Sustainable Energy Transformation Technologies, SH2706

Lecture No 21

Title:

Principles of Life-Cycle and Economic Assessment for ETS

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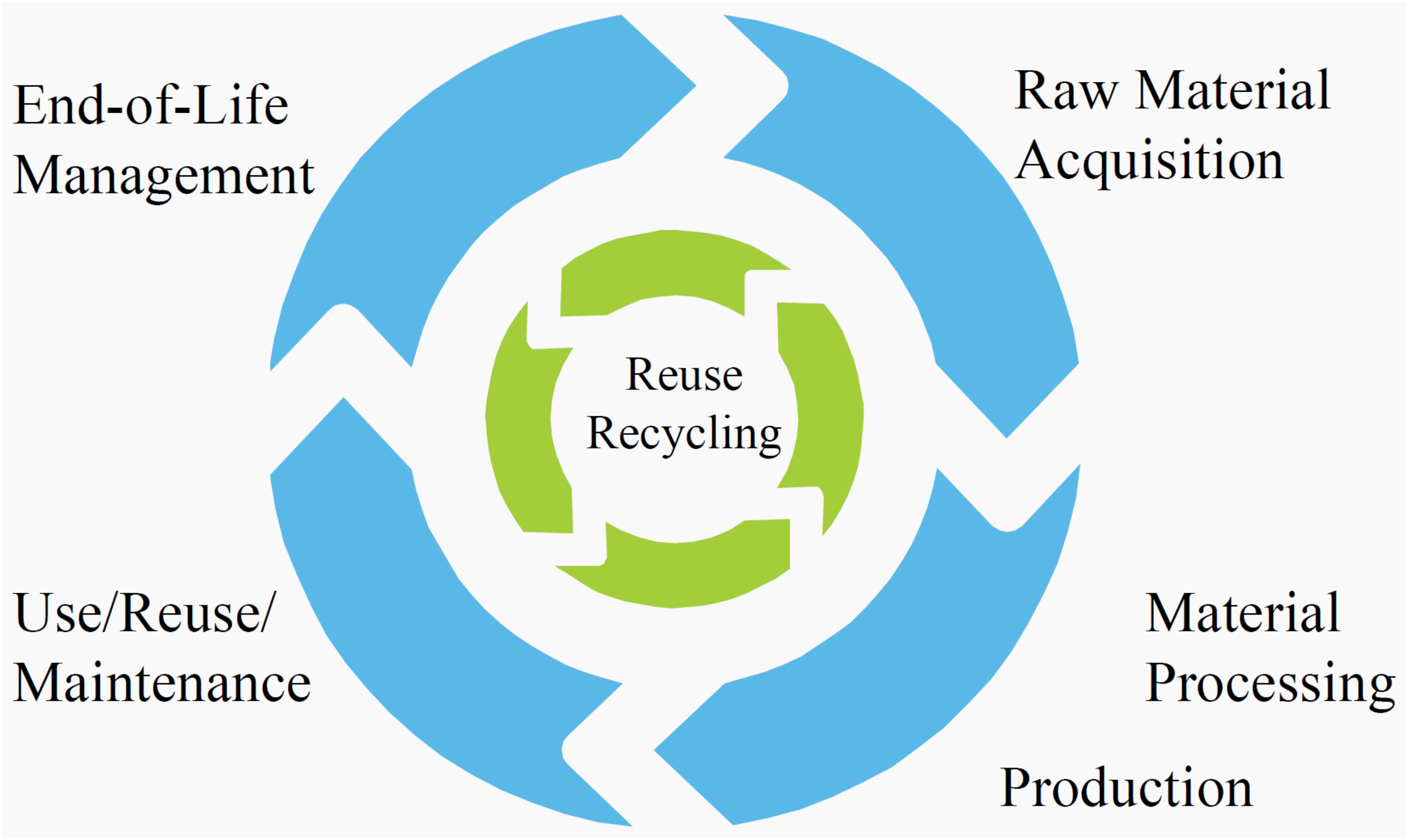
Life-Cycle Assessment - Outline

- 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

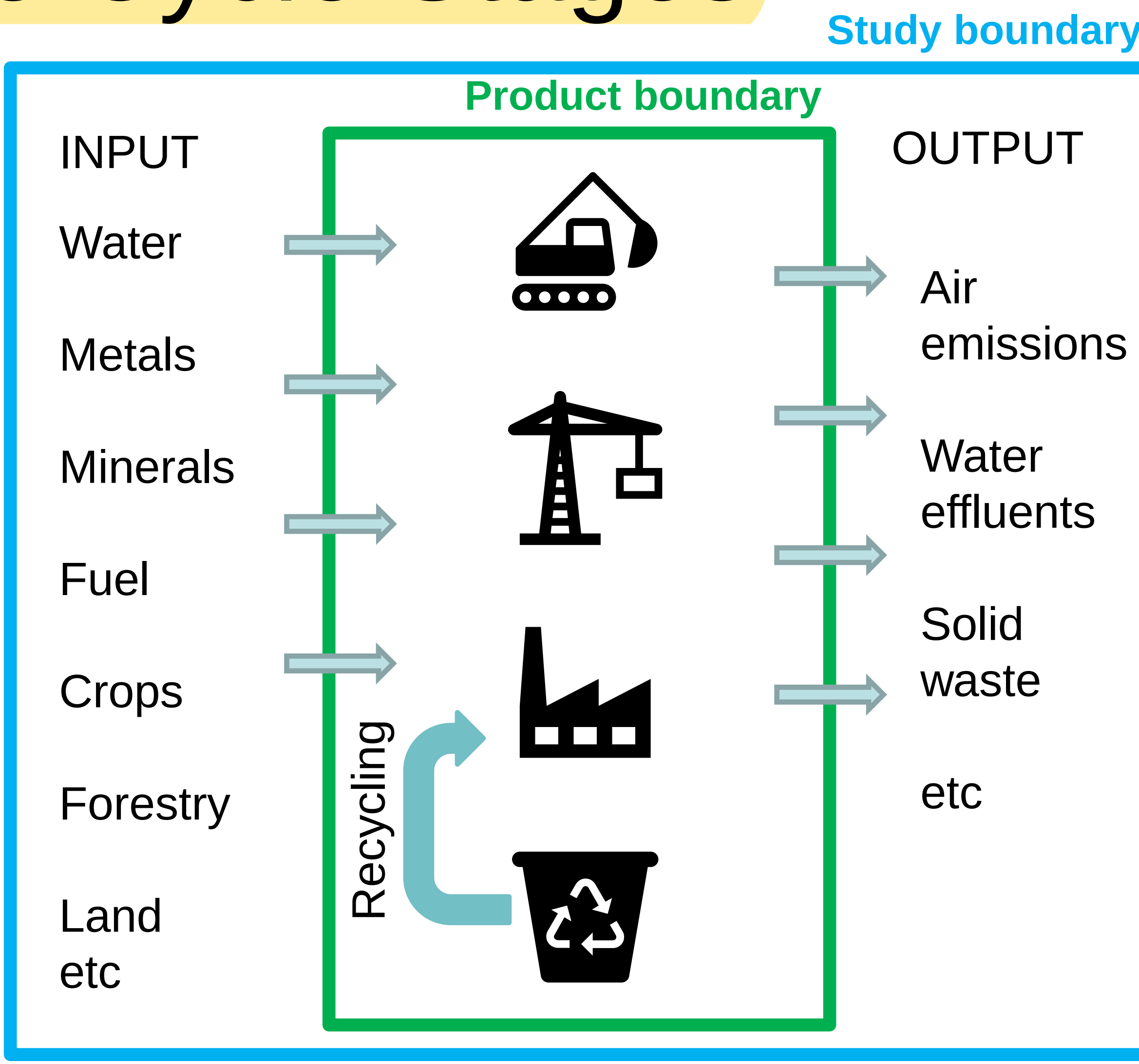
- LCA is also known as **life-cycle analysis** or **cradle-to-grave analysis**
- LCA can help to optimize a process including its interaction with the environment
- In particular it can provide
  - identification of energy and material inputs and environmental releases
  - evaluation of potential impacts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

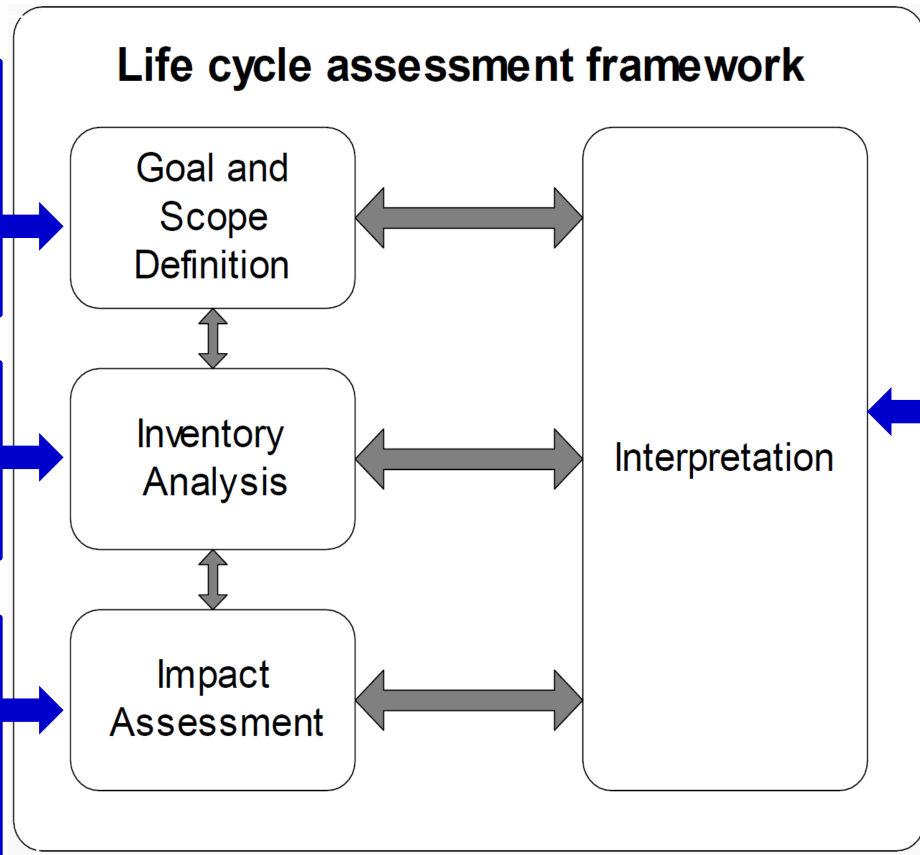


ISO 14040/14044

Determine the scope and system boundaries. Why perform LCA?

Data collection, modelling and analysis

Analysis of inputs and outputs using category indicators. Group normalize, weight results



Draw conclusions, check for completeness, contribution, sensitivity analysis, consistency with goal & scope analysis, etc.

LCA is an iterative process!

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 SO_2 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

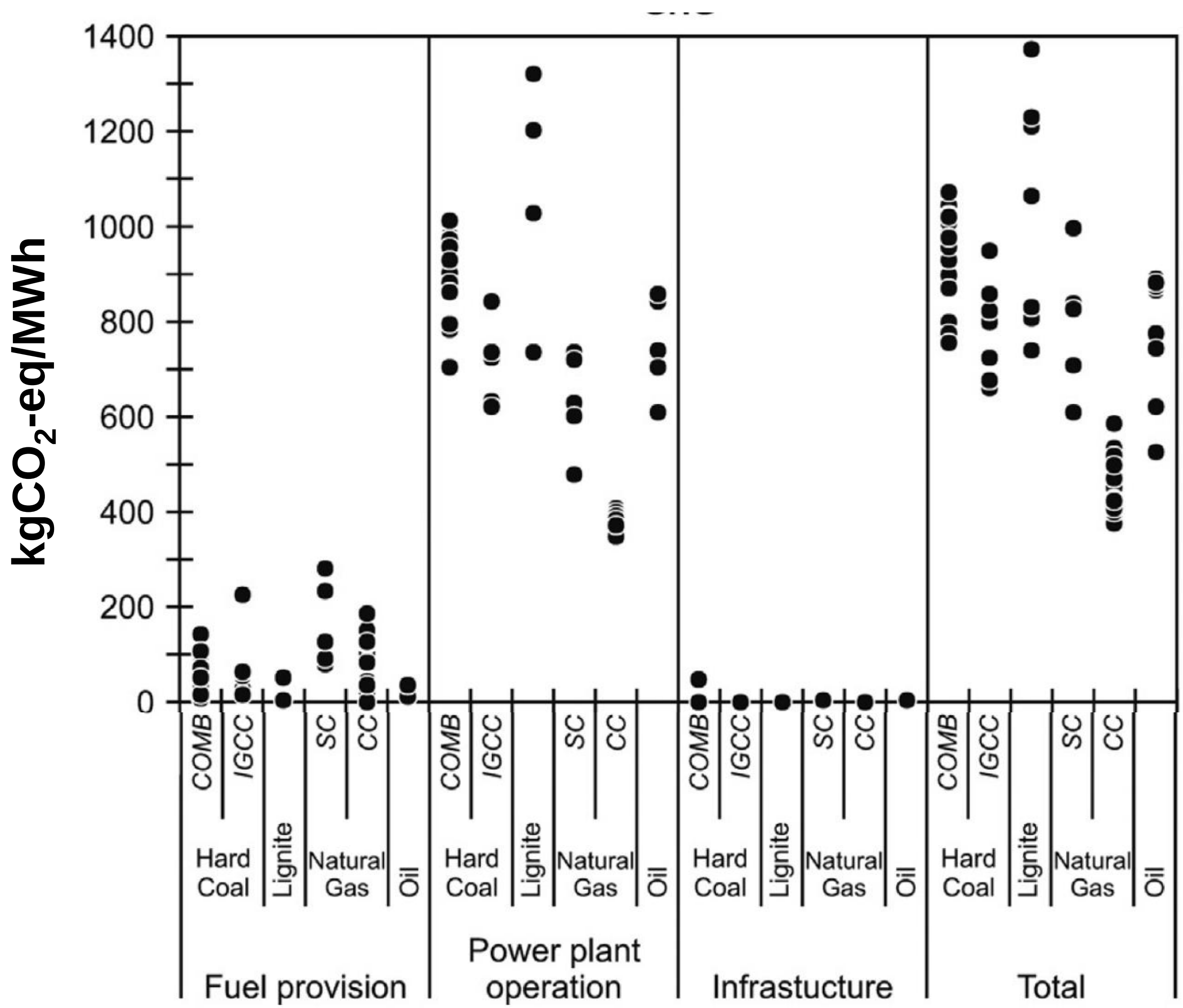
- Emissions of GHG, NO_x and SO_2 were selected based on their importance
  - energy sector contributes with 19% of NO_x, 56% of SO_2 and 40% of GHG emissions
  - NO_x and SO_2 (along with NH_3) are responsible for acidification
  - NO_x (along with NH_3) is responsible for eutrophication

- NH_3 is primarily emitted from animal waste in agriculture, NO_x and SO_2 emissions provide a reasonable approximation for contributions to acidification and eutrophication

Presented Results of the Study

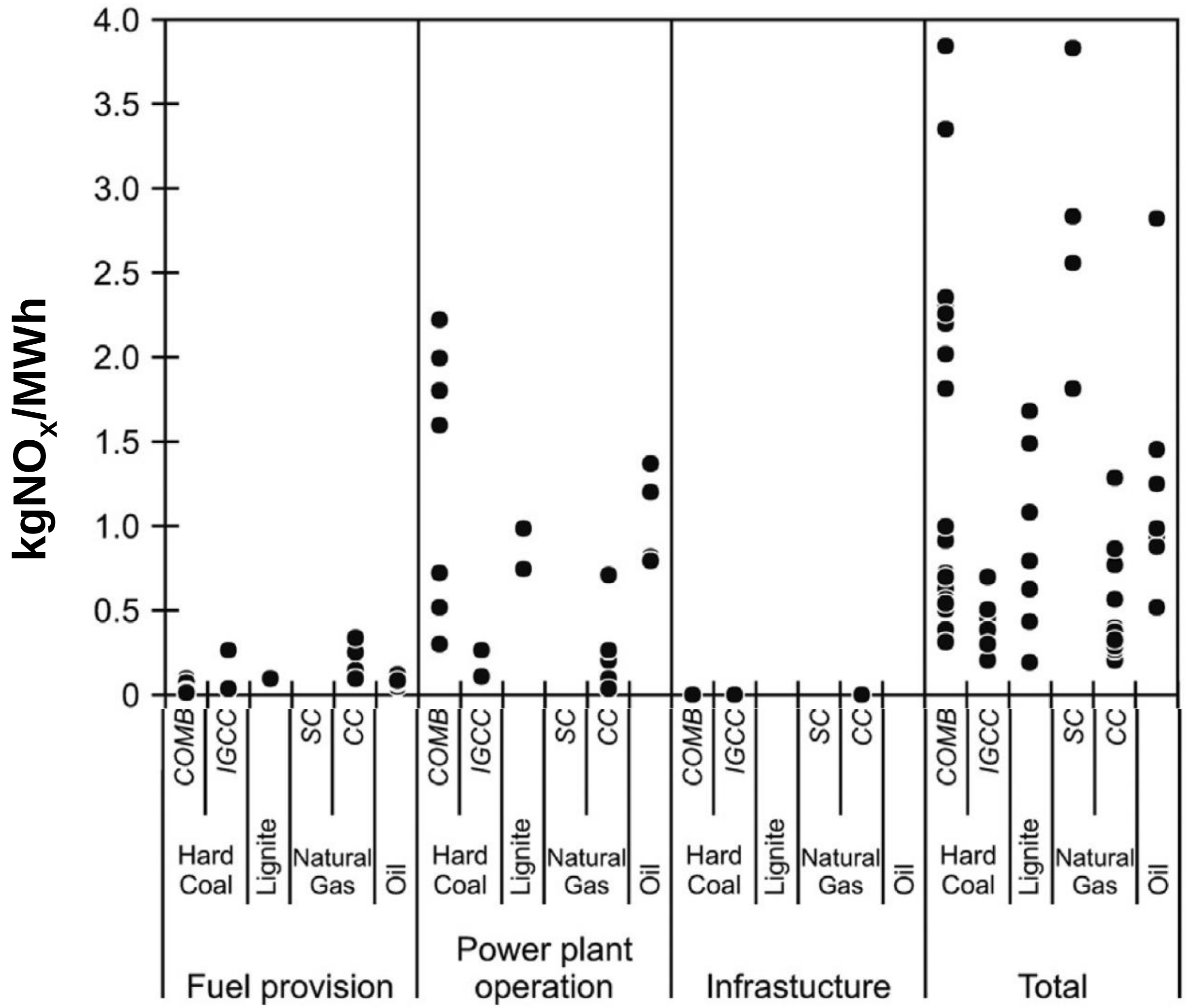
- The results are presented by energy technology
- For each technology, GHG (labelled CO_2-eq), NOx and SO2 emissions were evaluated for the following three life cycle phases:
  - fuel provision (from the extraction of the fuel to the gate of the plant)
  - plant operation (operation and maintenance, including residue disposal)
  - infrastructure (commissioning and decommissioning)

GHG Emissions from Fossil Fuels



COMB – direct combustion
IGCC – coal gasification
SC – single cycle
CC – combined cycle

NO_x Emissions from Fossil Fuels



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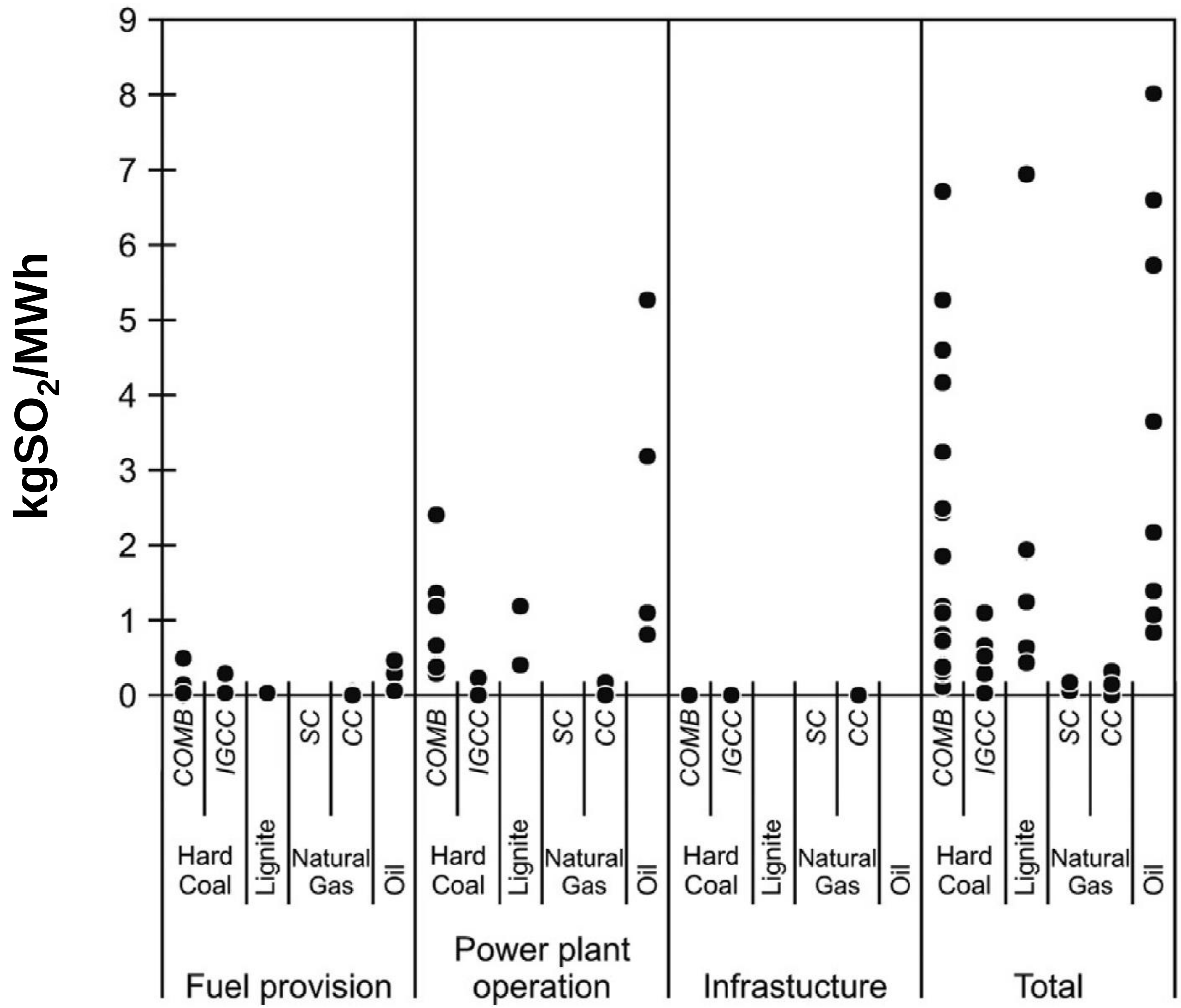
SO_2 Emissions from Fossil Fuels



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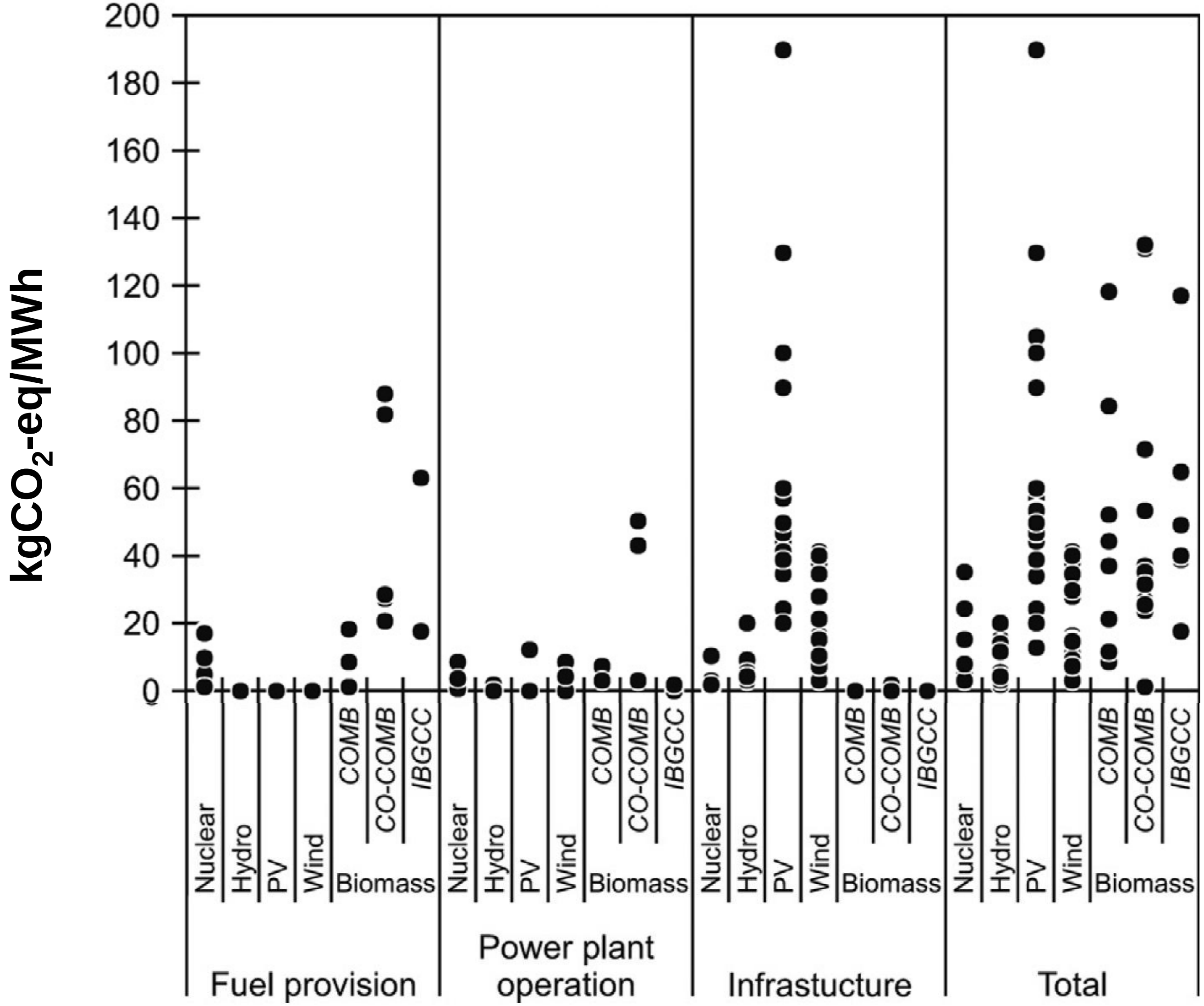
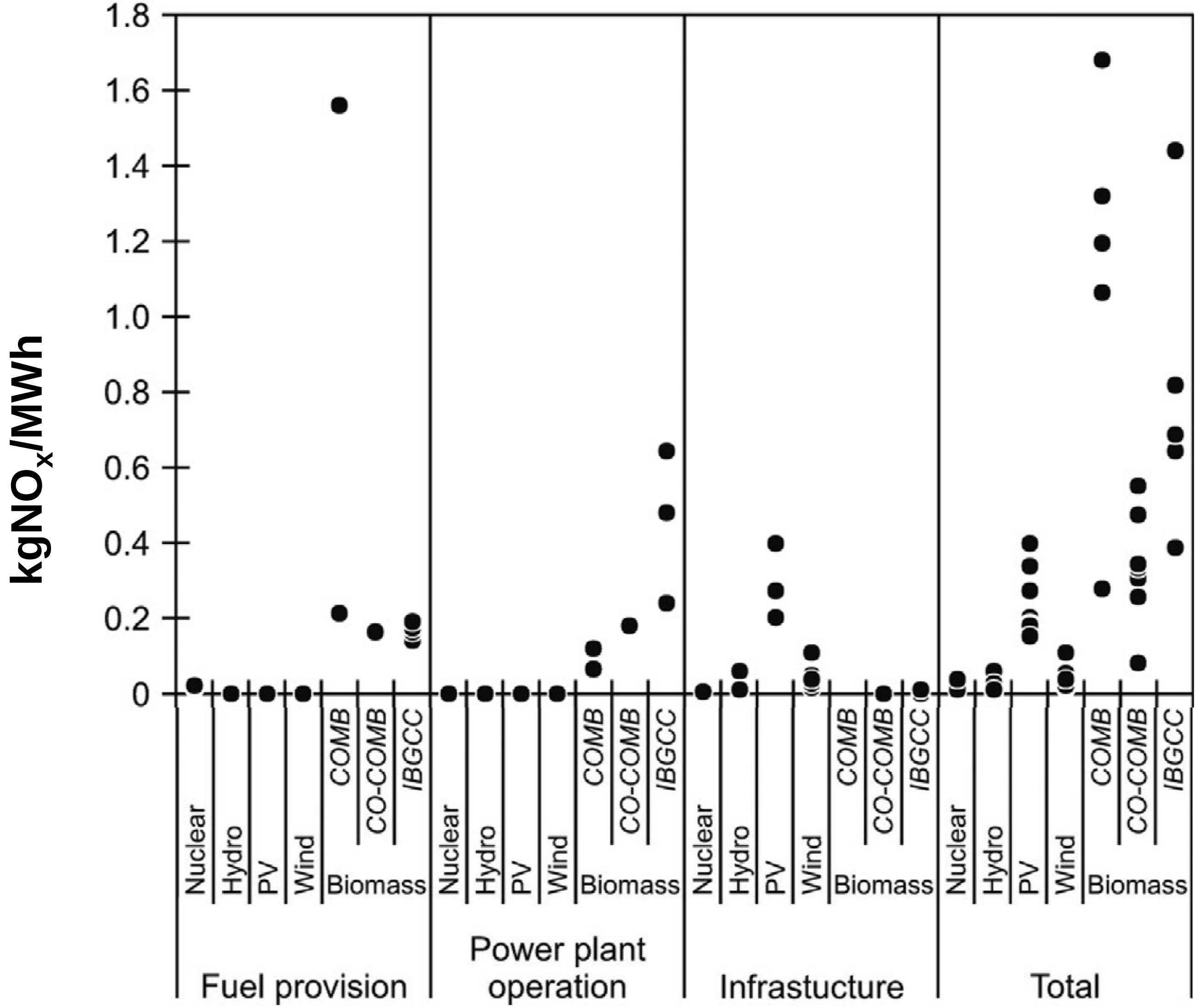
GHG Emissions from Renewables&Nuclear



COMB – direct combustion
CO-COMB – co-combustion with fossil fuel
IBGCC – biomass gasification

NO_x Emissions from Renewables&Nuclear



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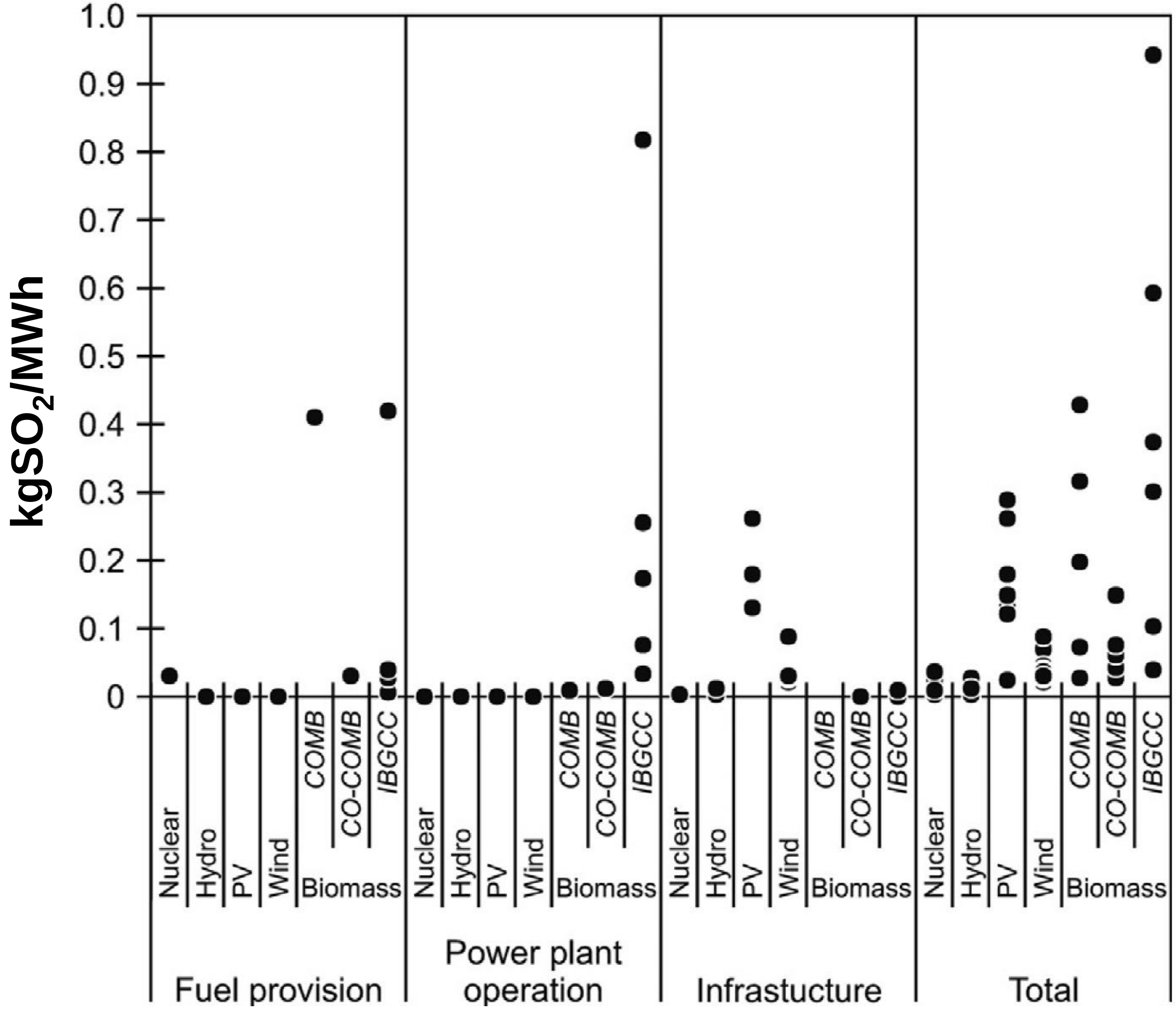
SO_2 Emissions from Renewables&Nuclear



COMB – direct combustion

CO-COMB – co-combustion with fossil fuel

IBGCC – biomass gasification

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÷1050 kgCO_2-eq/MWh
  - emissions for coal gasification (IGCC) is 660÷800 kgCO_2-eq/MWh mainly due to higher efficiency (up to 52%)
- Data for NO_x and SO_2 emissions from direct combustion showed significant variability (2÷4 kgNO_x/MWh and 2÷7 kgSO_2/MWh for old plants; 0.3÷1 kgNO_x/MWh and 0.1÷1 kgSO_2/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 kgCO_2-eq/MWh
- Similar to hard coal, NO_x and SO_2 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 kgCO_2-eq/MWh
- Fuel provision represented up to 30% of GHG emissions
- SC plants had higher emissions: 610÷850 kgCO_2-eq/MWh

Summary for Oil

- 10 studies were included
- GHG and NOx emissions were mainly related to plant operation
- In base load operation energy efficiency is high (<=58%) and the corresponding GHG emission is 530 kg/CO_2-eq/MWh
- Peak-load power has lower efficiency (30-40%) and the GHG emissions increase to 750-900 kg/CO_2-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 kgCO_2-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 SO_2 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÷5 kgCO_2-eq/MWh for run-of-river systems and 11÷20 kgCO_2-eq/MWh for dam-reservoirs
- The highest emissions were found in IOA study

IOA – Input-Output Analysis

Summary for Solar PV

- 22 studies included
- GHG emissions showed great variability: 13÷130 kgCO_2-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

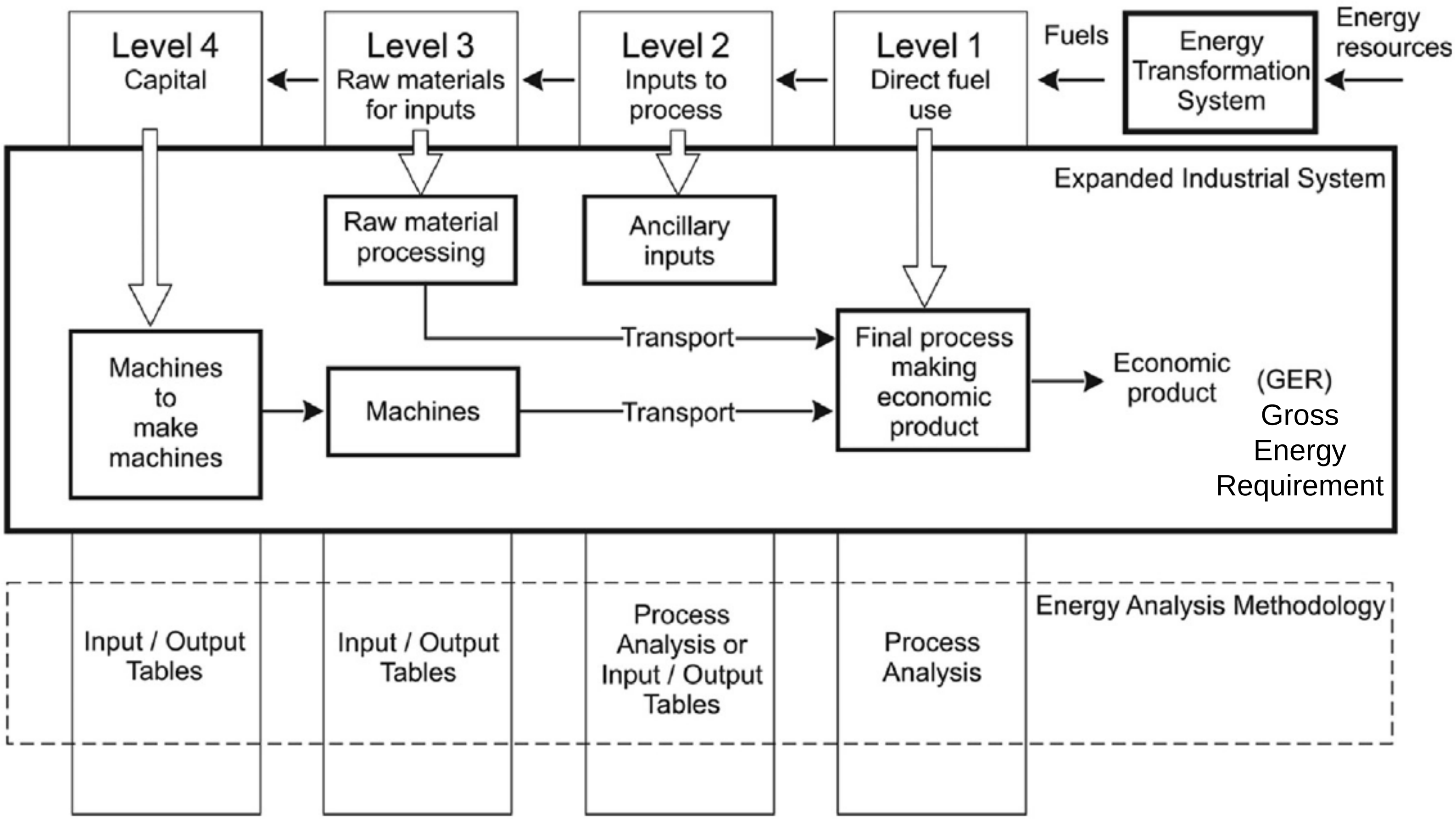
Method

- Energy Analysis (EA) on a life-cycle analysis
  - it is necessary to trace the flow of energy through the relevant industrial sector
  - Based on 1^{st} principle of Thermodynamics: the sum of all the outputs from the system **x** their energy requirements must be equal to the sum of inputs **x** 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

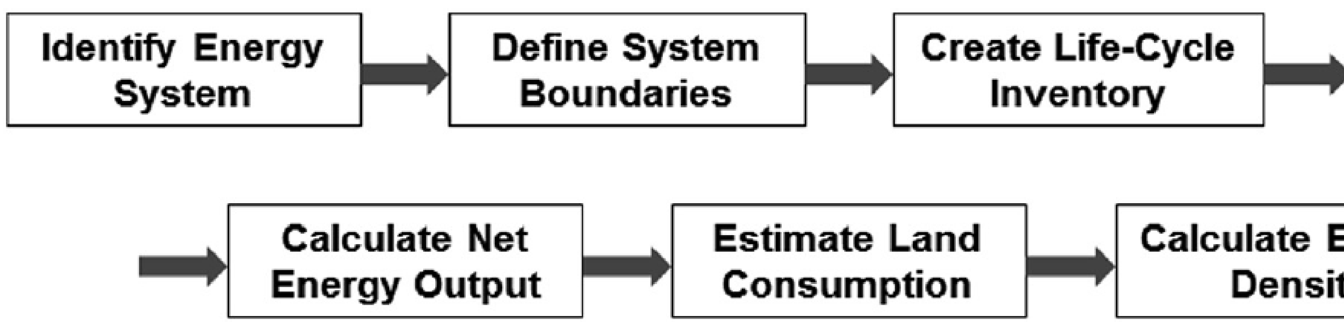
    $E_{con,L}$ - total energy invested in construction

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

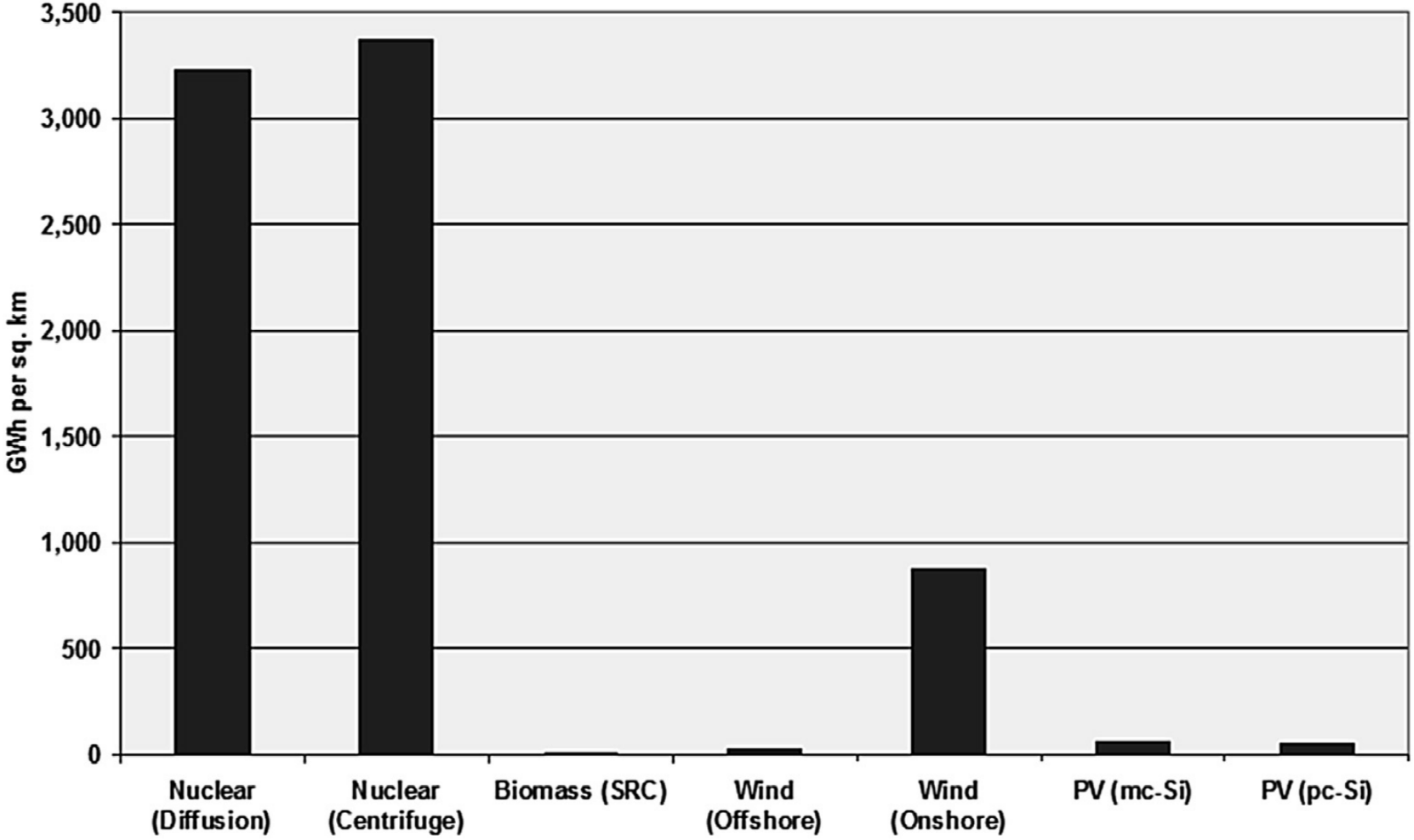
    $E_{dec,L}$ - total energy required for decommission of plant

Energy Density – Spatial Footprint

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

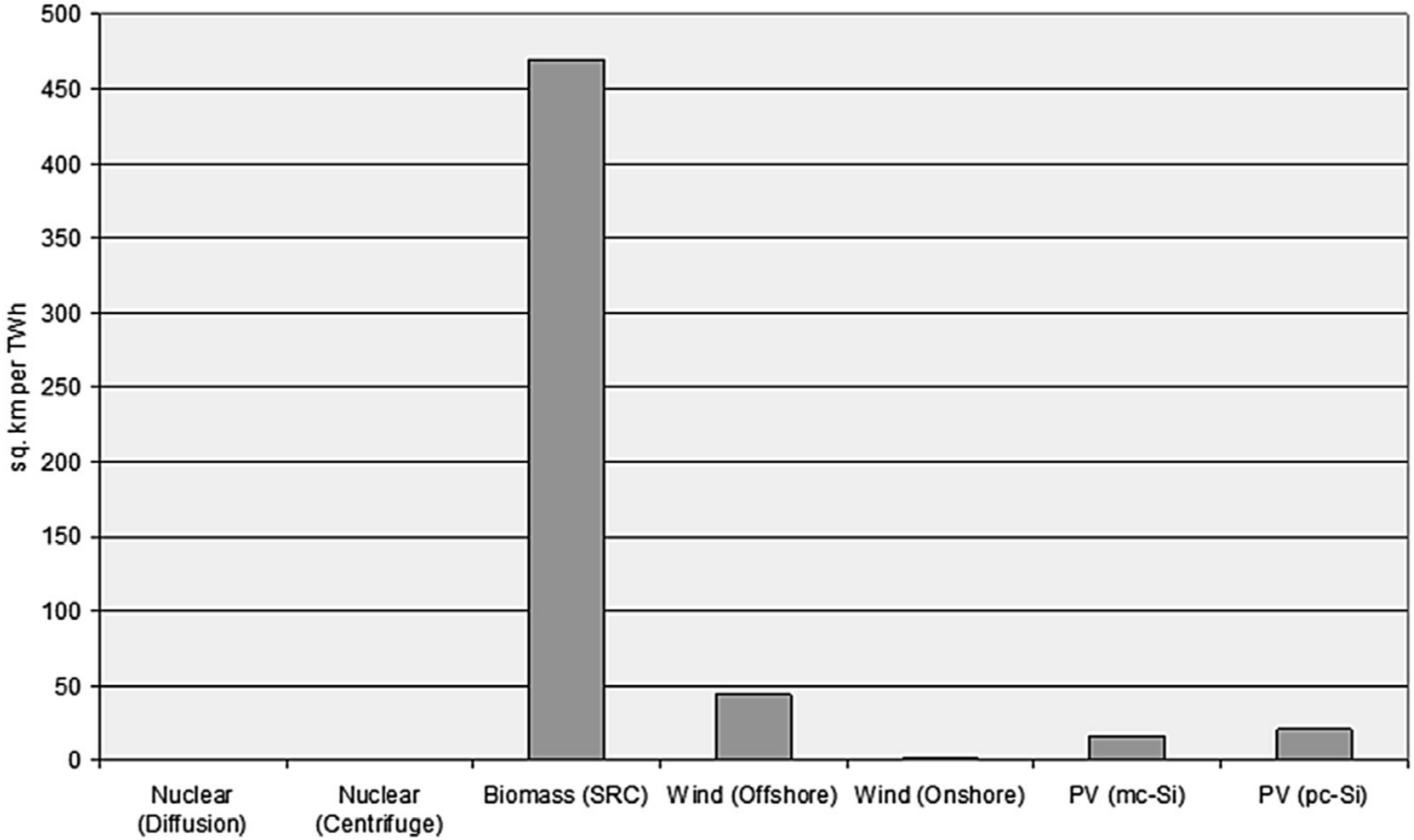


Results – Energy Density



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 Calculational 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

$$C' = \frac{C}{1+i}$$

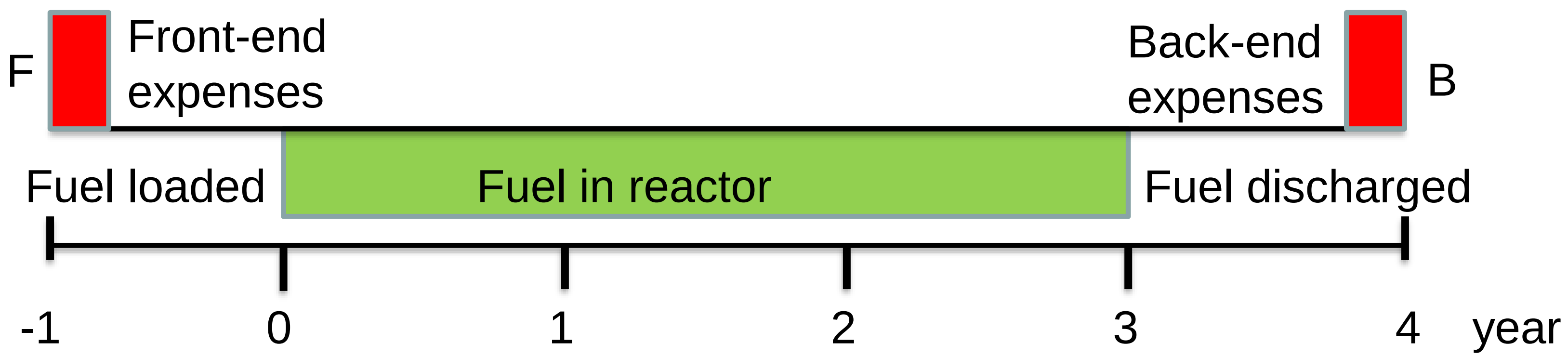
C' is a current value of an expense C

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: $PV = F\left(1+i\right) + B\big/\left(1+i\right)^4$

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.

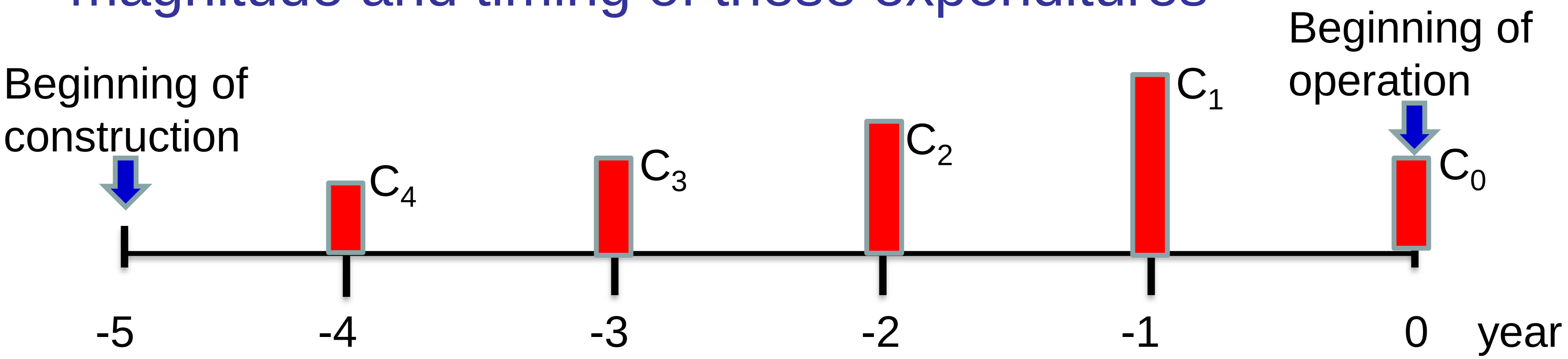
- The effective deflated interest rate will be:

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

- 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

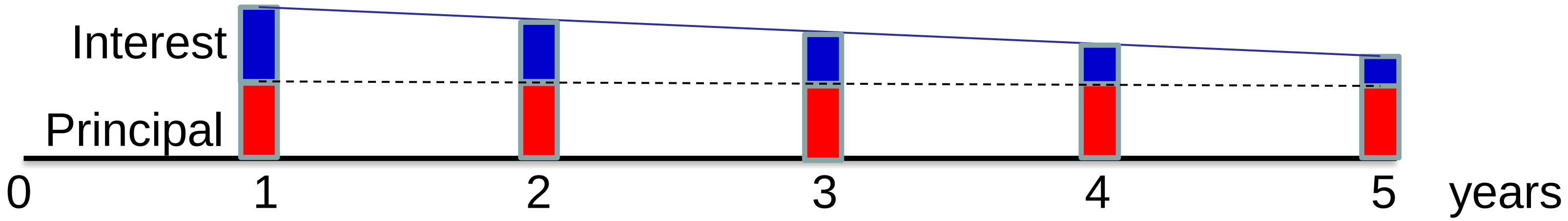


- The total capital cost is the sum of present value of all expenditures. Using year 0 as the reference time point:

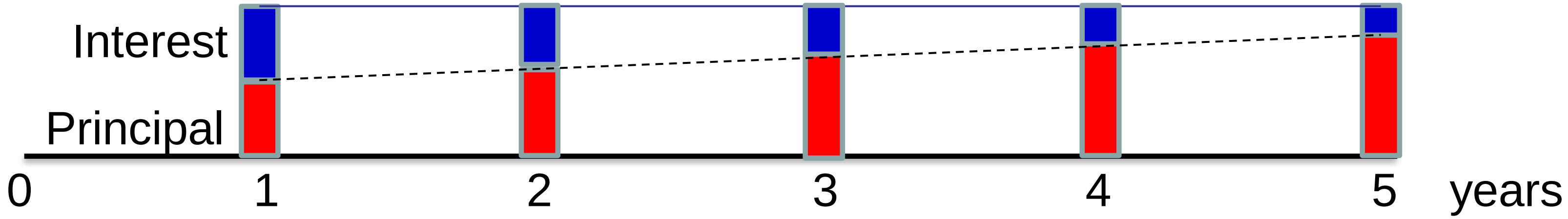
$$C = C_0 + C_1\left(1+i\right) + C_2\left(1+i\right)^2 + C_3\left(1+i\right)^3 + C_4\left(1+i\right)^4 = \sum\nolimits_{k=0}^{4} C_k\left(1+i\right)^k$$

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

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

- 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 $\boldsymbol{C_u}$ 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})** x **number of units produced (E)**
- The revenue in each year will cover the expenditure in the year if $\mathbf{L_{cap}}$ x $\mathbf{E = C_u}$
- 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 $\boldsymbol{L_{fc}}$ 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

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

Revenues

- As already noted, the annual revenue required to cover a capital investment is $L_{cap} * E$,
  - 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

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

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

Capital Tax - L_{ctax}

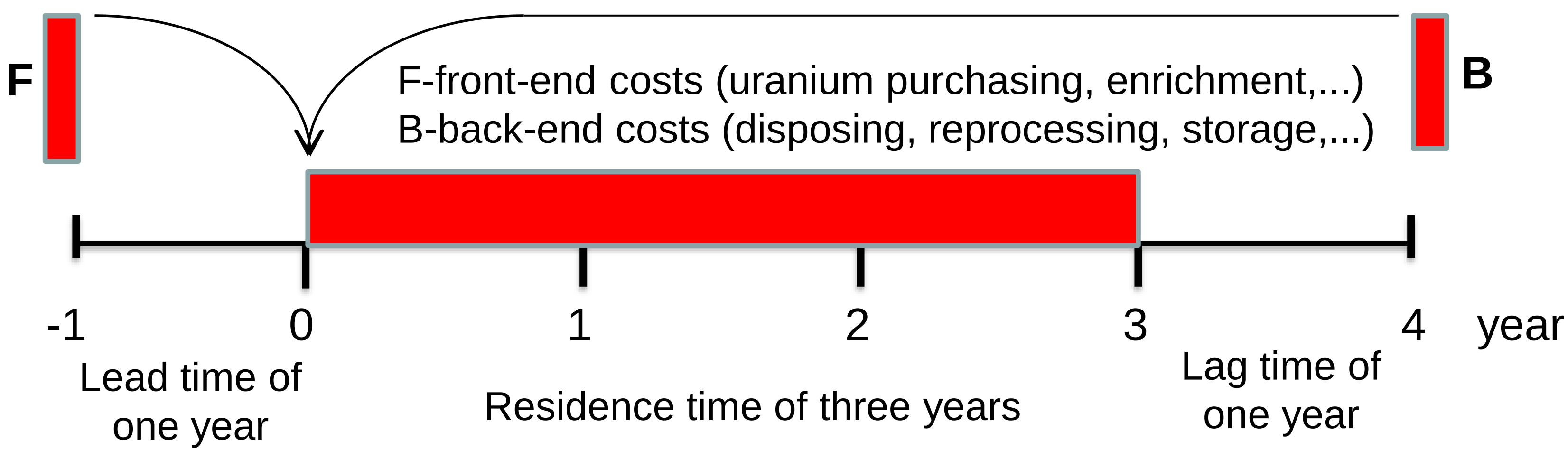
- Including also interests paid on bonds and depreciation, the levelized cost of electricity to cover taxes on capital can be found as:

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

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

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

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 expences on fuel can be found as

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

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:

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

The total Power Cost - LCOE

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

$$L_{tot} = LCOE = \underbrace{L_{cap}}_{\text{Capital cost}} + \underbrace{L_{ctax}}_{\text{Tax on revenues}} + \underbrace{L_{fc}}_{\text{Fixed charges}} + \underbrace{L_{b}}_{\text{Fuel cost}} + \underbrace{L_{btax}}_{\text{Fuel tax}} + \underbrace{L_{om}}_{\text{O\&M cost}}$$

- 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
Tax rate	0.5
Plutonium (€/g)	30
Capital cost of plant (€/kWe)	1000
Fixed O&M cost (€/kWe/y)	17
Variable O&M cost (€/kWe/y)	1

core fabricat. (€/kg)	1150
Axial bl. fabr. (€/kg)	50
Radial bl. fab (€/kg)	150
core reprocess (€/kg)	600
Axial bl. reprocess (€/kg)	600
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

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

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

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

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

Fixed Charges

- Fixed charges on a capital investment are found as

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

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

O&M

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

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

$$\frac{\left(17\,\frac{€}{\text{kWe}\cdot\text{y}}\times 1000\cdot 10^{3}\,\text{kWe} + 1\,\frac{€}{\text{kWe}\cdot\text{y}}\times 0.70\times 1000\cdot 10^{3}\,\text{kWe}\right)\times 10^{2}\,\frac{¢}{€}}{6.1\times 10^{9}\,\frac{\text{kWh}}{\text{y}}} = 0.29\,\frac{¢}{\text{kWh}}$$

The levelized power cost

- Similar calculations gives:

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

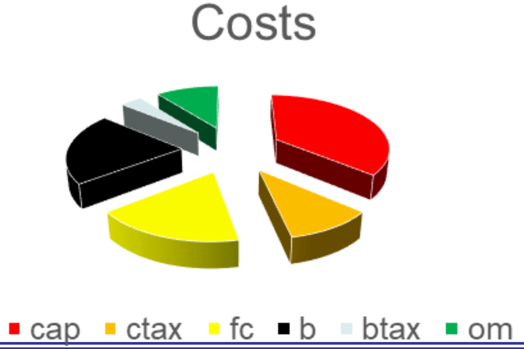
$$L_b = \frac{F(1+i)^{ld} + \frac{B}{(1+i)^{lg+N}}}{\frac{E}{N}\left[\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \cdots + \frac{1}{(1+i)^N}\right]} = 0.59\frac{¢}{\text{kWh}}$$

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

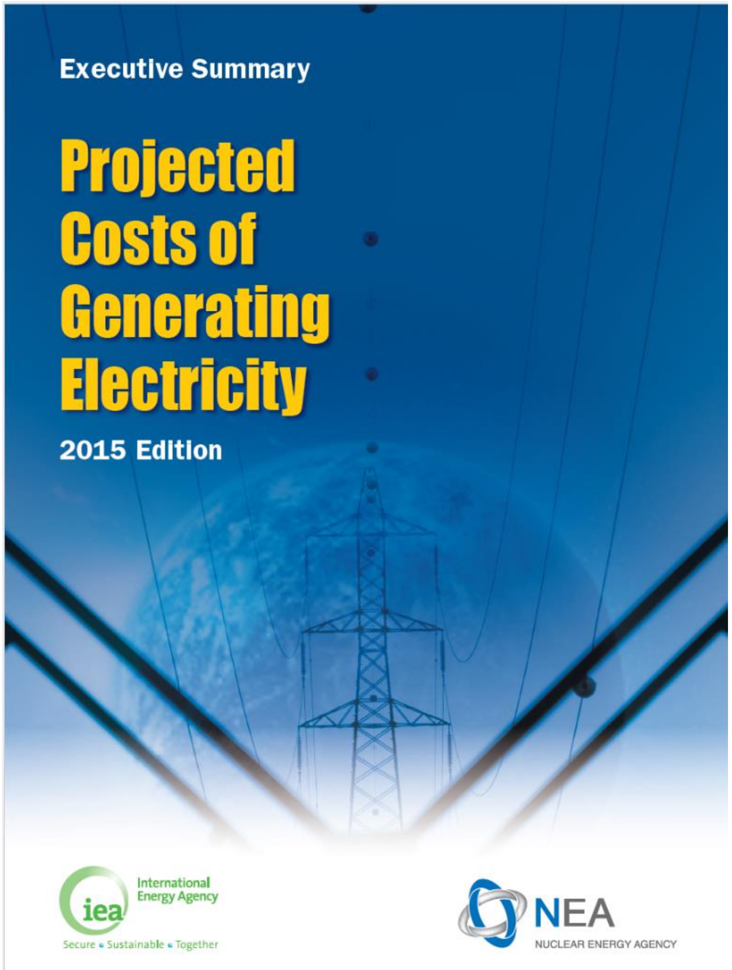
Total

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

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



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 CO_2 emissions

LCOE Calculation

- The following formula is used in the study

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

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*

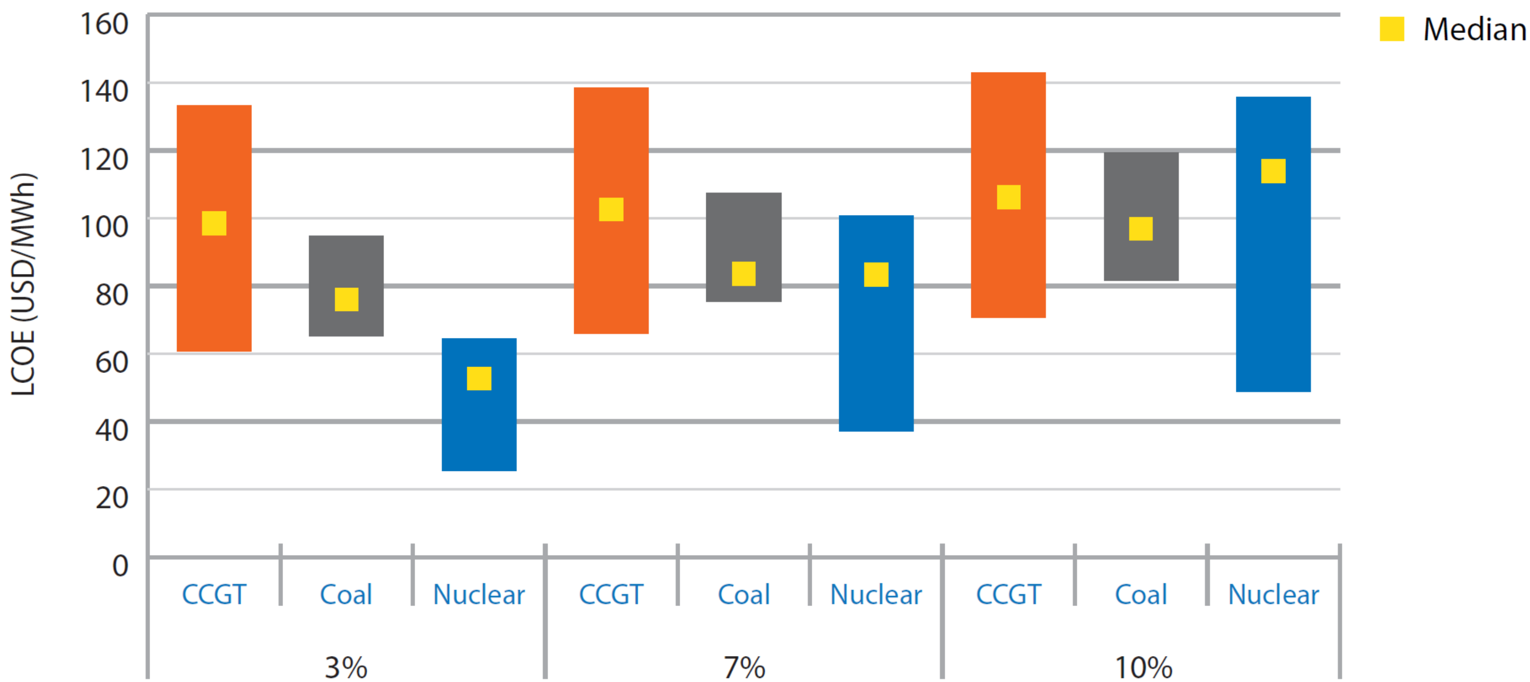
Carbon$_k$: carbon cost in year *k*

Decommissioning$_k$: decommissioning cost in year *k*

Assumptions

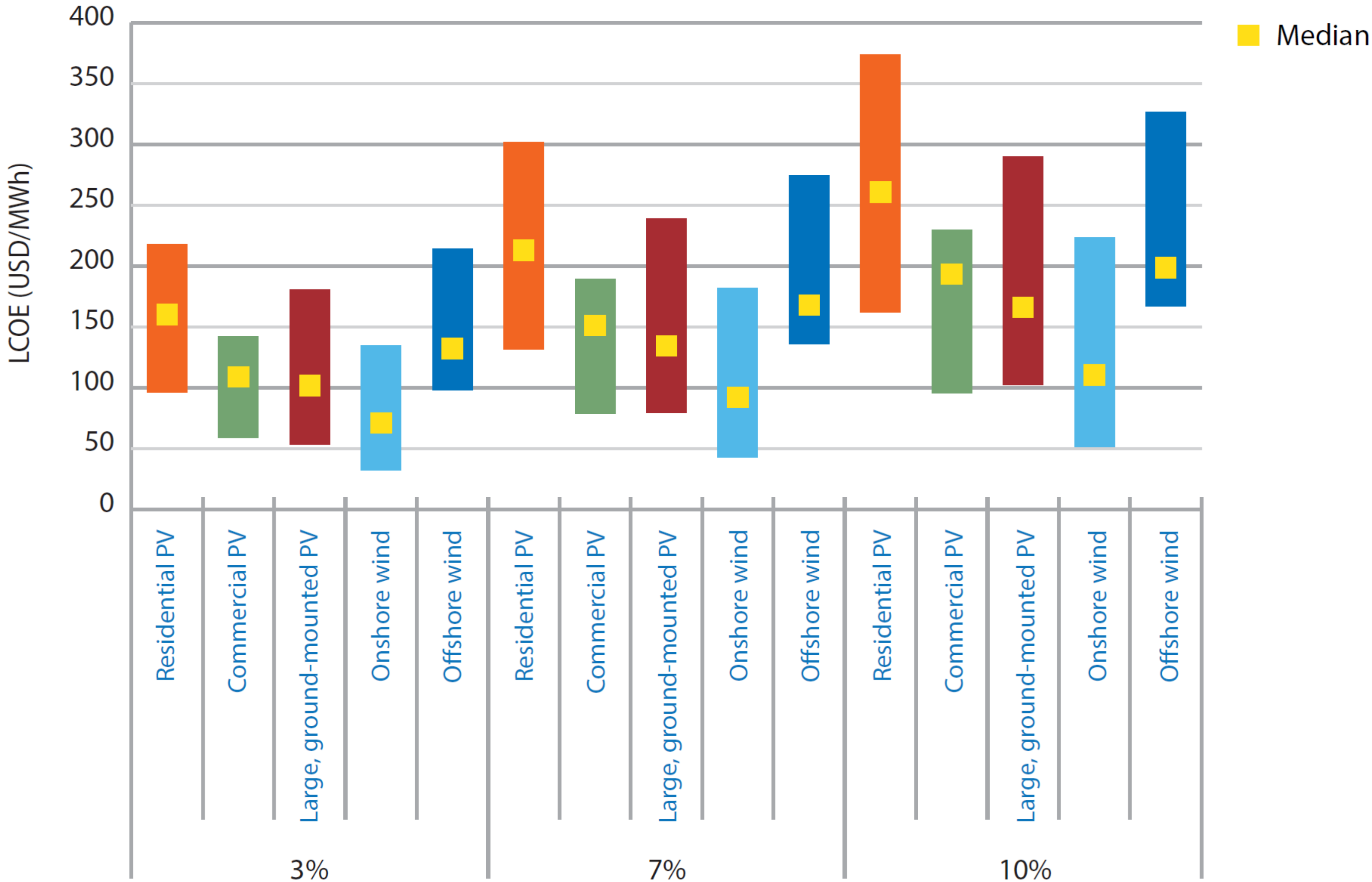
- For baseload technologies a standard load factor of 85% has been chosen – country-specific for renewables
- The cost of the compensating electricity for variable technologies (wind and solar) is not taken into account
- Such compensating capacity must be mobilised at short notice and they otherwise 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

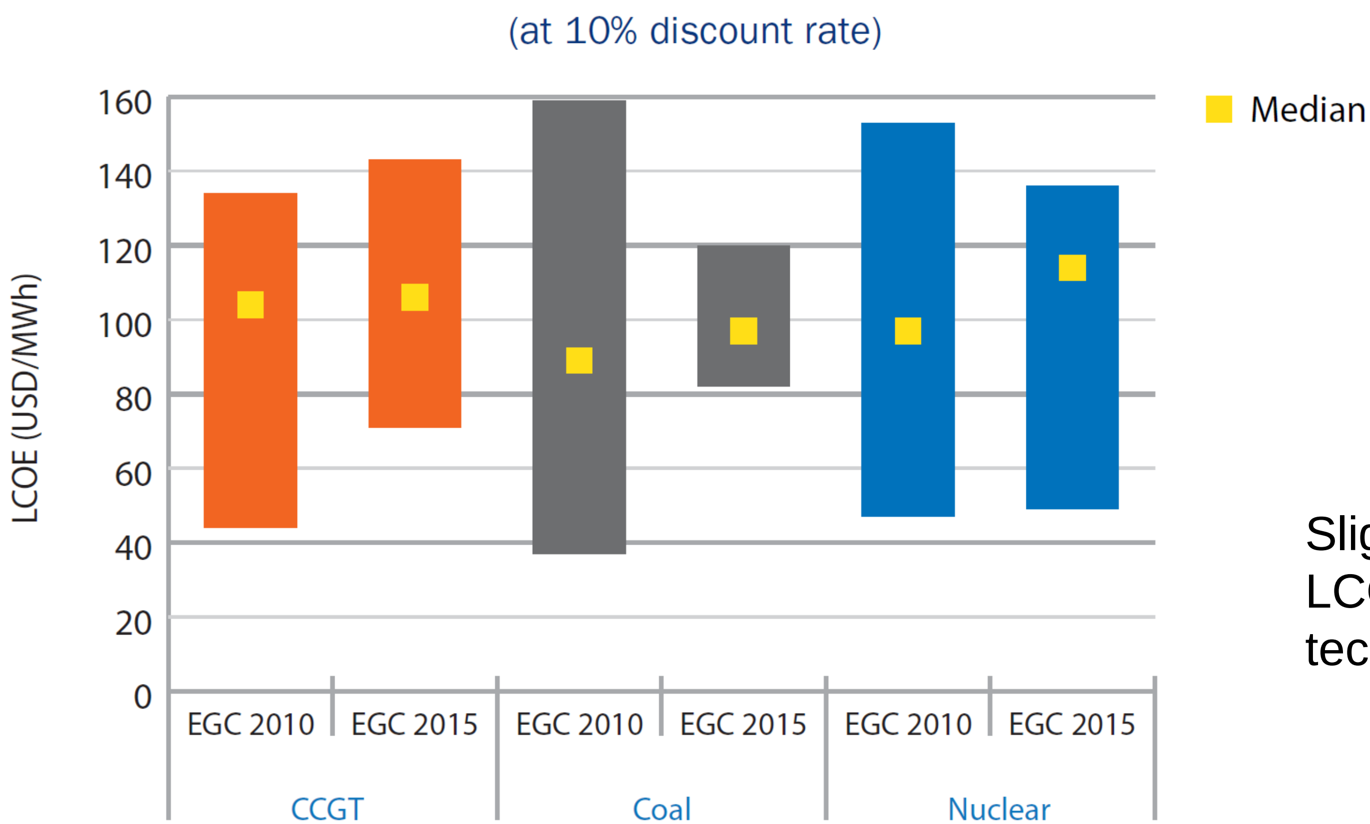


Ranges presented include results from all countries analysed in the study (1821 plants in 22 countries)

LCOE Ranges Solar PV & Wind

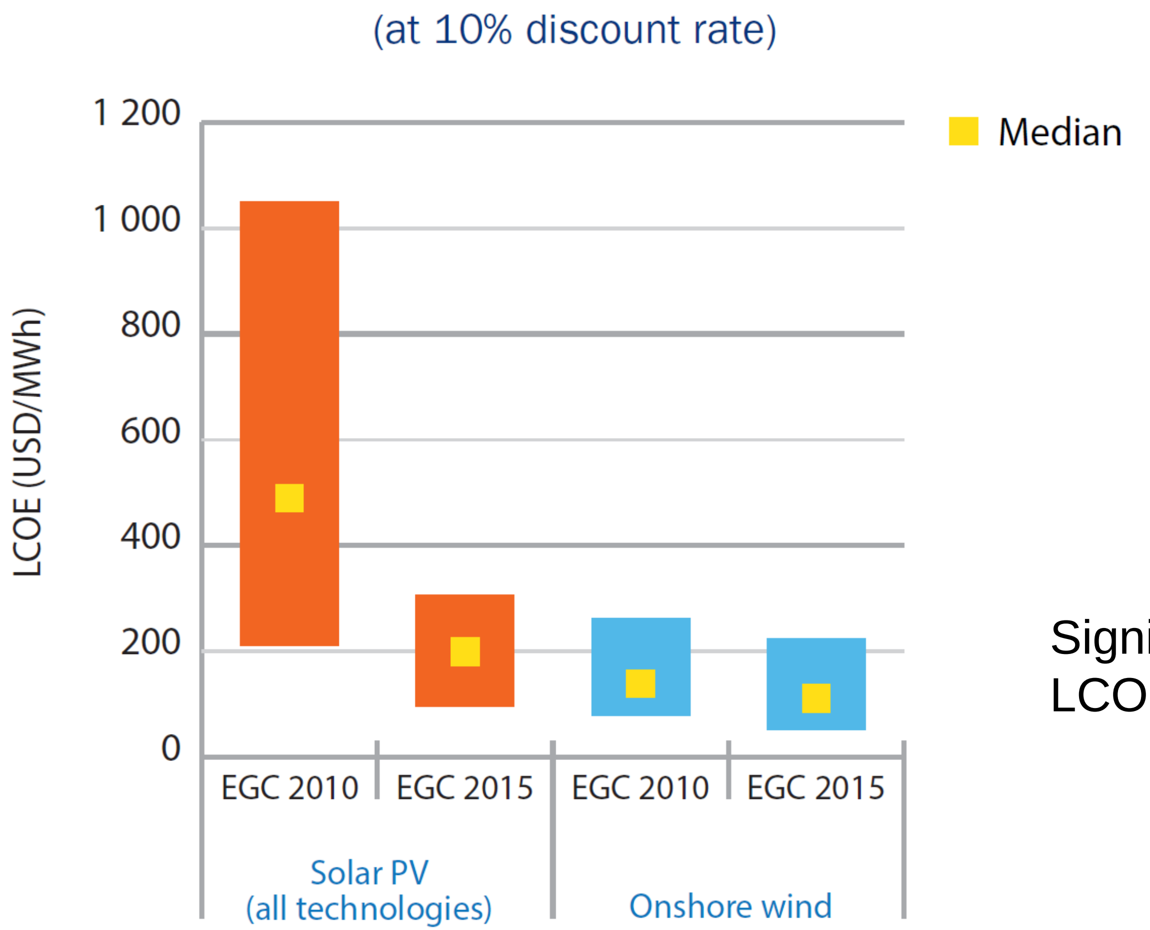


2010-2015 Comparison: Baseload



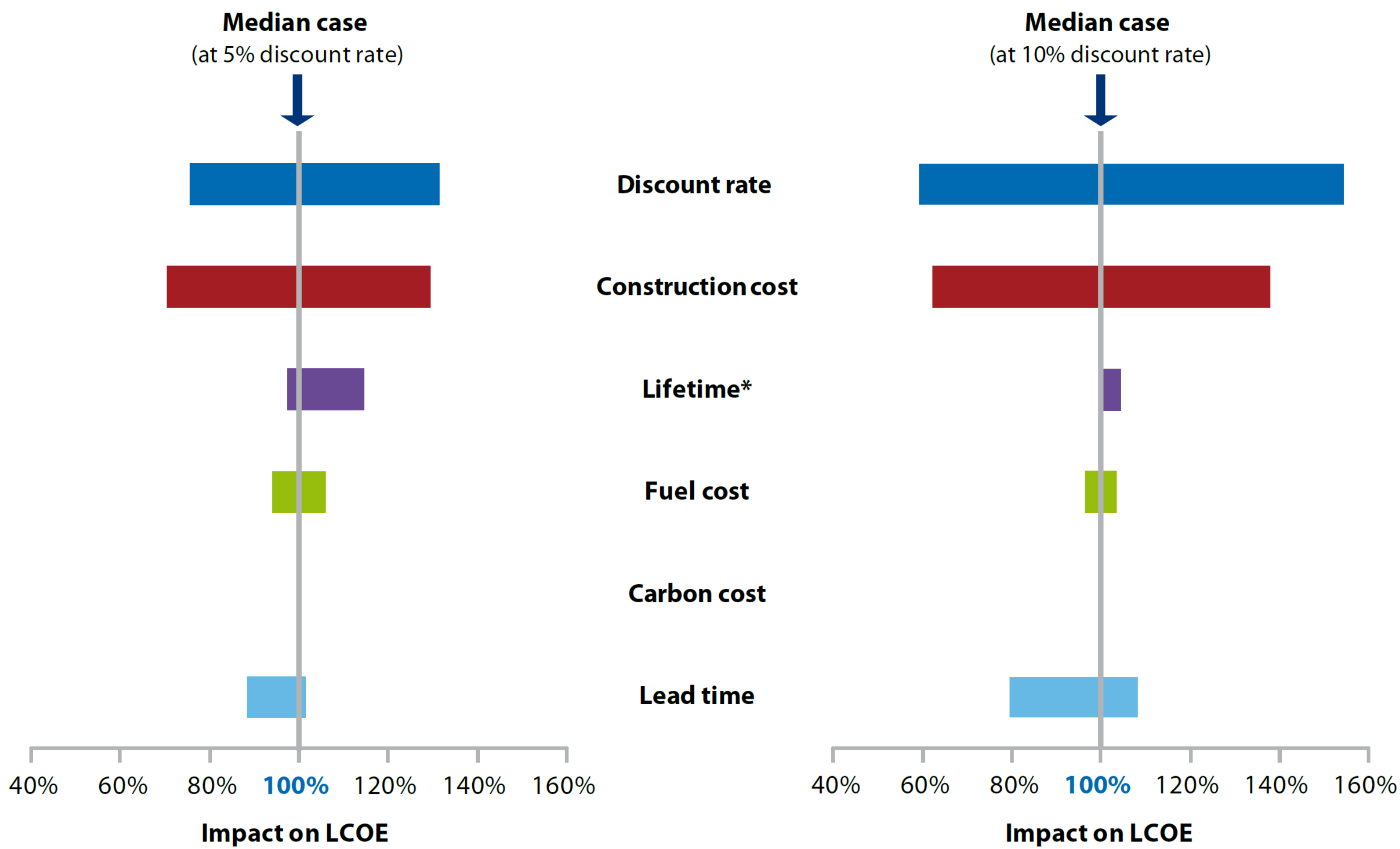
Slight increase of LCOE for all technologies

2010-2015 Comparison: PV&Wind



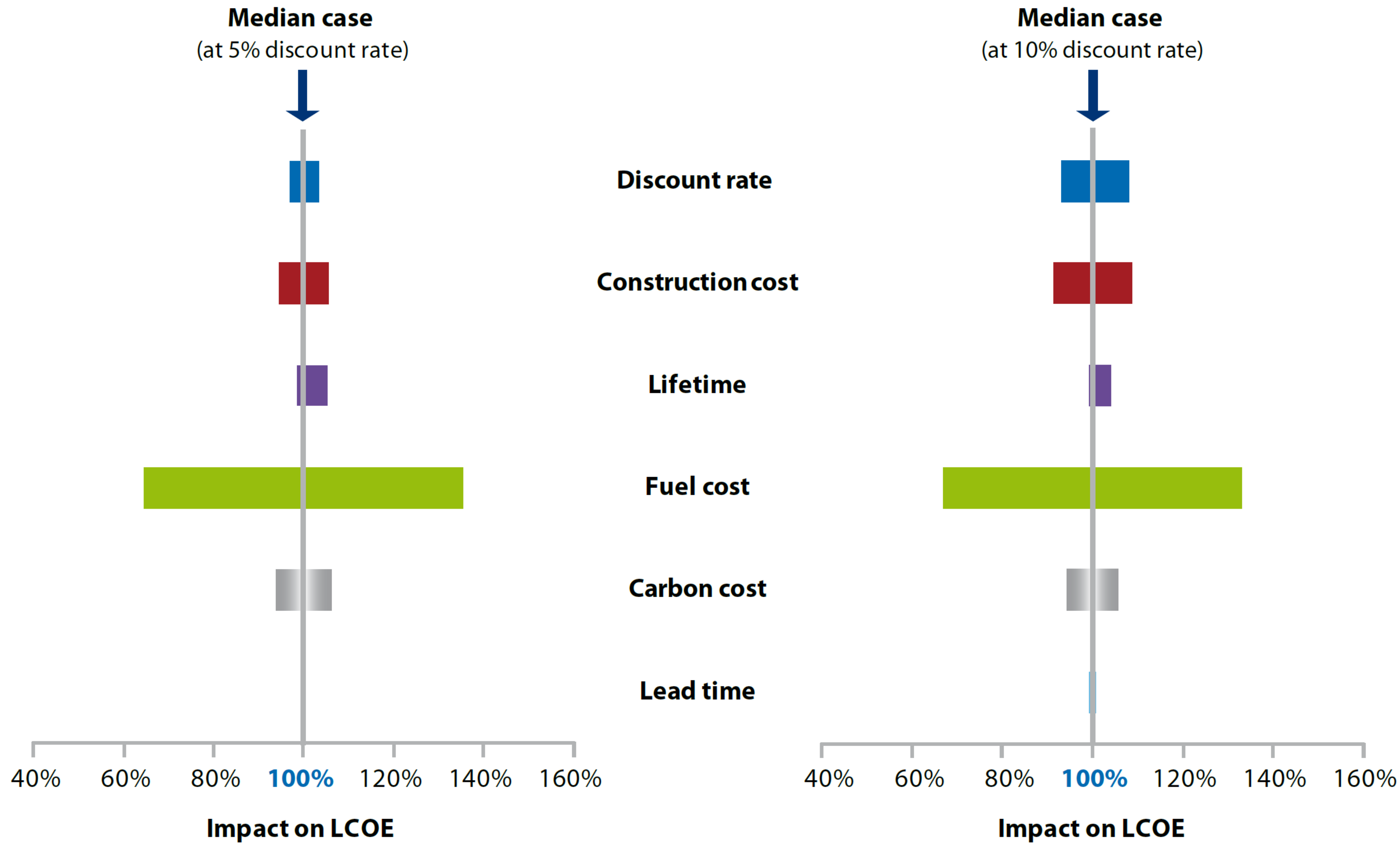
Significant drop of LCOE for solar PV

Sensitivity of LCOE for Nuclear



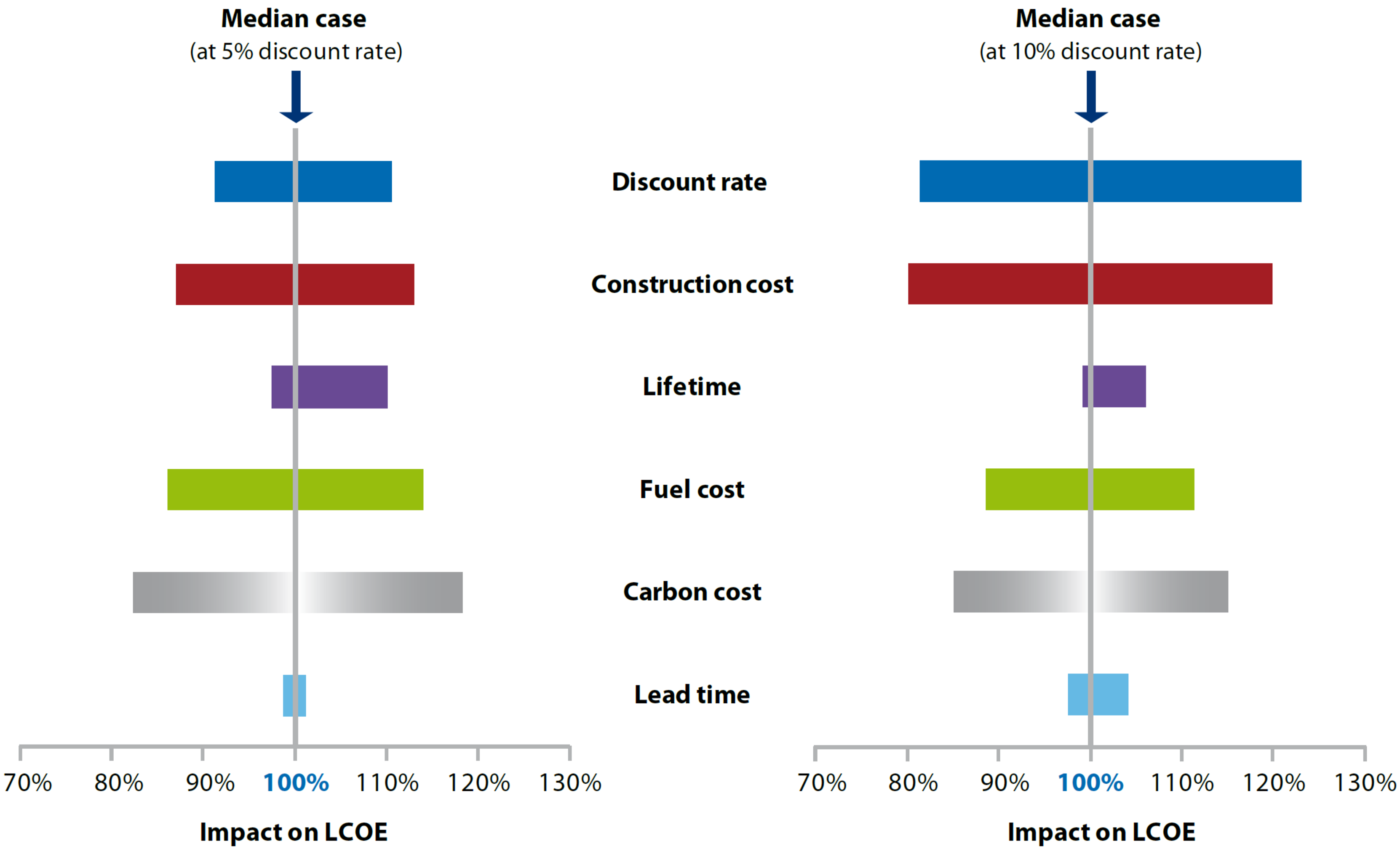
IEA&NEA 2010

Sensitivity of LCOE for Gas



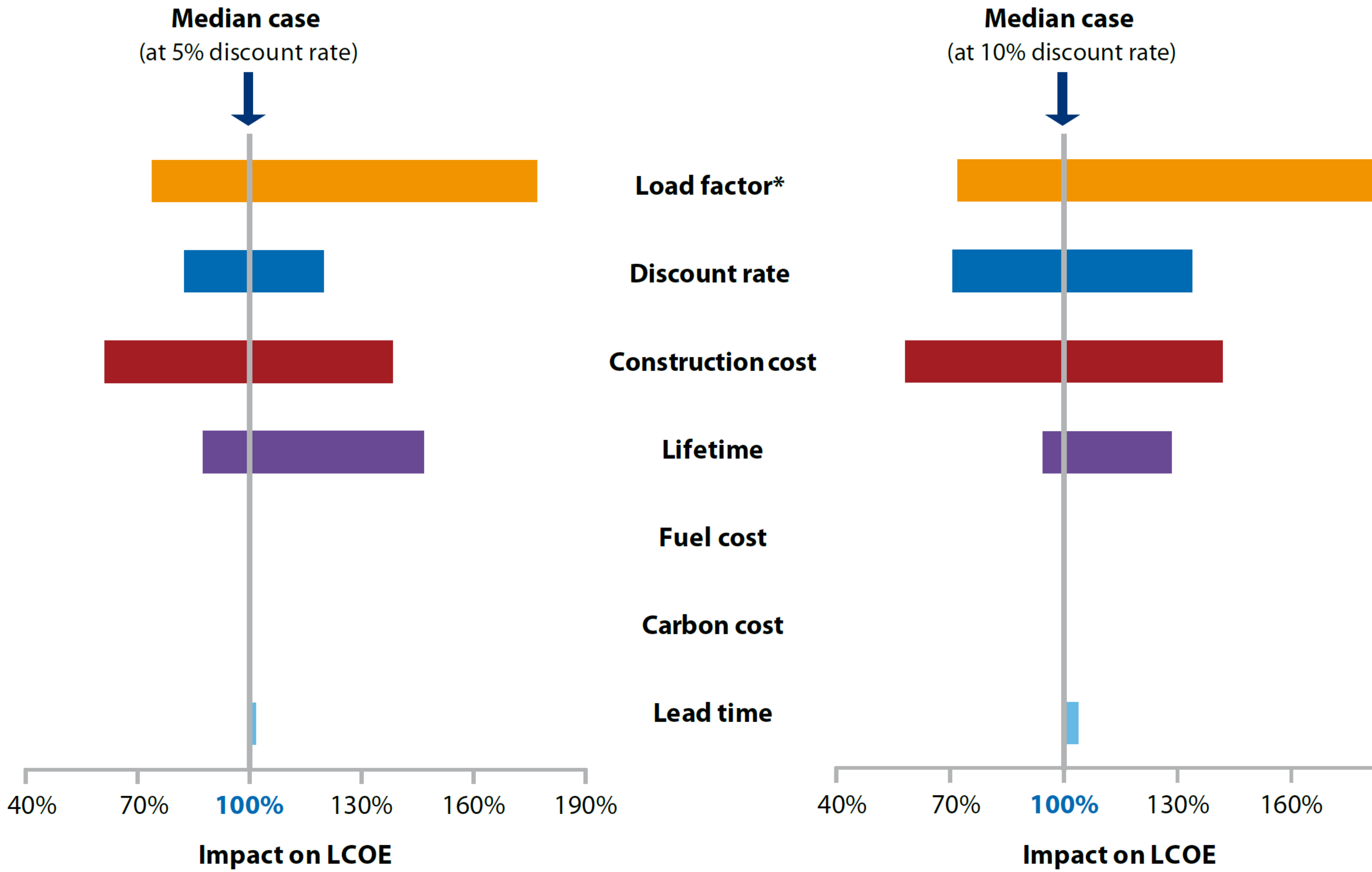
IEA&NEA 2010

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