river systems and $11\div20$ kgCO₂-eq/MWh for dam-reservoirs
- The highest emissions were found in IOA study

Summary for Solar PV

- 22 studies included
- GHG emissions showed great variability: $13 \div 130 \text{ kgCO}_2\text{-eq/MWh}$, mainly due to local conditions (source of electricity for manufacturing, type of panels, climate conditions, etc.)

Land-Take Requirements – A Detailed Study

- A case study on life-cycle energy density and land-take requirements (in the UK perspective) has been performed by V.K.M. Cheng and G.P. Hammond
 - in *J. of the Energy Institute*, 90(2017)201-213
 - Provided in Canvas
- The authors investigated claims found in the literature, that some of the renewable power generators take up far more land than fossil or nuclear

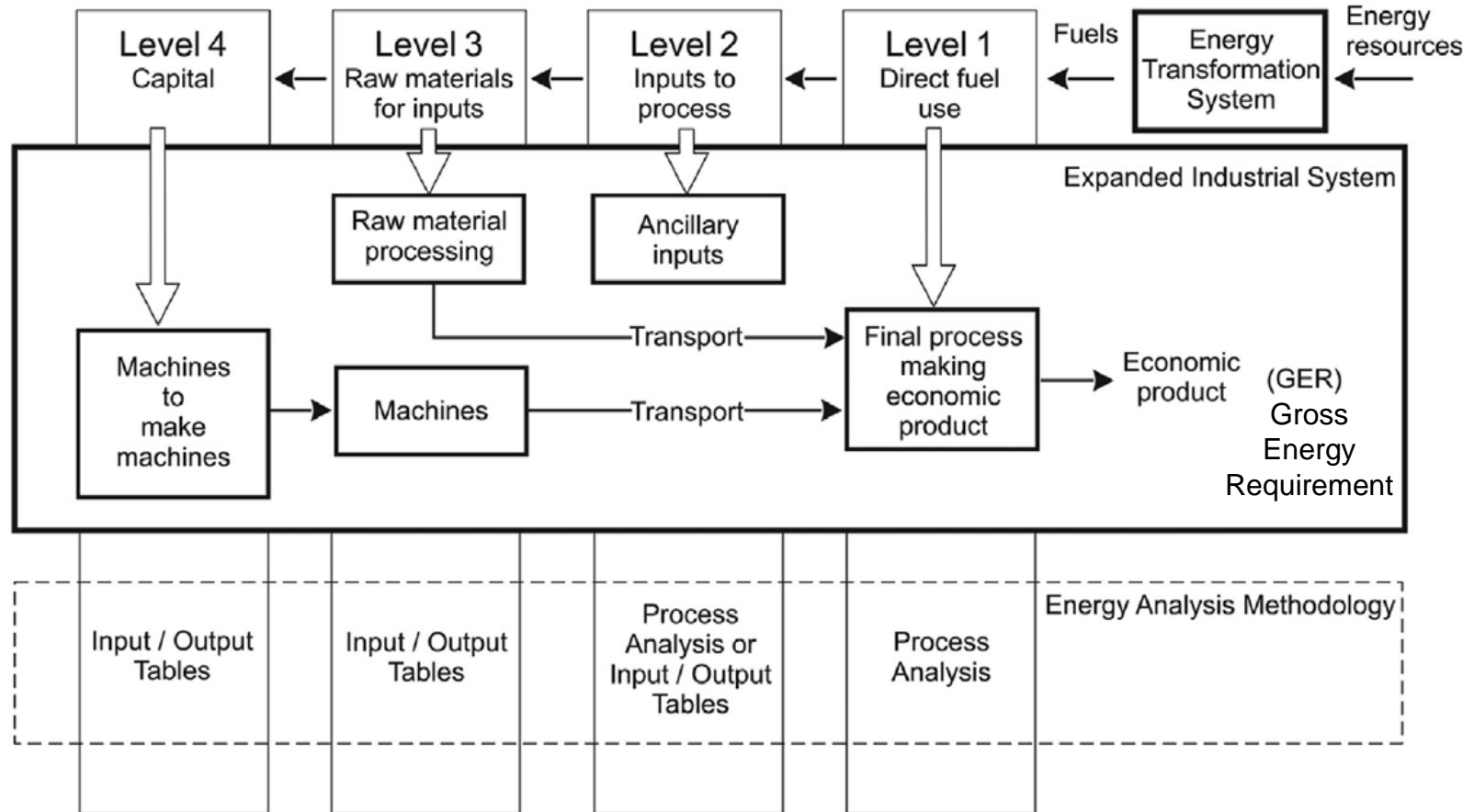
Method

- Energy Analysis (EA) on a life-cycle analysis
 - it is necessary to trace the flow of energy through the relevant industrial sector
 - Based on 1st principle of Thermodynamics: the sum of all the outputs from the system \times their energy requirements must be equal to the sum of inputs \times their individual energy requirements
 - upstream system boundary (“cradle”) – e.g. coal at the mine to downstream system boundary (“grave”) – e.g. waste disposal
 - for example: for wind turbines – the primary resources associated with the construction should include material used to fabricate the turbines

Levels of Regression

- Depending on the required level of accuracy, different levels of regression may be employed.
- A first level of analysis includes only the direct energy consumption (usually majority of life-cycle energy)
- A second level considers energy that is required to manufacture feedstock materials (needed for production)
- A third level includes energy consumed whilst manufacturing capital equipment (to manufacture machines)
- A fourth level would include machines used to manufacture machines

Levels of Regression



Energy Metrics

- An energy generator should produce more useful energy over its entire life-time than it is required to build, maintain and fuel it
- Energy Analysis (EA) yields the whole life or Gross Energy Requirement (GER) of the energy generator
- The sum of all primary energies required to yield one unit of delivered energy is known as Energy Requirement of Energy (ERE)
- The ratio of the energy output to the corresponding energy input is known as Energy Ratio, Energy Gain Ratio (EGR) or Energy Payback Ratio

Energy Gain Ratio - EGR

- EGR (Energy Gain Ratio) is defined as

$$EGR = \frac{E_{n,L}}{E_{mat,L} + E_{con,L} + E_{op,L} + E_{dec,L}}$$

- where:

$E_{n,L}$ – net energy produced over the lifetime

$E_{mat,L}$ – total energy invested in materials

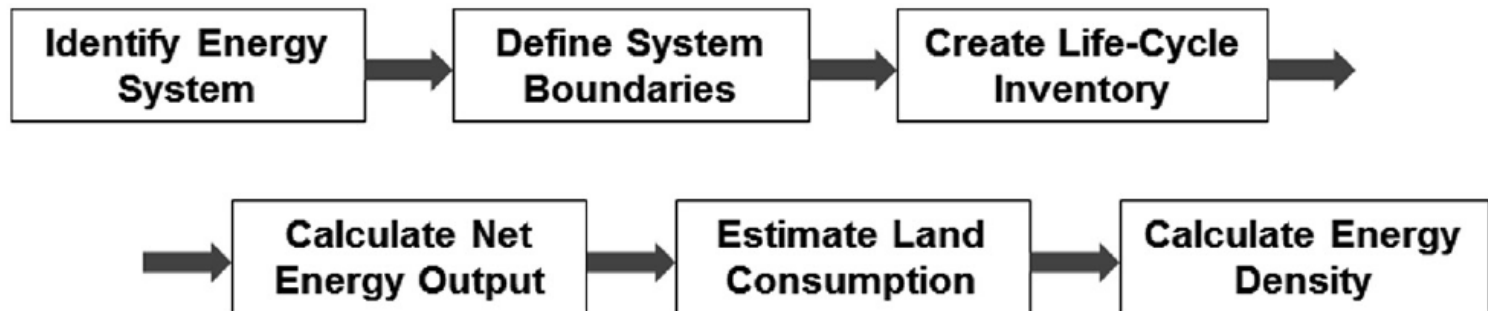
$E_{con,L}$ - total energy invested in construction

$E_{op,L}$ - total energy required to operate the plant

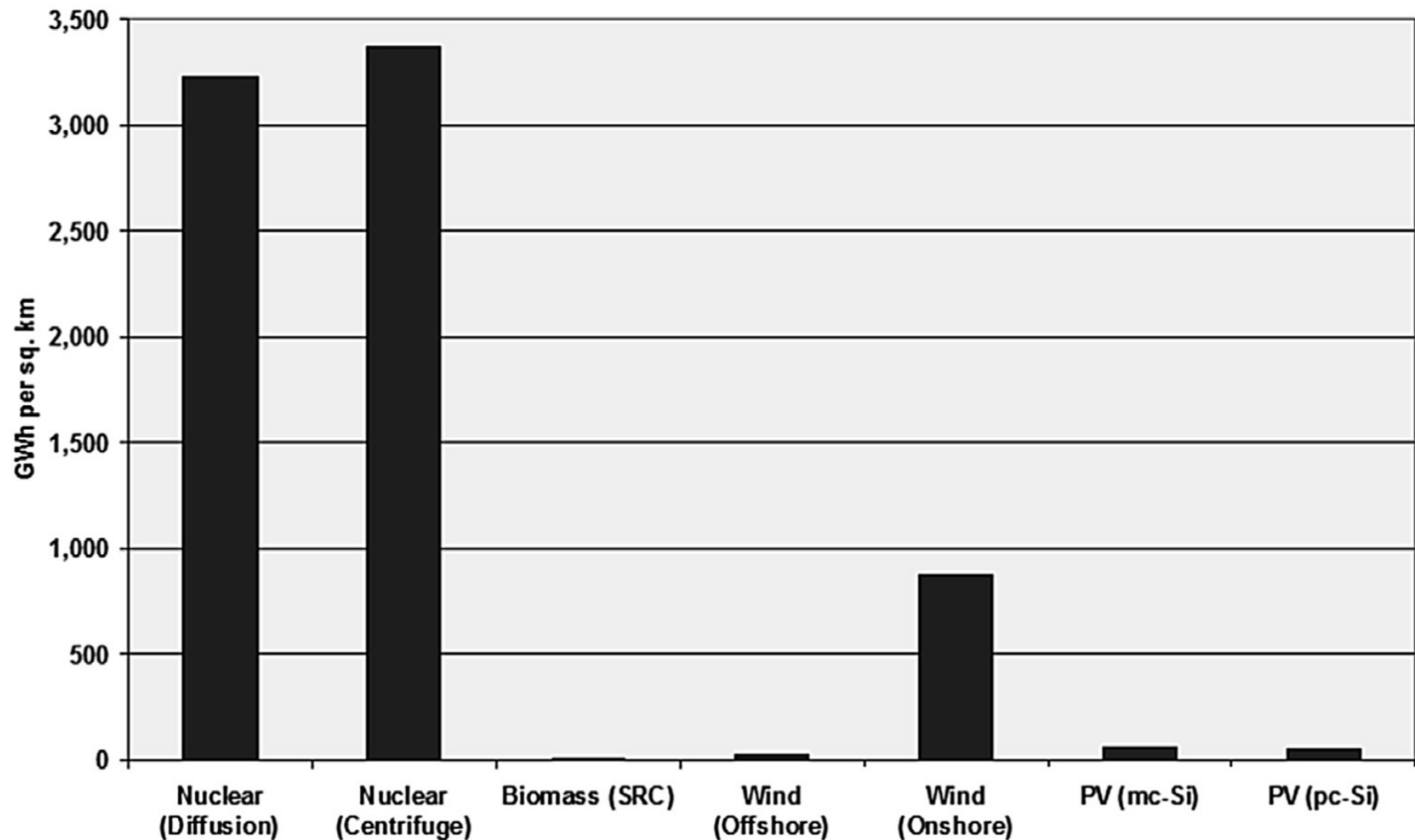
$E_{dec,L}$ - total energy required for decommission of plant

Energy Density – Spatial Footprint

- The ratio of net energy output to the total land required is called the Energy Density: $ED = \text{NET_EN_OUT} / \text{LAND_A}$
- Spatial Footprint is effectively the inverse of the energy density: $SF = \text{LAND_A} / \text{NET_EN_OUT}$
- Sequence of the energy density calculations

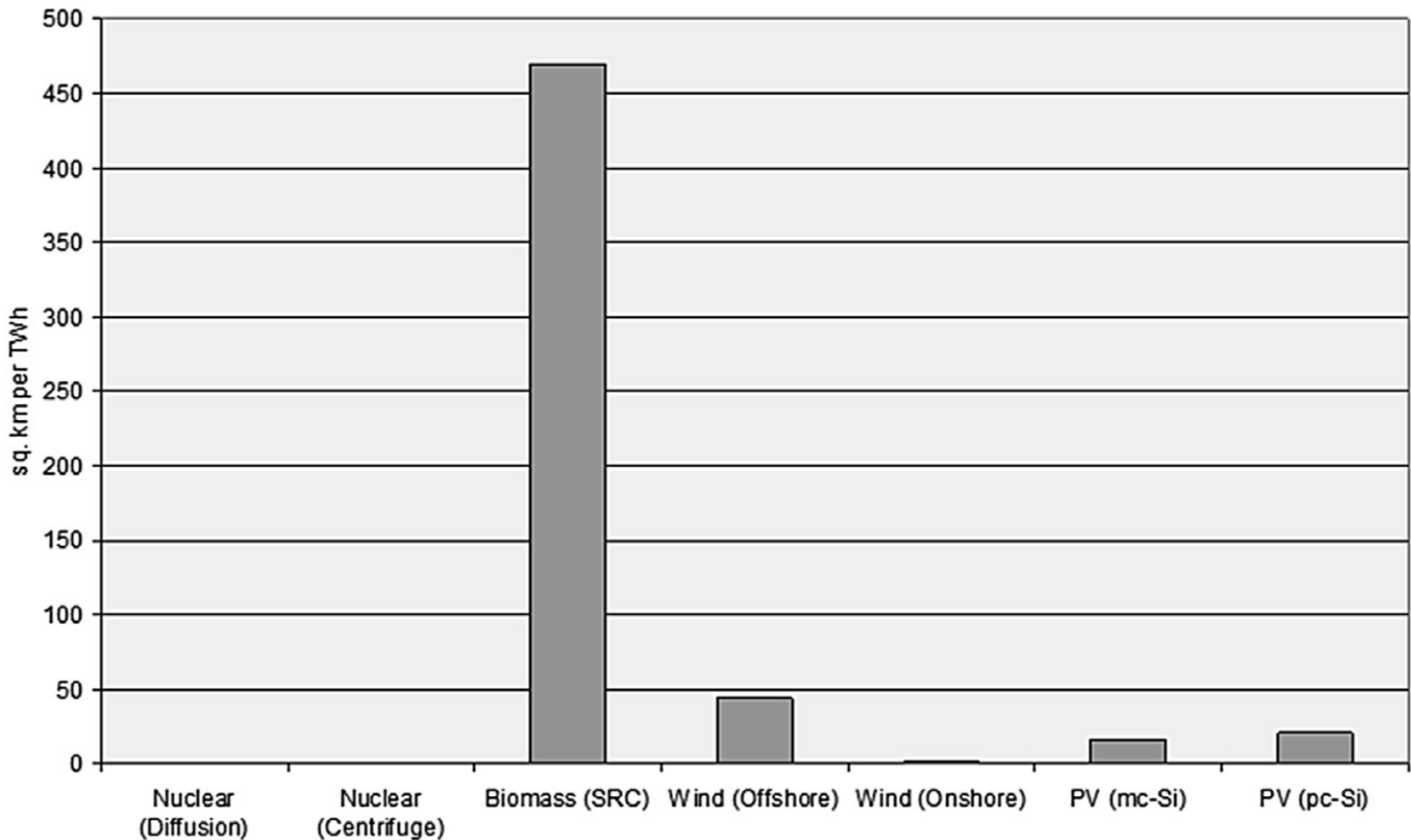


Results – Energy Density



Ref: Cheng&Hammond (2017)

Results – Spatial Footprint



Ref: Cheng&Hammond (2017)

Conclusions of the Study

- Several conventional and renewable power generators were evaluated
- It was shown that the nuclear fuel cycle (both with diffusion and centrifugal enrichment) has the highest energy density and the bioenergy the lowest
- Onshore wind power exhibited a relatively promising energy density among the renewable
- Surprisingly, the energy density of the offshore wind farms falls below that of PV arrays
- Renewables in general have energy densities orders-of-magnitude less than conventional systems

Economic Assessment - Outline

- Economics calculational approach
 - present value
 - cost of money
 - capital cost
 - tax
 - fuel cost & tax
 - O&M
- LCOE
- Summary of recent study by IEA&NEA on LCOE for various technologies using data from 181 plants in 22 countries

Economics Computational Approach

- Both engineering analysis and economic analysis should be employed for a large engineering projects and a comprehensive understanding of both disciplines is desirable
- For almost all ETSs, the product that is ultimately sold in the marketplace is electricity
- Thus it is important to know the average amount to charge for electricity since it determines revenues and revenues must be sufficient to cover costs

Principle Costs in ETSs

- **The capital cost**, which is incurred while constructing the plant
- **The fuel cost**, which is incurred while operating the plant
- **The operation and maintenance (O&M) cost**, which is incurred over the life of the plant
- **Income taxes**, which are incurred as a consequence of engaging in a private enterprise
- **Other costs**, which are incurred as a consequence of engaging in any commercial enterprise

Time Value of Money

- Money is a valuable asset with a variable time value determined by an **interest rate i**
- The total amount of money that has to be paid back at the end of the year, when borrowing amount **C** at the beginning of the year with interest rate **i** is

$$\text{Pay back} = \underbrace{C}_{\text{Principal}} + \underbrace{iC}_{\text{Interest}} = C(1+i)$$

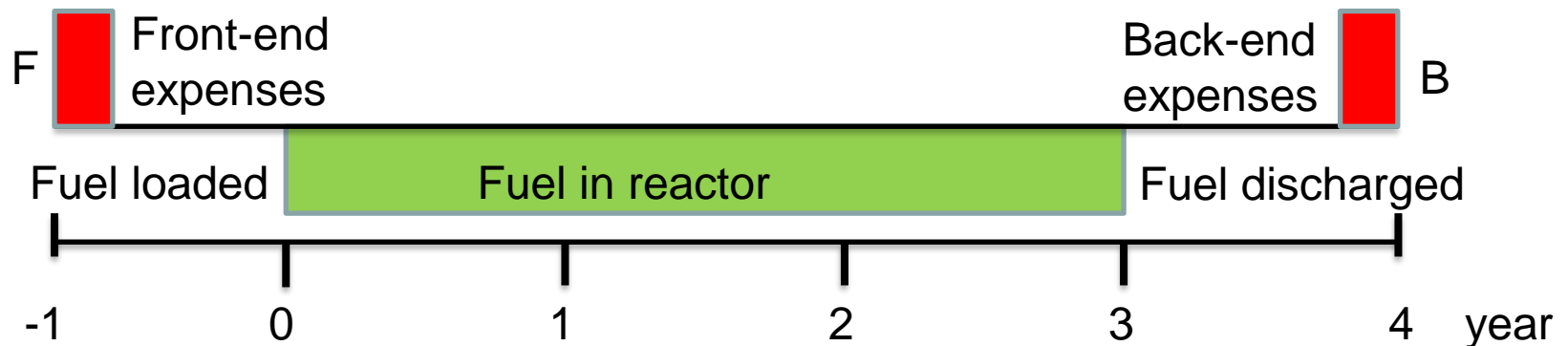
- If we expect a cost **C** at the end of a year, we can invest amount **C'** at the beginning of the year with interest rate **i** such that **$C'(1+i) = C$** . Thus $C' = \frac{C}{1+i}$ C' is a current value of an expense C

Present Value Concept

- With **present value concept** we can find an amount of money in any year that is equivalent to an amount in any other year
- This concept is very useful when analysing economics of an electricity generating plant (which is usually costly enterprise)
- It is useful to determine the current value of the past cost or the cost that will occur in the future
 - if we invested amount **C** two years ago, its current value is $C(1+i)^2$
 - thus if we had an expenditure **C** two years ago, its current value is $C(1+i)^2$. In general, expense **C** that occurred **n** years ago has present value $C(1+i)^n$. Similarly $C' = \frac{C}{(1+i)^n}$ is a present value of an expense C in n years

Example – Present Value

- As an example, we will calculate the present value of cost for fuel in a nuclear reactor



- For convenience, we chose year 0 (time when fuel is loaded to the reactor) as the reference time: we have two expenses: ***F*** in year -1 and ***B*** in year 4, thus, the present value of expenses is: $PV = F(1+i) + B/(1+i)^4$

Cost of Money

- Cost of money – or interest rate – is the key component of any economic analysis
- This value is a function of the financial arrangements adopted for the project
- Big projects (like a nuclear power plant) are usually financed with a combination of **bonds** (debts) and **stocks** (equity)
- A single interest rate i is found as a weighted mean:

$$i = b \cdot i_b + e \cdot i_e$$

b – fraction of funds obtained by debts (bonds)

e – fraction of funds obtained by equity (stocks)

i_b – bond interest rate

i_e – equity interest rate

Example – Cost of Money

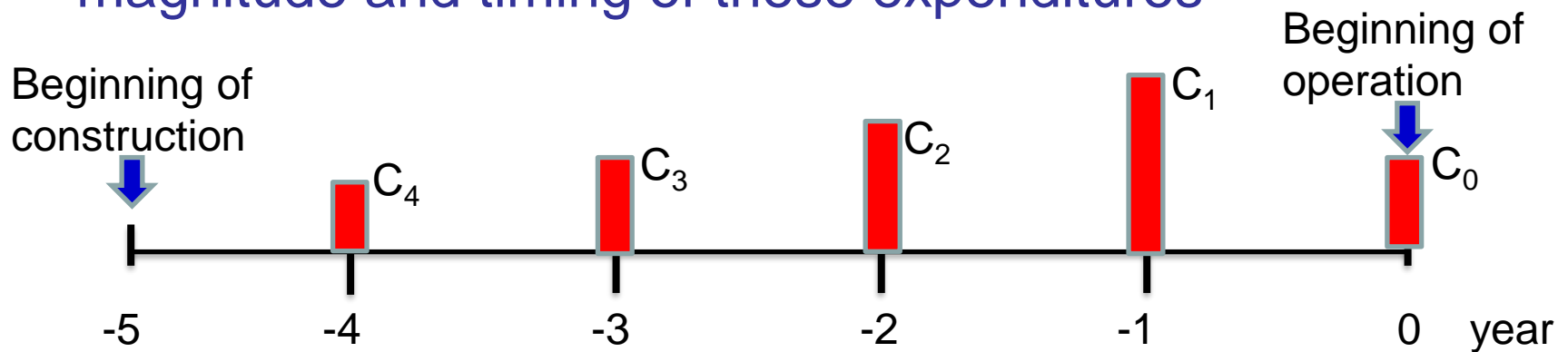
- A plant is financed with bonds in 55% and with stocks in 45%. Let the deflated (with given real rate of return not including inflation) bond interest rate be 2.5% and deflated interest rate for stocks be 7% per year.
- The effective deflated interest rate will be:

$$i = b \cdot i_b + e \cdot i_e = 0.55 \cdot 0.025 + 0.45 \cdot 0.07 = 0.045$$

- Thus we get $i = 4.5\%$

Capital Cost - Construction

- Plant construction occurs over a certain period of time and involves nonuniform expenditures
- The complete capital cost is determined by both the magnitude and timing of these expenditures

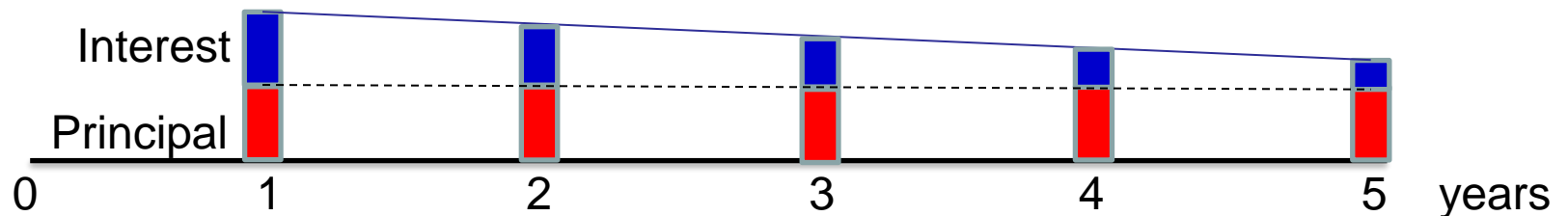


- The total capital cost is the sum of present value of all expenditures. Using year 0 as the reference time point:

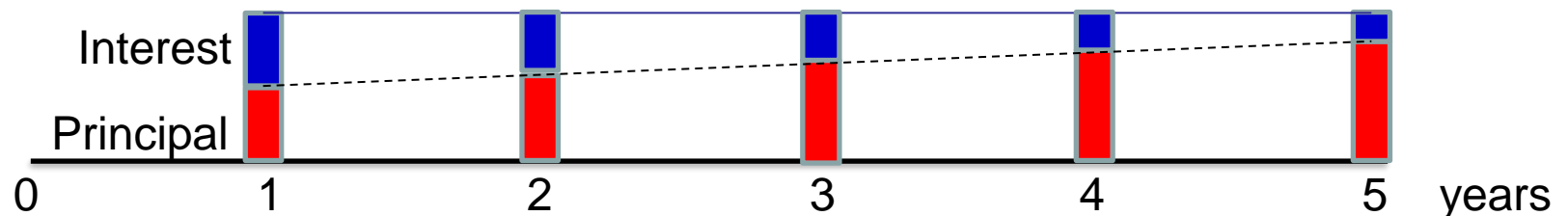
$$C = C_0 + C_1(1+i) + C_2(1+i)^2 + C_3(1+i)^3 + C_4(1+i)^4 = \sum_{k=0}^4 C_k(1+i)^k$$

Paying Back Capital Investment

- After the plant is completed, it is necessary to recover revenues sufficient to repay the original investment
- Capital investment cost can be paid back in two ways
 - with equal payments C/K each year to return the principle C over K years plus interest on the outstanding balance



- with equal annual payments of both the principle and the interest



Paying Back Capital Investment

- If an initial investment **C** is to be paid back uniformly over **K** years at an annual interest rate of **i**, then

$$C = \frac{C_u}{(1+i)^K} + \dots + \frac{C_u}{(1+i)^2} + \frac{C_u}{(1+i)} = C_u \sum_{k=1}^K \frac{1}{(1+i)^k}$$

- Solving for the uniform annual payment gives

$$C_u = \frac{C}{\sum_{k=1}^K \frac{1}{(1+i)^k}} = C \cdot \frac{i \cdot (1+i)^K}{(1+i)^K - 1}$$

This expression is known as the **sinking-fund repayment equation** or the **amortization equation**

- The annual payment **C_u** is a cost to the project and must be covered by revenues obtained from electricity sale

Levelized Charge for Electricity

- Revenues obtained from sale of electricity are determined as: **amount charged for a unit of electricity (L_{cap})** \times **number of units produced (E)**
- The revenue in each year will cover the expenditure in the year if $L_{cap} \times E = C_u$
- Thus the constant, or **levelized**, charge for electricity sufficient to cover capital expenditures is

$$L_{cap} = \frac{C_u}{E} = \frac{C}{E} \cdot \frac{i \cdot (1+i)^K}{(1+i)^K - 1}$$

E – number of units of electricity produced per year

C – initial investment

L_{cap} – levelized charge for electricity to cover capital expenditures

Fixed Charges

- Annual expenses associated with capital investment, such as: property insurance, property taxes and replacement costs are known as ***fixed charges***
- For an investment ***C***, the constant annual fixed charges may be expressed as ***f · C***, where value of ***f*** varies with location, tax structure, etc.
- Fixed charges must also be covered by revenues obtained from the sale of electricity
- Let ***L_{fc}*** be the levelized charge for unit electricity to cover fixed charges, then

$$L_{fc} \cdot E = f \cdot C \Rightarrow L_{fc} = f \cdot C / E$$

Taxes

- If a power plant is owned by private utility, then taxes must be paid on revenues
- The calculation of taxes is complicated by provisions in the tax law which allows that certain costs are deducted from revenues before taxes are assessed
- Main deductions concerns
 - interest paid on bonds
 - depreciation allowed on capital equipment
- The following pattern is employed for taxes on capital

$$\left(\begin{array}{c} \text{taxes on} \\ \text{capital} \end{array} \right) = (\text{tax rate}) \cdot \left[\text{revenues} - \left(\begin{array}{c} \text{interest} \\ \text{paid on} \\ \text{bonds} \end{array} \right) - \text{depreciation} \right]$$

Revenues

- As already noted, the annual revenue required to cover a capital investment is $L_{cap} \cdot E$,
 - L_{cap} – levelized charge for unit of electricity necessary to cover the return of and the return on the investment
 - E – amount of electrical energy produced in a year
- If we define L_{ctax} as the levelized charge for a unit of electricity sufficient to cover taxes, then the annual revenue which will be obtained to cover both capital investment and taxes is

$$\text{Revenue} = (L_{cap} + L_{ctax}) \cdot E$$

We have already calculated L_{cap} ,
but L_{ctax} remains to be calculated

Capital Tax - L_{ctax}

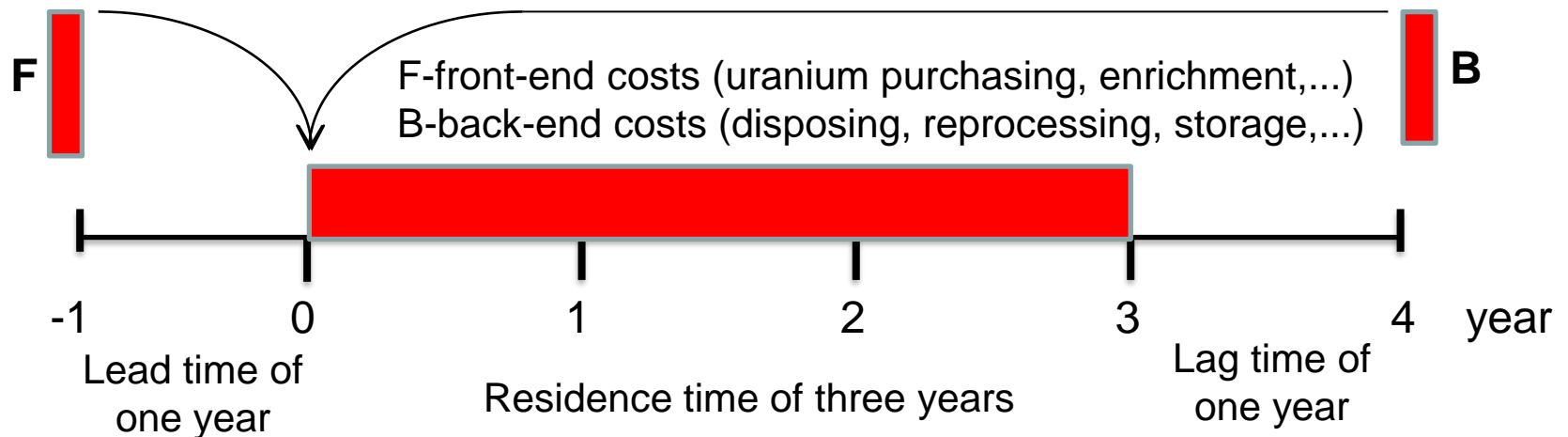
- Including also interests paid on bonds and depreciation, the levelized cost of electricity to cover taxes on capital can be found as:

$$L_{ctax} = \frac{t}{1-t} \frac{L_{cap} \cdot E - cdep}{E} - \frac{\left(\frac{t}{1-t}\right) \left(\frac{bi_b}{i}\right) \left[C - \frac{KC_u}{(1+i)} + \frac{KiC}{(1+i)} \right]}{E \left[\frac{(1+i)^K - 1}{i \cdot (1+i)^K} \right]}$$

t -tax rate, i -effective interest rate, i_b – debt (bond) interest rate, b – fraction of funds obtained by bond, C – initial capital investment, C_u – uniform payment; K – number of years to pay back the initial investment C , E – amount of electrical energy produced in a year, $cdep$ – uniform depreciation allowance in each year ($cdep=C/K$)

Fuel Cost

- The ability to predict fuel cost in a power plant is often crucial to the project
- We show here example of fuel cost calculation for nuclear power plant
 - it contains many processes that occur at different points in time



Fuel Cost

- The levelized fuel cost can be found as

$$L_b = \frac{F(1+i)^{ld} + \frac{B}{(1+i)^{lg+N}}}{\frac{E}{N} \left[\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \dots + \frac{1}{(1+i)^N} \right]}$$

i – effective interest rate, E – amount of electrical energy produced in a year, N – number of batches of fuel in a reactor, F – front-end-cost, B – back-end cost, ld – lead time, lg – lag time

Fuel Tax - L_{btax}

- The levelized cost of electricity to cover tax expenses on fuel can be found as

$$L_{btax} = \frac{t}{1-t} \left[\frac{F(1+i)^{ld} + \frac{B}{(1+i)^{lg+N}}}{\frac{E}{N} \left[\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \dots + \frac{1}{(1+i)^N} \right]} - \frac{F(1+i)^{ld} + \frac{B}{(1+i)^{lg}}}{E} \right]$$

t -tax rate, i -effective interest rate, E – amount of electrical energy produced in a year, N – number of batches of fuel in a reactor, F – front-end-cost, B – back-end cost, ld – lead time, lg – lag time

O&M Costs

- The levelized cost of electricity to cover the operation and maintenance expenses are found as:

$$L_{om} = \frac{(\text{Fixed O\&M}) + (\text{Variable O\&M}) \times (\text{capacity factor})}{E}$$

The total Power Cost - LCOE

- The total levelized cost of electricity (LCOE) is found as

$$L_{tot} = LCOE = L_{cap} + L_{ctax} + L_{fc} + L_b + L_{btax} + L_{om}$$

Capital Tax on Fixed Fuel Fuel O&M
cost revenues charges cost tax cost

- LCOE is a useful parameter that enables a comparison between different technologies
- It indicates the margin electricity price to make profit on selling electrical power

Example – Fast Breeder Reactor

Parameter	Value
Power (MWe)	1000
Capacity factor (%)	70
Refuelling interval (y)	1
Plant lifetime (y)	30
Lead and Lag time (y)	1

Parameter	Value
Bond fraction	0.55
Equity fraction	0.45
Uninflated bond interest rate	0.025
Uninflated equity interest rate	0.07
Fixed charge fraction of capital cost, f	0.03

Parameter	Core	Axial blanket	Radial blanket
Number of batches	2	2	5
Plutonium charge (kg/y)	1480	0	0
Plutonium discharge (kg/y)	1410	160	135
Heavy metal charge (kg/y)	12600	9360	8480
Heavy metal discharge (kg/y)	11600	9150	8290

Parameter	Value	core fabricat. (€/kg)	1150
Tax rate	0.5	Axial bl. fabr. (€/kg)	50
Plutonium (€/g)	30	Radial bl. fab (€/kg)	150
Capital cost of plant (€/kWe)	1000	core reprocess (€/kg)	600
Fixed O&M cost (€/kWe/y)	17	Axial bl. reprocess (€/kg)	600
Variable O&M cost (€/kWe/y)	1	Rad. bl. reprocess (€/kg)	600

Effective Interest Rate

- We find the effective interest rate as

$$i = b \cdot i_b + e \cdot i_e = 0.55 \cdot 0.025 + 0.45 \cdot 0.07 = 0.045$$

Capital Return

- Return of and return on capital investment is found as

$$C = 1000 \frac{\text{€}}{\text{kWe}} \times 1000 \times 10^3 \text{ kWe} = 1.0 \times 10^9 \text{ €}$$

$$C_u = 1.0 \times 10^9 \text{ €} \times 0.061 \frac{\text{€}}{\text{€} \times \text{y}} = 6.1 \times 10^7 \frac{\text{€}}{\text{y}}$$

$$E = 1000 \times 10^3 \text{ kWe} \times 0.70 \times 8760 \frac{\text{hr}}{\text{y}} = 6.1 \times 10^9 \frac{\text{kWh}}{\text{y}}$$

$$L_{cap} = \frac{6.1 \times 10^7 \frac{\text{€}}{\text{y}} \times 10^2 \frac{\text{¢}}{\text{€}}}{6.1 \times 10^9 \frac{\text{kWh}}{\text{y}}} = 1 \frac{\text{¢}}{\text{kWh}}$$

Fixed Charges

- Fixed charges on a capital investment are found as

$$L_{fc} = f \cdot C / E \quad f = 0.03$$

$$L_{fc} = \frac{0.03 \frac{\text{€}}{\text{€} \times \text{y}} \times 1.0 \times 10^9 \text{€} \times 10^2 \frac{\text{¢}}{\text{€}}}{6.1 \times 10^9 \frac{\text{kWh}}{\text{y}}} = 0.49 \frac{\text{¢}}{\text{kWh}}$$

O&M

- The levelized cost of electricity to cover the operation and maintenance expenses is found as

$$L_{om} = \frac{(\text{Fixed O\&M}) + (\text{Variable O\&M}) \times (\text{capacity factor})}{E} =$$
$$\frac{\left(17 \frac{\text{€}}{\text{kWe} \cdot \text{y}} \times 1000 \cdot 10^3 \text{kWe} + 1 \frac{\text{€}}{\text{kWe} \cdot \text{y}} \times 0.70 \times 1000 \cdot 10^3 \text{kWe} \right) \times 10^2 \frac{\text{¢}}{\text{€}}}{6.1 \times 10^9 \frac{\text{kWh}}{\text{y}}} = 0.29 \frac{\text{¢}}{\text{kWh}}$$

The levelized power cost

- Similar calculations gives:

$$L_{ctax} = \frac{t}{1-t} \frac{L_{cap} \cdot E - cdep}{E} - \frac{\left(\frac{t}{1-t}\right) \left(\frac{bi_b}{i}\right) \left[C - \frac{KC_u}{(1+i)} + \frac{KiC}{(1+i)} \right]}{E \left[\frac{(1+i)^K - 1}{i \cdot (1+i)^K} \right]} = 0.29 \frac{\text{¢}}{\text{kWh}}$$

$$L_b = \frac{F(1+i)^{ld} + \frac{B}{(1+i)^{lg+N}}}{\frac{E}{N} \left[\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \dots + \frac{1}{(1+i)^N} \right]} = 0.59 \frac{\text{¢}}{\text{kWh}}$$

$$L_{btax} = 0.1 \frac{\text{¢}}{\text{kWh}}$$

Total

$$L_{tot} = L_{cap} + L_{ctax} + L_{fc} + L_b + L_{btax} + L_{om} =$$

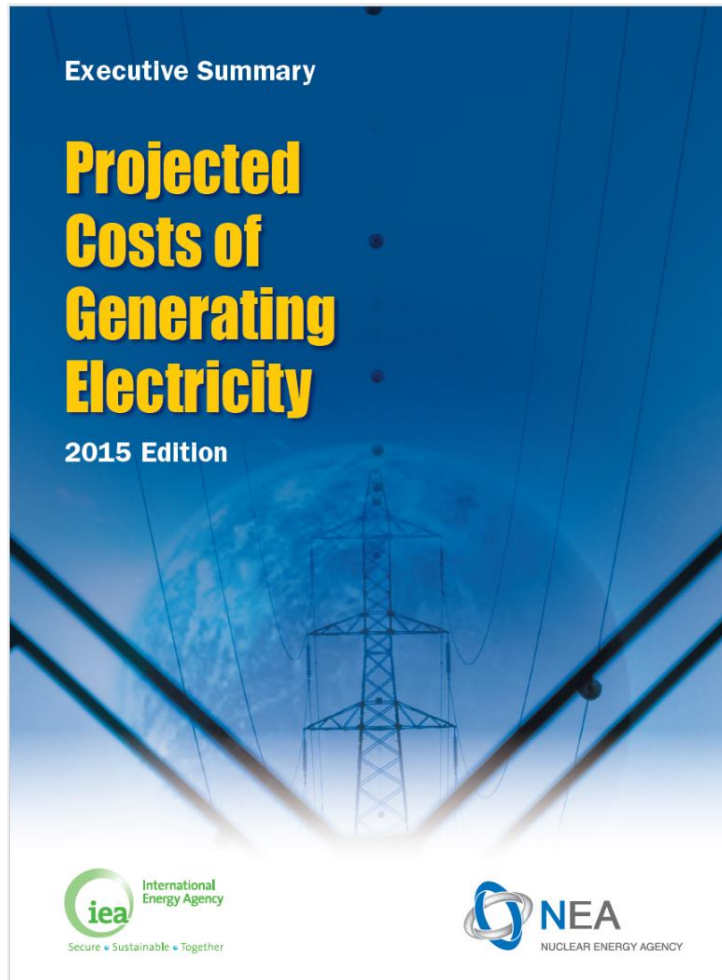
$$(1.00 + 0.29 + 0.49 + 0.59 + 0.1 + 0.29) \frac{\text{¢}}{\text{kWh}} = 2.76 \frac{\text{¢}}{\text{kWh}}$$

Costs



■ cap ■ ctax ■ fc ■ b ■ btax ■ om

Reporting LCOE



International Energy Agency (IEA) and Nuclear Energy Agency (NEA) are releasing report on Projected Costs of Generating Electricity on a regular basis every 5 years. The data presented in 2015 Edition are used in this lecture.

LCOE Calculations

- LCOE calculations are based on levelized average lifetime cost approach, using the discounted cash flow method
- The calculations use a combination of generic, country-specific and technology-specific assumptions for the various technical and economic parameters
- Three discount rates were used (3%, 7% and 10%)
- Costs are calculated at the plant level (busbar) and do not include the transmission nor distribution costs
- LCOE calculations do not capture other systematic costs or externalities beyond CO₂ emissions

LCOE Calculation

- The following formula is used in the study

$$\text{LCOE} = \frac{\sum_k (Investment_k + O \& M_k + Fuel_k + Carbon_k + Decommissioning_k) \times (1+i)^{-k}}{\sum_k (Electricity_k) \times (1+i)^{-k}}$$

Electricity_k: amount of electricity produced in year *k*

Investment_k: investment cost in year *k*

O&M_k: operation and maintenance cost in year *k*

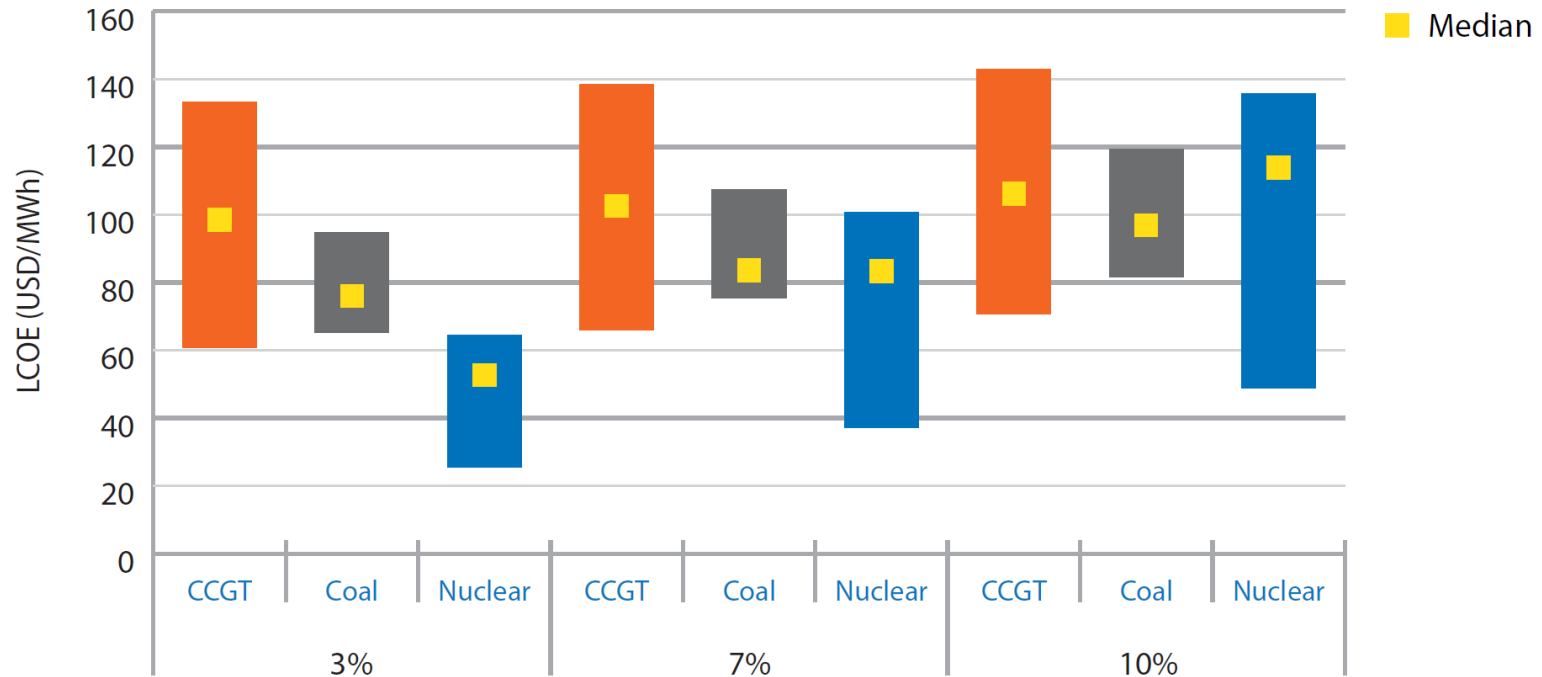
Carbon_k: carbon cost in year *k*

Decommissioning_k: decommissioning cost in year *k*

Assumptions

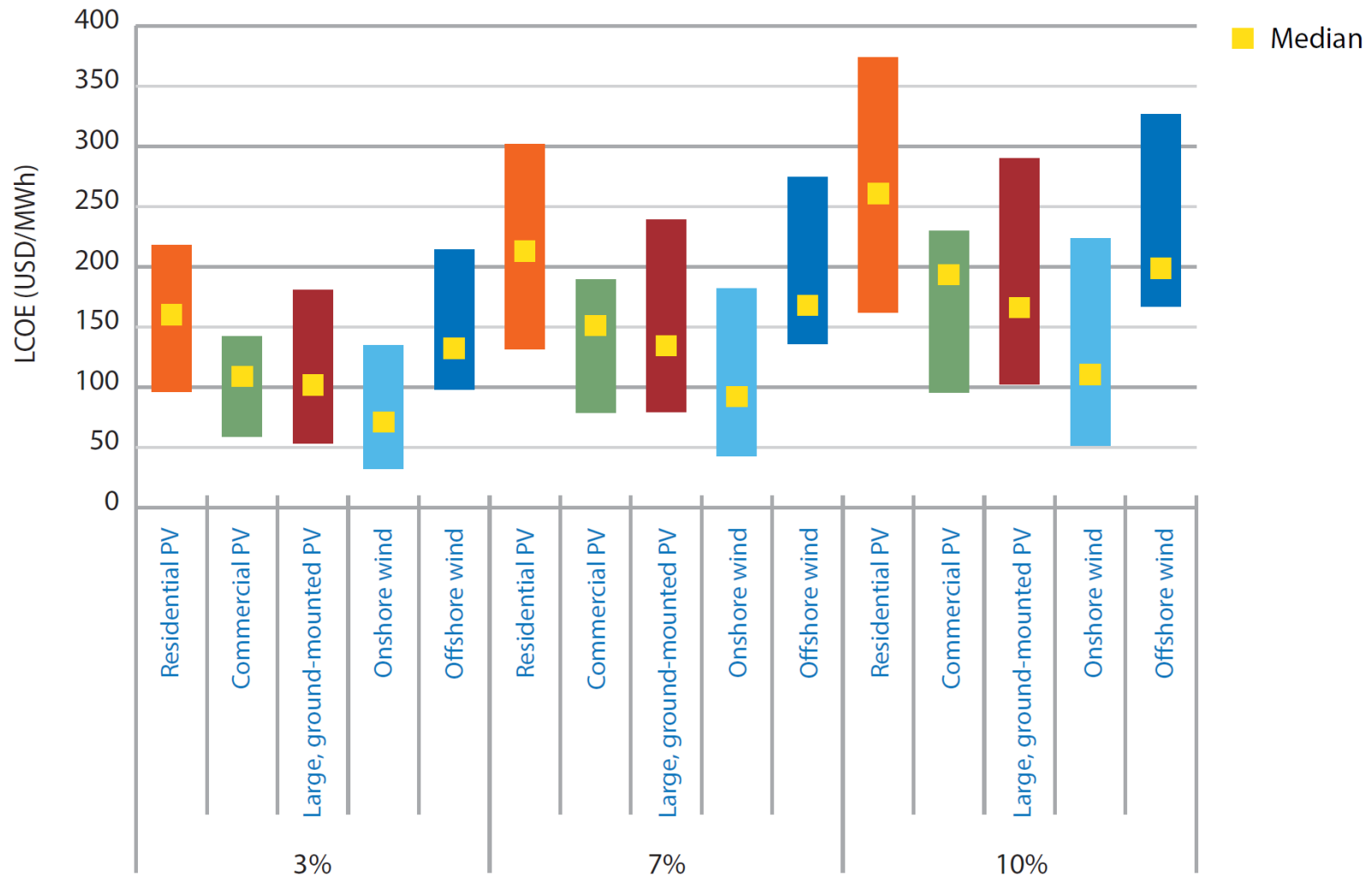
- For baseload technologies a standard load factor of 85% has been chosen – country-specific for renewables
- The cost of the compensating electricity for variable technologies (wind and solar) is not taken into account
- Such compensating capacity must be mobilised at short notice and they otherwise must stay idle
 - this incurs significant additional costs, but there is no consensus yet how such costs should be taken into account
- Only carbon capture and compression costs are included for relevant plants (which is the main part of costs)
 - costs for transporting and storing the sequestered carbon is not considered (costs and methods are uncertain yet)

LCOE Ranges – Baseload Technologies



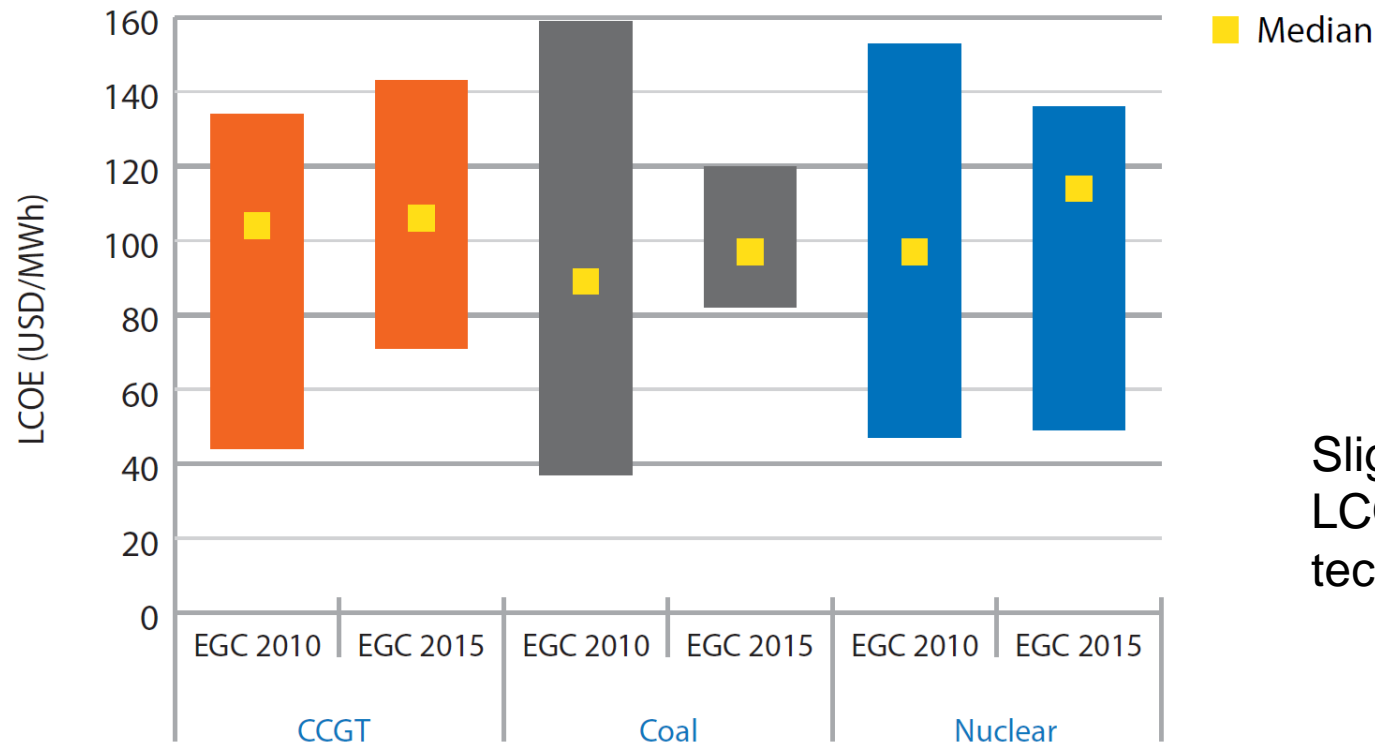
Ranges presented include results from all countries analysed in the study (1821 plants in 22 countries)

LCOE Ranges Solar PV & Wind



2010-2015 Comparison: Baseload

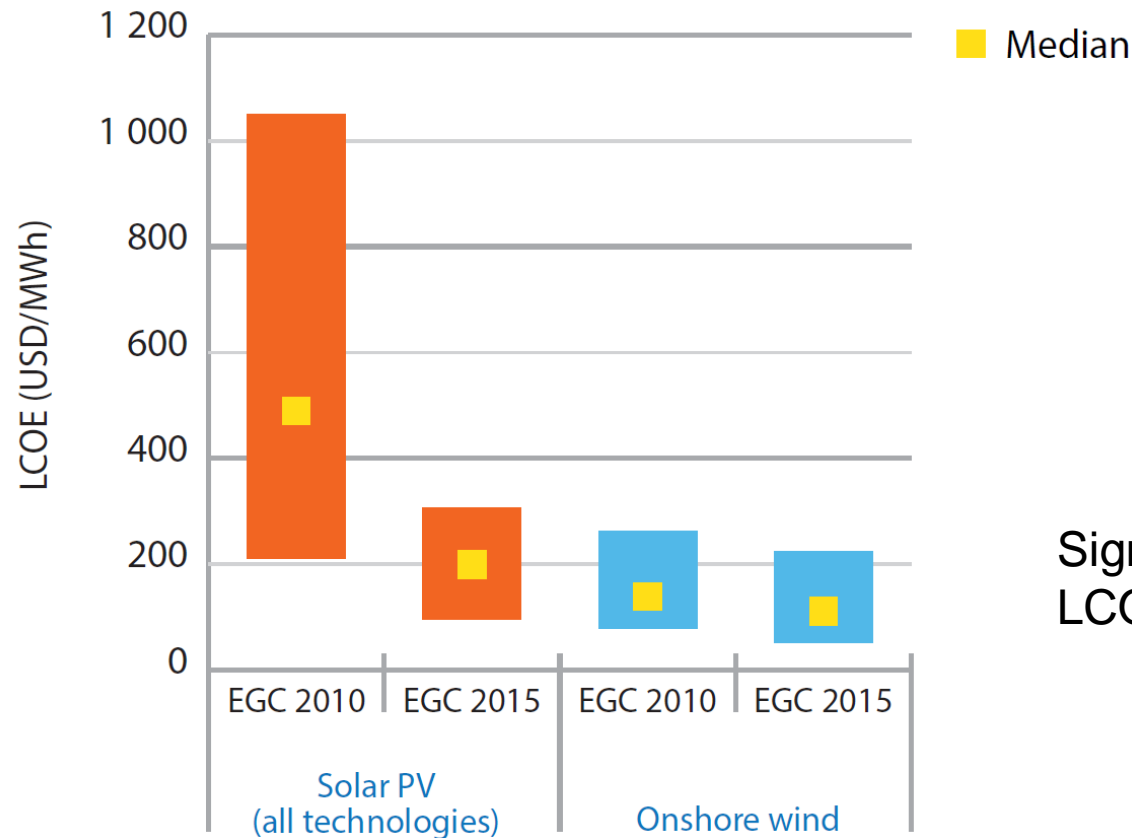
(at 10% discount rate)



Slight increase of
LCOE for all
technologies

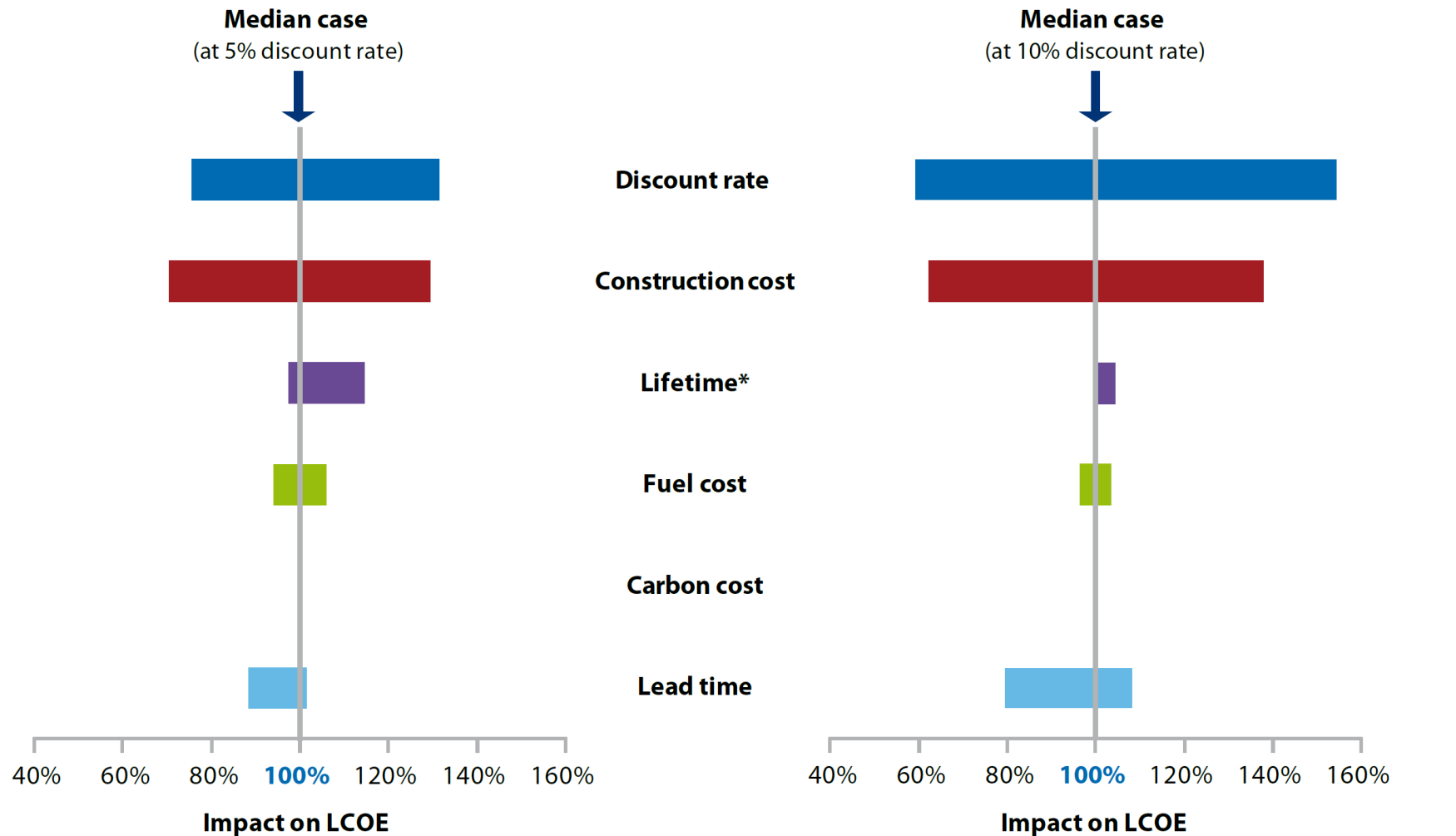
2010-2015 Comparison: PV&Wind

(at 10% discount rate)



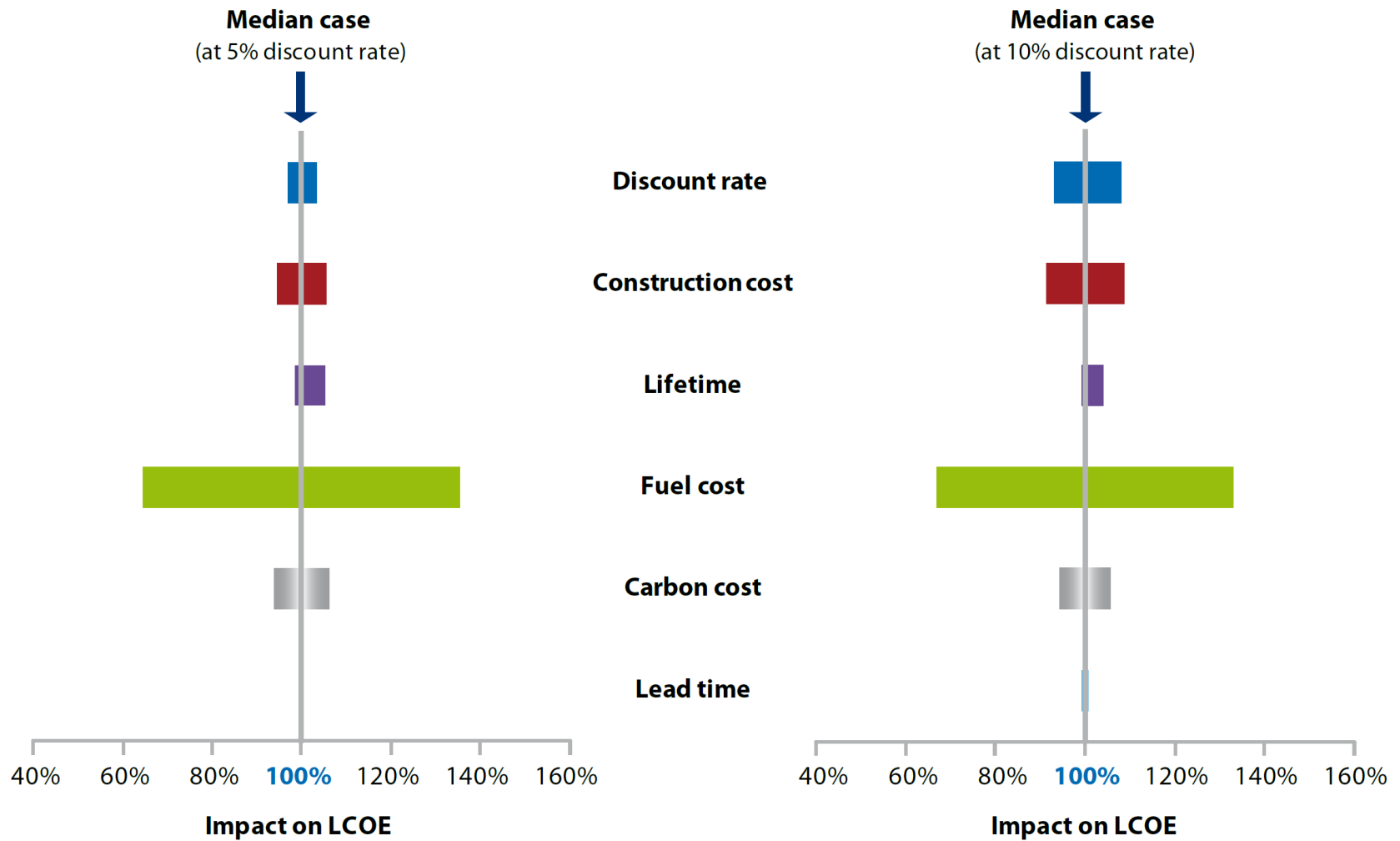
Significant drop of
LCOE for solar PV

Sensitivity of LCOE for Nuclear



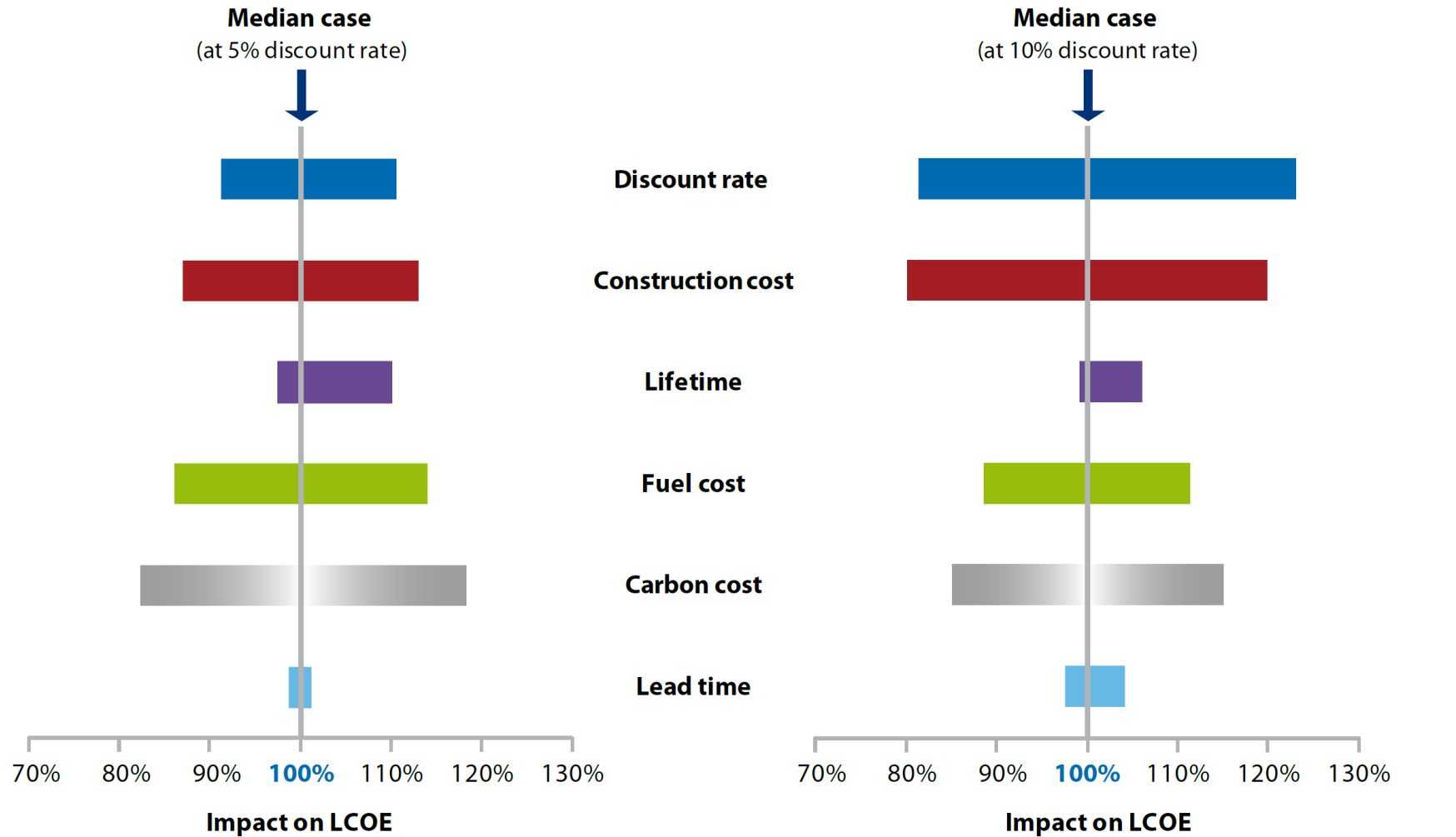
IEA&NEA 2010

Sensitivity of LCOE for Gas



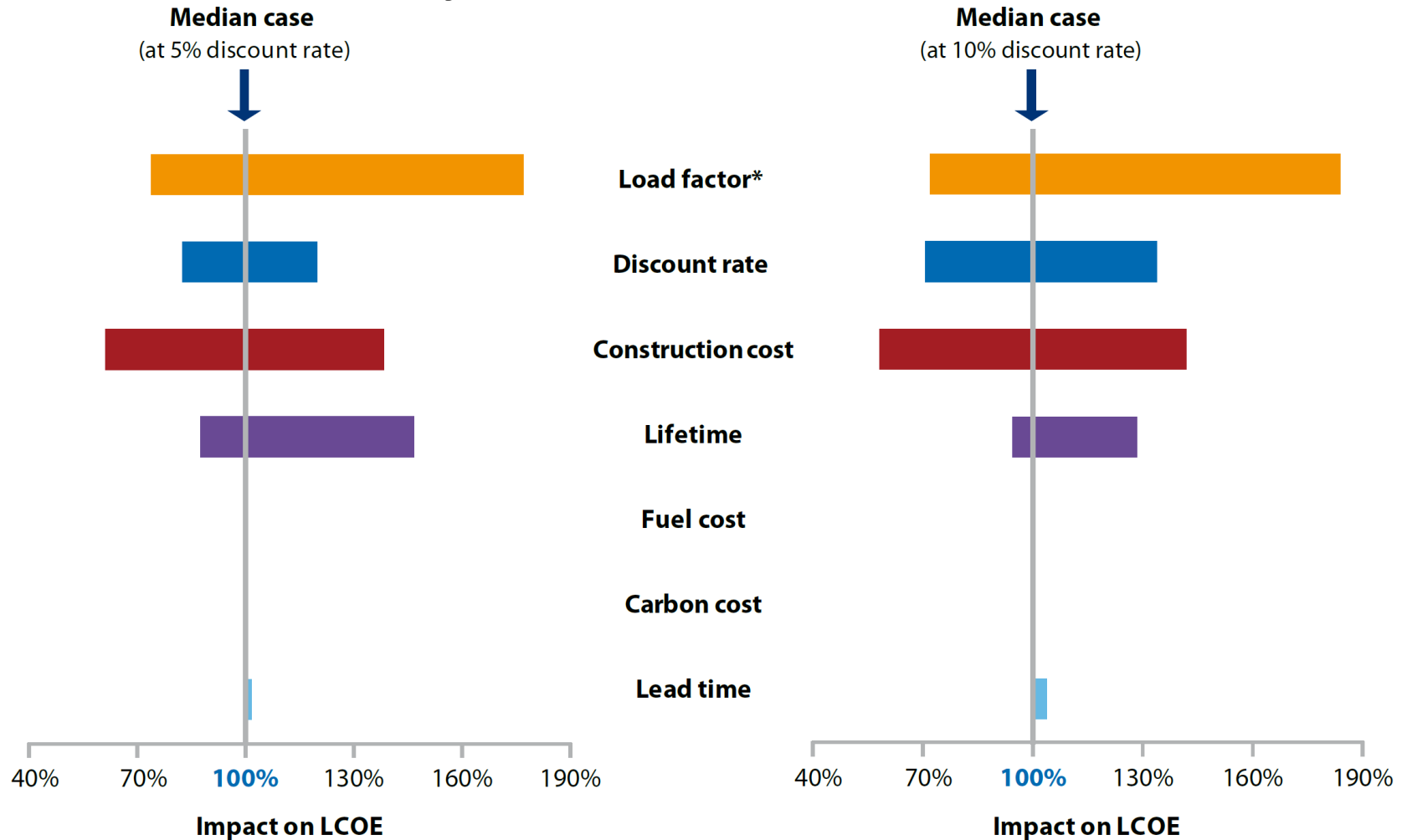
IEA&NEA 2010

Sensitivity of LCOE for Coal



IEA&NEA 2010

Sensitivity of LCOE for Wind



IEA&NEA 2010

Conclusions

- 2010 study noted significant increase in the cost of baseload technologies, the data of 2015 study suggest that this increase was stopped
- Costs for renewables (in particular PV) have declined significantly over the past five years
- There is no single technology that can be said to be the cheapest under all circumstances