ETH zürich

RRE
Reliability and Risk Engineering

Introduction to Modeling and Optimization of Sustainable Energy Systems:

Techno-economic Key Performance Indicators (KPIs)

Prof. Dr. Giovanni Sansavini
Reliability and Risk Engineering

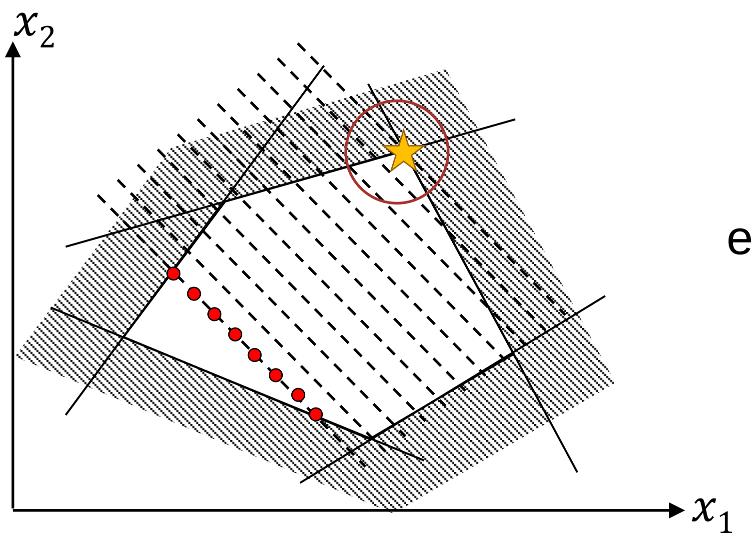
Since the last lecture, you are able to …

✓ Define and critically evaluate environmental KPIs deriving from life cycles assessment (LCA)

Optimization problem: The objective function is key

$$\min_{\boldsymbol{x}} \quad z = f(\boldsymbol{x})$$

$$\begin{aligned} \text{s.t.} \quad & g_j(x) \leq 0, \quad && j = 1, \dots, n \\ & h_i(x) = 0, \quad && i = 1, \dots, o \end{aligned}$$



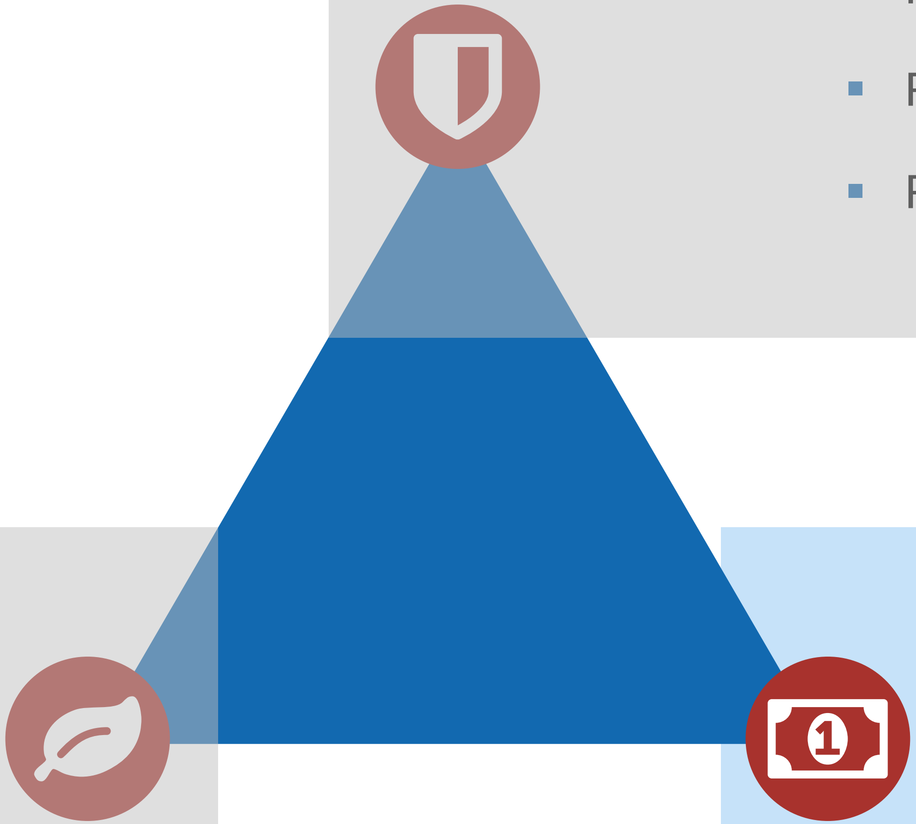
e.g. linear problem (Lecture 2)

Energy trilemma: Different metrics for different requirements

Lecture 8

availability of sources
ensuring supply of energy
Security

- Reliability
- Risk
- Resilience



Thermodynamic

- Cumulative energy demand (CED)
- Conversion and storage efficiency

Lecture 6

Sustainability
climate protection
life cycle

Equity
price development
competition

- Net Present Value (NPV)
- Internal Rate of Return (IRR)
- Levelized Cost of Energy (LCOE)
- Total Annual Cost (TAC)

After this lecture, you are able to …

Define and critically evaluate:

- Thermodynamic KPIs for energy systems:
  - Cumulative energy demand (CED), related to LCA seen in Lecture 6
  - Energy conversion efficiency
  - Energy storage efficiency (round-trip efficiency vs. self-discharge efficiency)

- Economic KPIs for energy systems:
  - Net present value (NPV)
  - Internal rate of return (IRR)
  - Levelized cost of energy (LCOE)
  - Total annual cost (TAC)

ETH zürich

RRE
Reliability and Risk Engineering

Thermodynamic KPIs:
CED, conversion and storage efficiencies

Cumulative Energy Demand (CED)

Definition (VDI 4600)

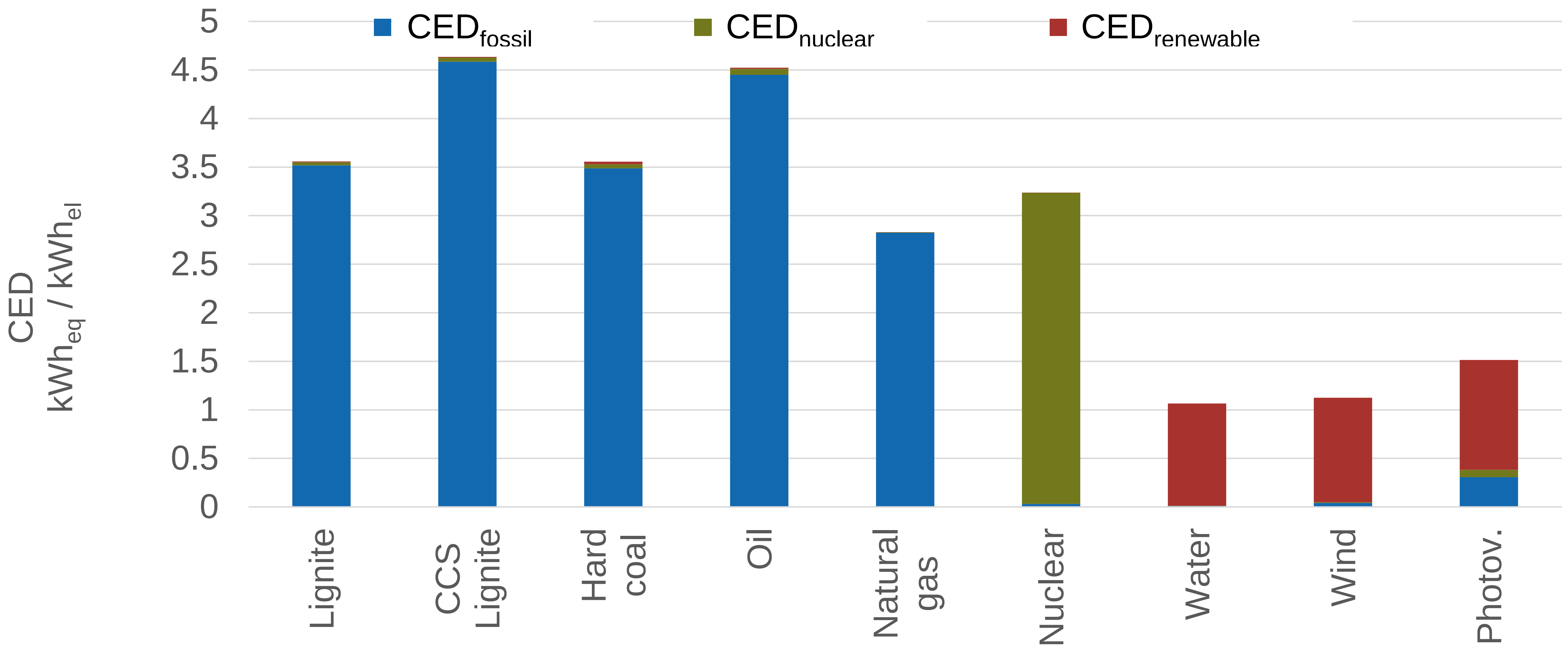
The CED states the entire demand,
valued as primary energy,
which arises in connection with the

- production,
- use,
- disposal

of an economic good (product or service).

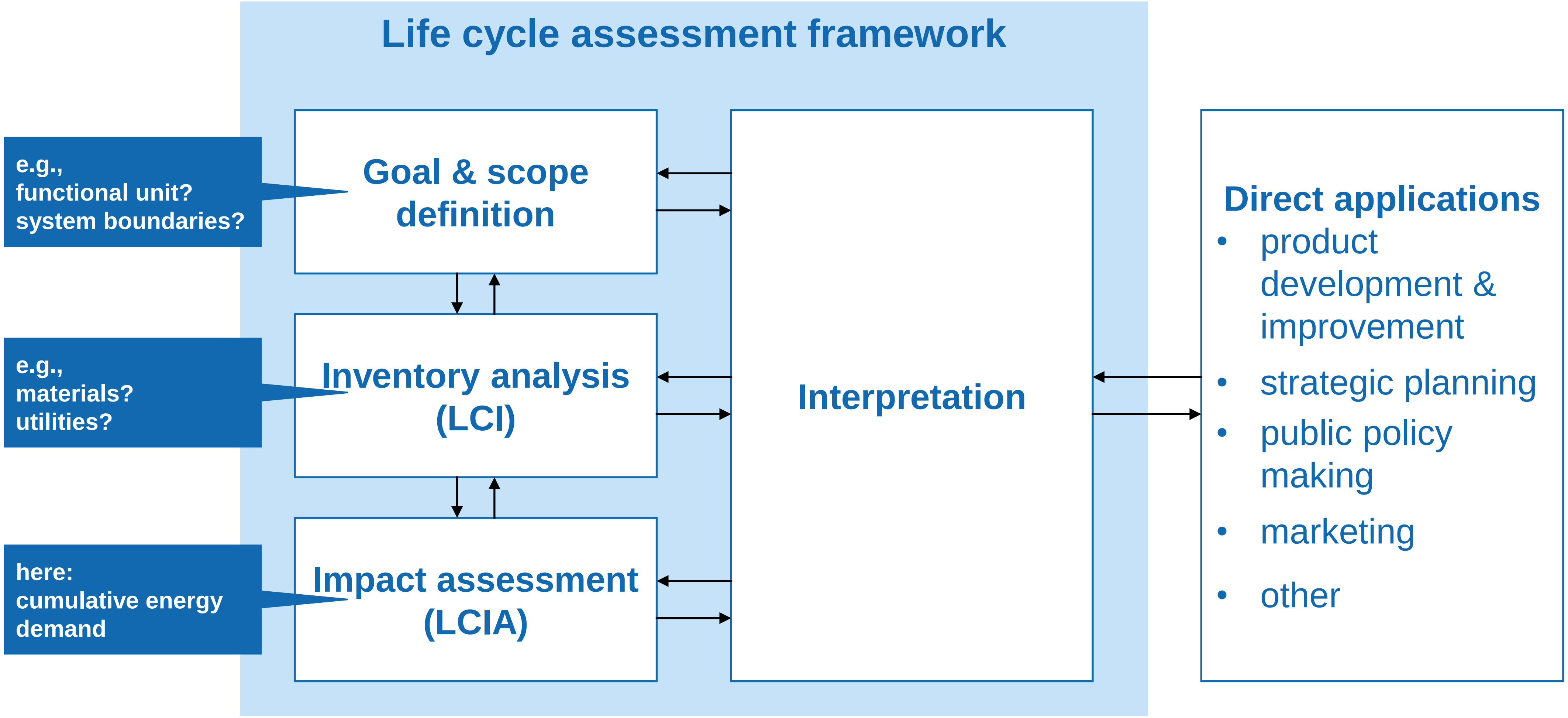
The Life Cycle Perspective

Cumulative energy demand of power generation technologies



How to obtain the life-cycle CED?

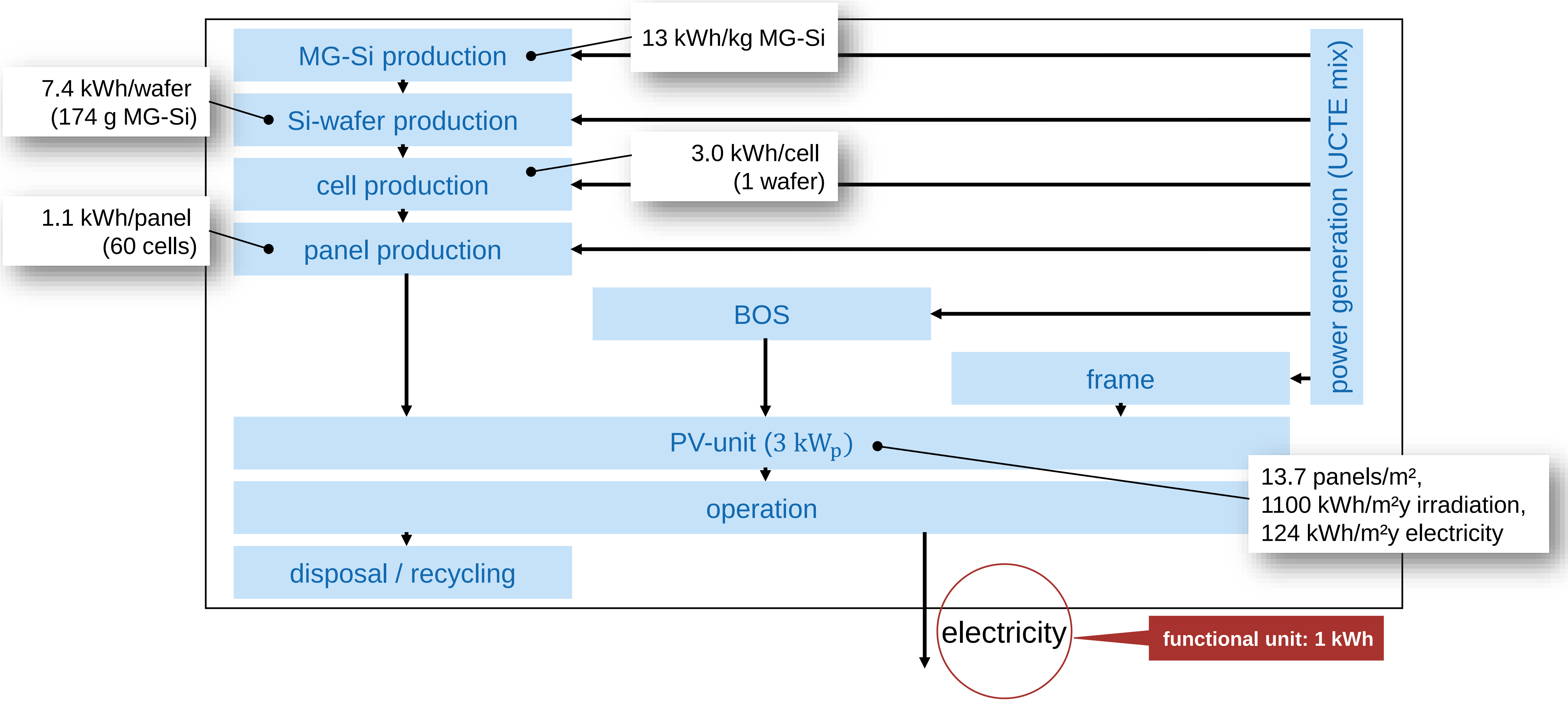
Stages of life cycle assessment (DIN EN ISO 14040)



Follow life cycle assessment approach!

DIN EN ISO 14040:2021-02.

Example: Photovoltaic power generation (I)



Example: Photovoltaic power generation (II)

a/b

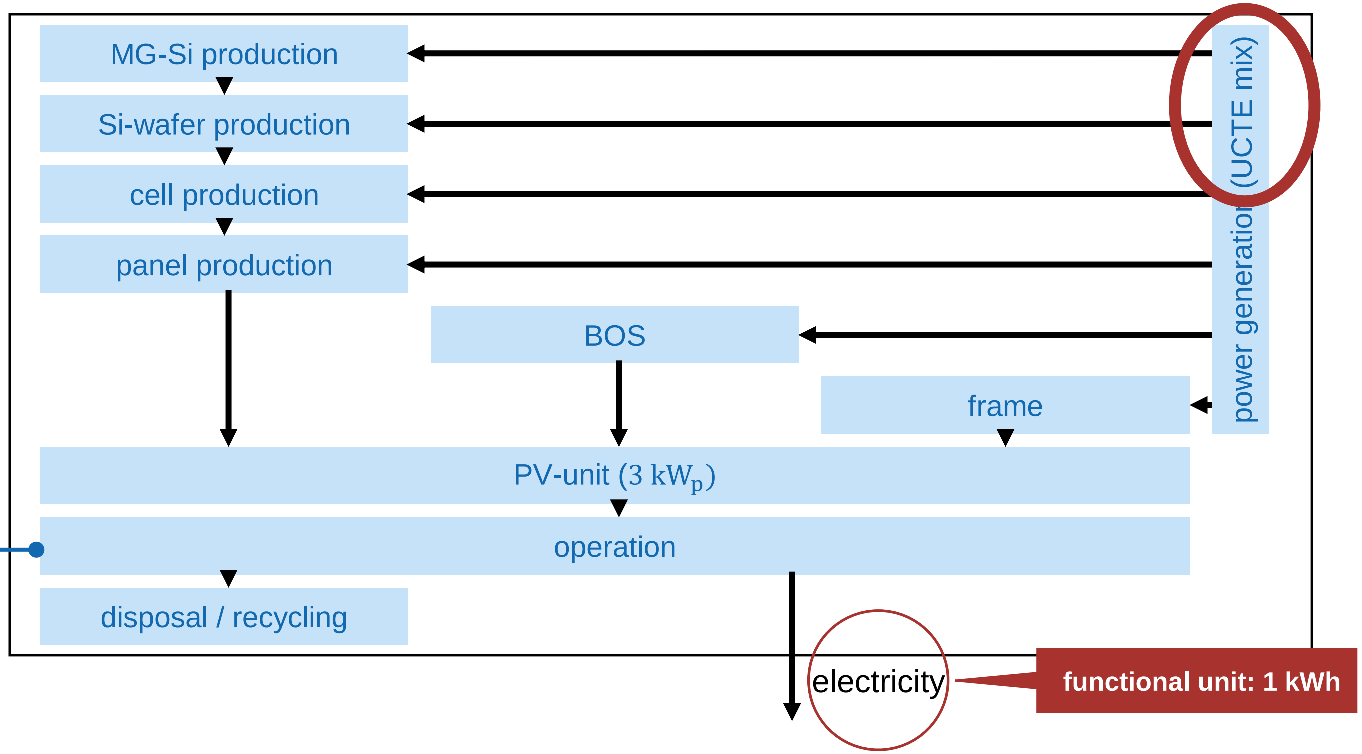
energy payback:
4 years &
3 months

(a)

production cost
10435 kWh / 3 kW_p

(b)

annual generation:
2480 kWh / 3kW_p



CED results over the life cycle (30y)

0.30 kWh_{fossil} / kWh_{el}
0.13 $kWh_{nuclear}$ / kWh_{el}
1.35 $kWh_{renewable}$ / kWh_{el}

After this lecture, you are able to …

- Thermodynamic KPIs for energy systems:

  ✓ Cumulative energy demand (CED), related to LCA seen in Lecture 6
  - Energy conversion efficiency
  - Energy storage efficiency (round-trip efficiency vs. self-discharge efficiency)

- Economic KPIs for energy systems:

  - Net present value (NPV)
  - Internal rate of return (IRR)
  - Levelized cost of energy (LCOE)
  - Total annual cost (TAC)

Conversion efficiency: Definition

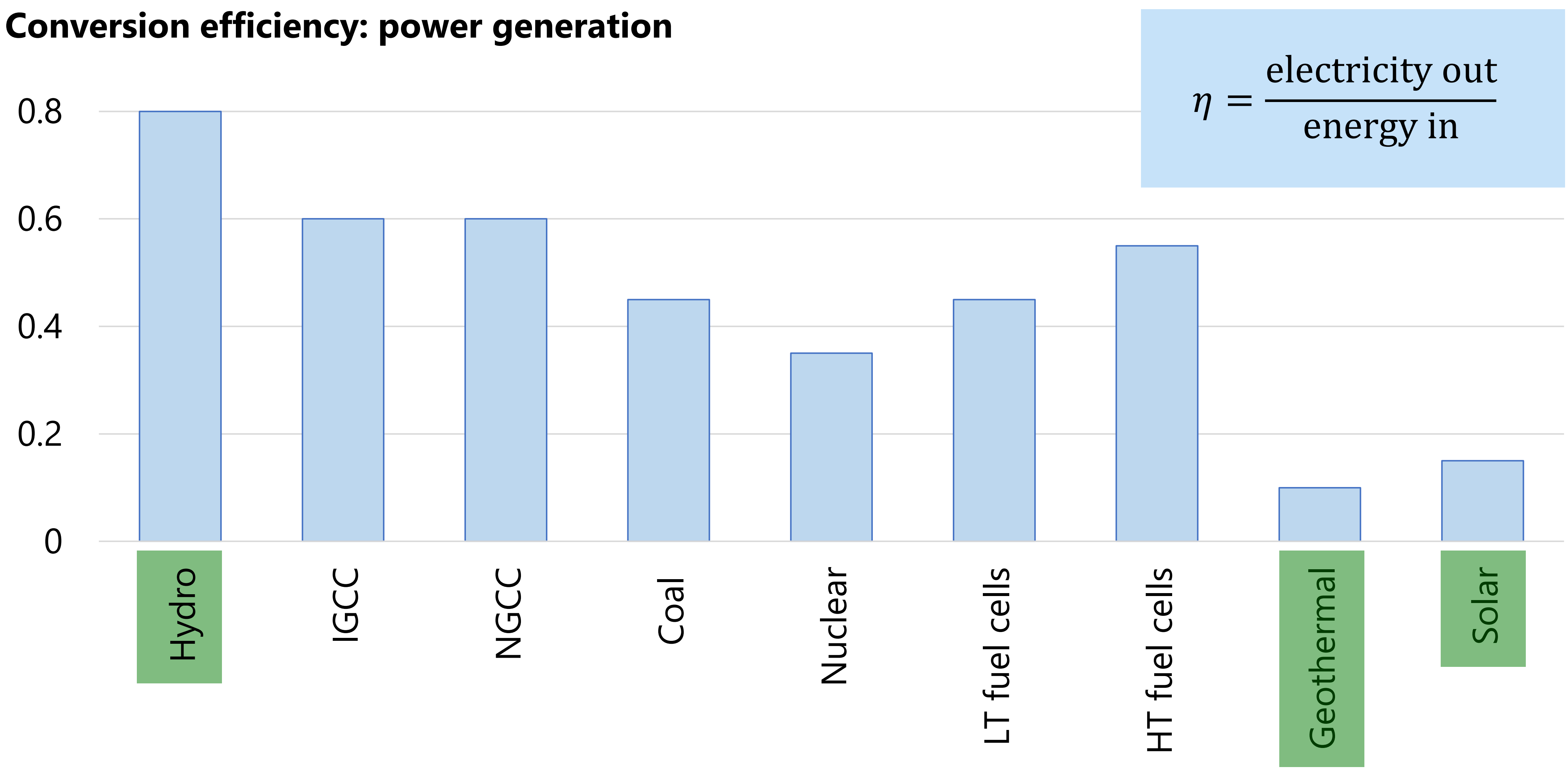
Ratio of measurable output P to amount of energy used E:

$$\eta = \frac{\text{measurable output}, P}{\text{energy used}, Q}$$

If output = energy ⇨ dimensionless performance criterion

Example: power generation efficiency $$\eta = \frac{P_{\mathrm{el}}}{Q_{\mathrm{fuel}}}$$

Efficiency as an indicator for sustainable electricity generation?



$$\eta = \frac{\text{electricity out}}{\text{energy in}}$$

Storage efficiency: Definitions

The **round-trip efficiency,** $\eta_{\text{round-trip}}$, is the product of charging and discharging efficiencies

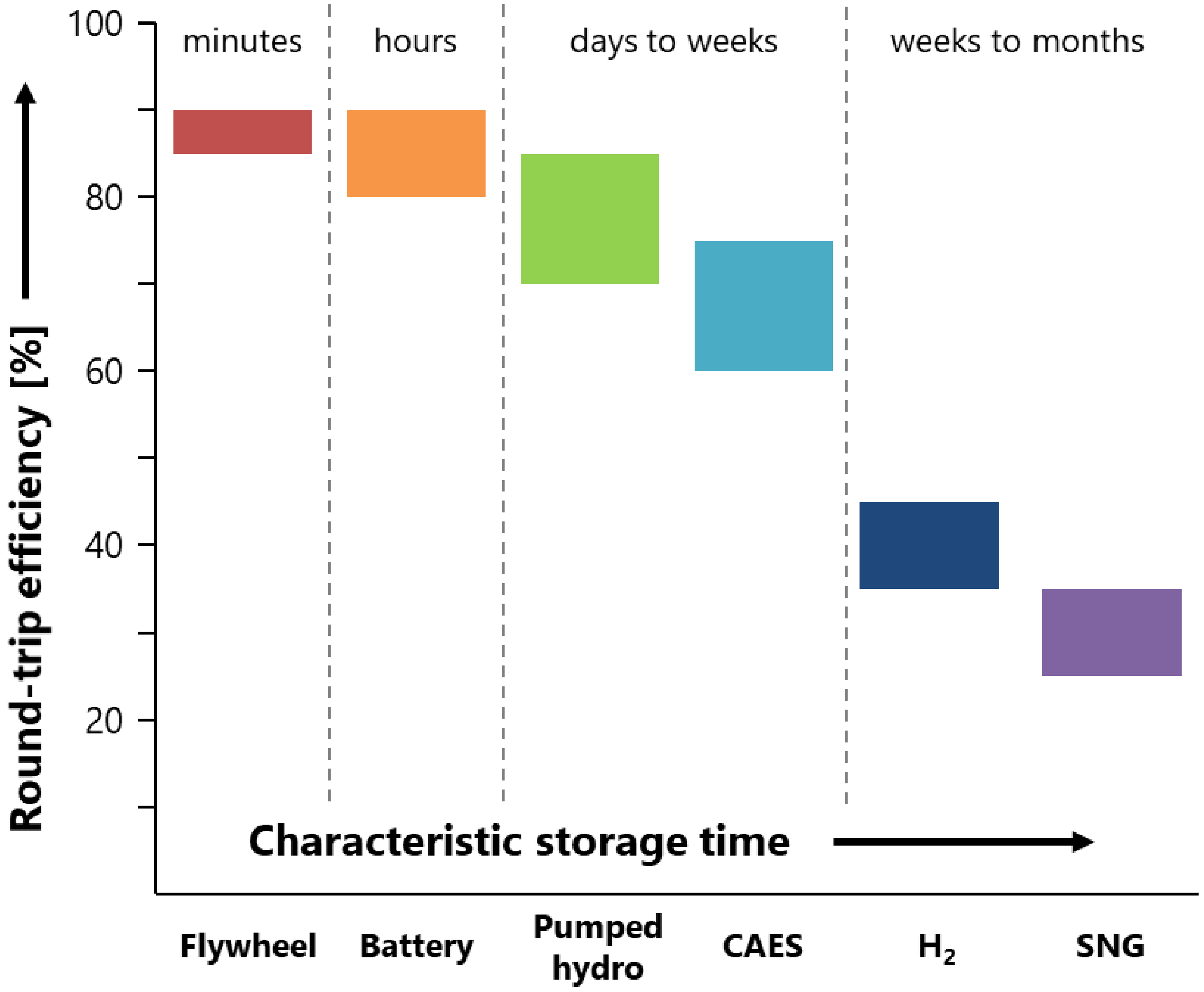
$$\eta_{\text{round-trip}} = \eta_{\text{charge}}\eta_{\text{discharge}}$$

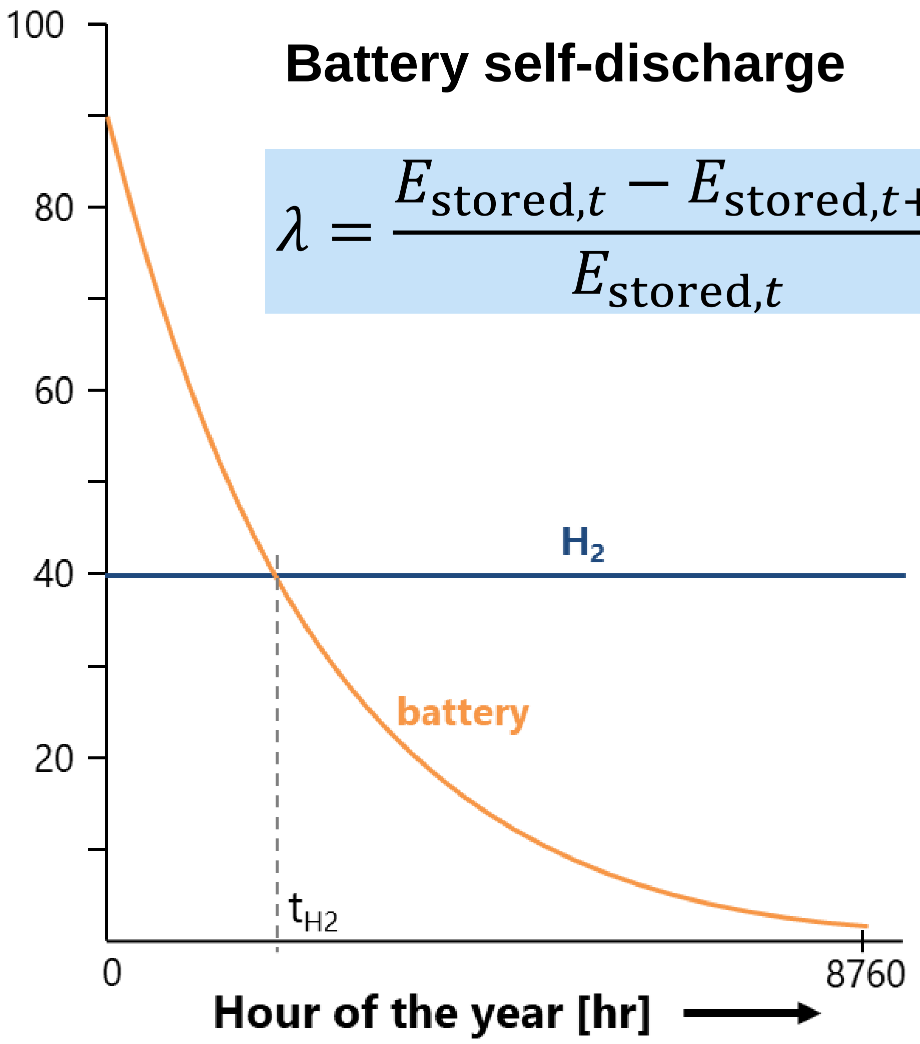
- The **charging efficiency**, η_{charge}, is the the fraction of usable energy within the storage technology, E_{stored}, per unit energy charged into the storage technology, E_{in}
- The **discharging efficiency**, $\eta_{\text{discharge}}$, is the fraction of usable energy outside the storage technology, E_{out}, per unit energy withdrawn from the storage technology, E_{stored}

$$\eta_{\text{charge}} = \frac{E_{\text{stored}}}{E_{\text{in}}}$$

$$\eta_{\text{discharge}} = \frac{E_{\text{out}}}{E_{\text{stored}}}$$

Charging efficiency is a dynamic concept due to self-discharging losses





$$\lambda = \frac{E_{\text{stored},t} - E_{\text{stored},t+1}}{E_{\text{stored},t}}$$

After this lecture, you are able to …

- ✓ Thermodynamic KPIs for energy systems:
  - ✓ Cumulative energy demand (CED), related to LCA seen in Lecture 6
  - ✓ Energy conversion efficiency
  - ✓ Energy storage efficiency (round-trip efficiency vs. self-discharge efficiency)

- Economic KPIs for energy systems:
  - Net present value (NPV)
  - Internal rate of return (IRR)
  - Levelized cost of energy (LCOE)
  - Total annual cost (TAC)

Summary on thermodynamic metrics

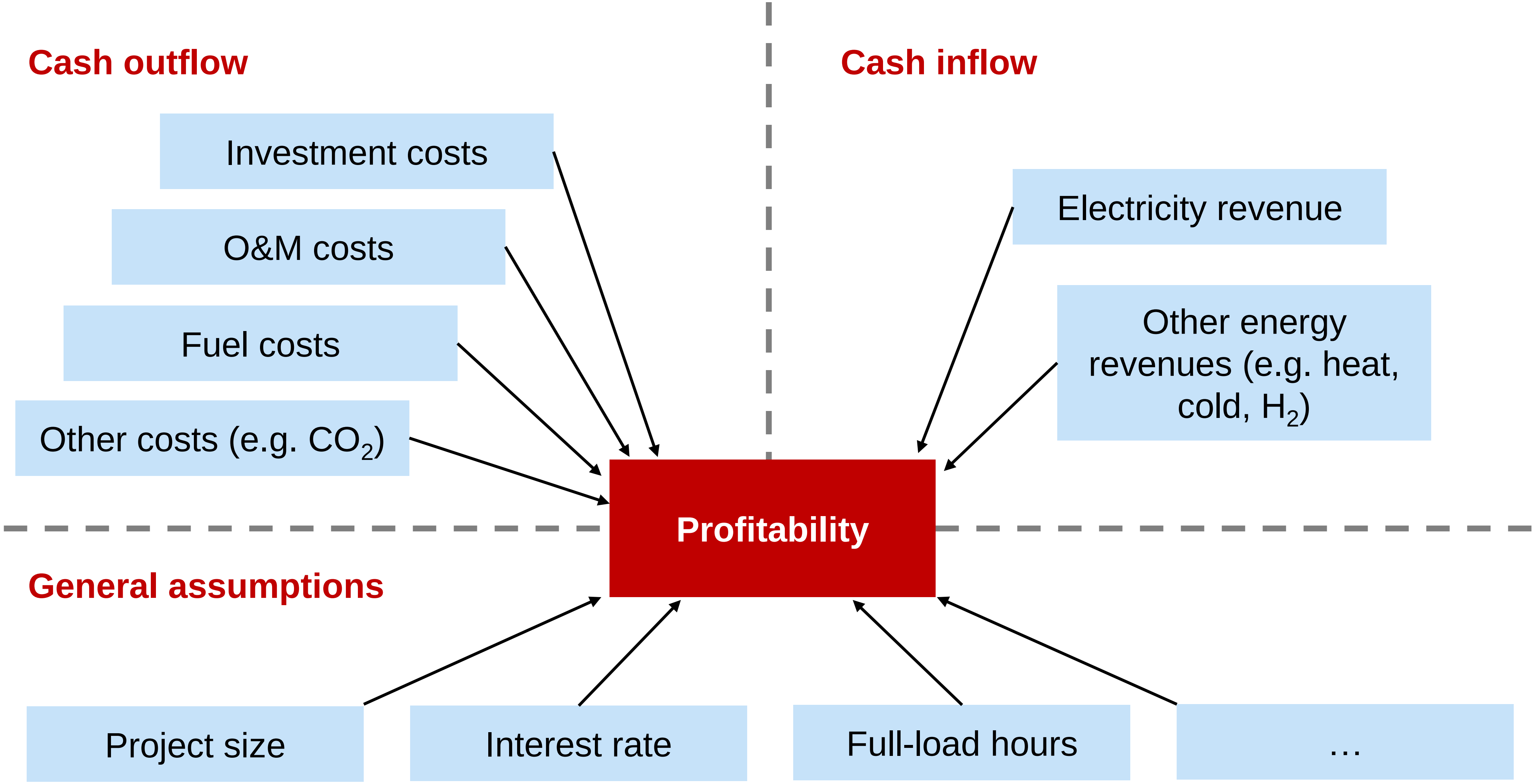
Indicator	Description	Formula
CED	Entire demand, valued as primary energy, which arises for production, use and disposal of an economic good	
Conversion efficiency	Ratio of energy produced to energy used	$\eta = \frac{P}{Q}$
Round-trip storage efficiency	Ratio of energy usable after a charging/discharging storage cycle to initial energy charged into the storage	$\eta_{\text{round-trip}} = \frac{E_{\text{out}}}{E_{\text{in}}}$
Self-discharge storage efficiency	Fraction of energy lost by the storage technology per unit time due to internal mechanisms	$\lambda = \frac{E_{\text{stored},t} - E_{\text{stored},t+1}}{E_{\text{stored},t}}$

Economic KPIs:
NPV, IRR, LCOE, TAC

Why economic analysis is important?

- **General idea**: Compare options with regard to their financial attractiveness (profitability) based on the analysis of cash flows over time
- A cash flow is a stream of money flowing into or out of the company
- Usually, technology investments start with a negative cash flow in year 0, followed by positive cash flows
- Four-step process:
  1. Identify influence factors
  2. Quantify influence factors
  3. Determine and discount cash flows
  4. Choose and calculate indicators

Step 1: Identify influence factors



Step 2: Quantify influence factors

- Determine values for factors that influence cash outflows, cash inflows, and general assumptions

			Gas Turbine Combined Cycle (GTCC)	Wind Turbine
Cash outflows	Investment cost	[kCHF/MW]	600	1200
	O&M costs (no fuel)	[kCHF/MW/year]	20	30
	Fuel price	[CHF/MWh]	15	-
	CO_2 price	[CHF/t_{CO2}]	50	-
Cash inflows	Electricity price	[CHF/MWh]	50	50
General assumptions	Project size	[MW]	100	100
	Discount rate	[-]	0.06	0.06
	Lifetime	[year]	25	25
	Full-load hours	[hour/year]	7500	2400
	Thermal efficiency	[-]	0.6	-

Step 3: Determine and discount net cash flows (more on this later)

- List cash outflows and inflows for all years of interest
- Calculate annual discounted net cash flows (the meaning of discounted cash flows will be clear in a minute)
- Use the discounted net cash flows within the calculation of relevant economic metrics
- Keep in mind that:
  - Energy systems have some relevant peculiarities, which makes the analysis of the investments in the energy sector particularly challenging. For example, they tend to be capital intensive and often have a long lifetime
  - Therefore, cash flows occur over long periods of time and they are risky (subject to uncertainty)
  - Discounting allows to sum and compare future cash flows

Step 4: Choose and calculate an economic metric

- Common metrics for investment analysis are **Net Present Value (NPV)** and **Internal Rate of Return (IRR)**
- Other common metrics to compare energy technologies and systems are **Levelized Cost of Energy (LCOE)** and **Total Annual Cost (TAC)**
- The concept of discounting is central to all metrics. This is based on the first basic principle of finance: *a Swiss franc today is worth more than a Swiss franc tomorrow*

- In the following, we will introduce and discuss the aforementioned economic metrics
- Other metrics are used (e.g. payback period, profitability index), but are not discussed here

Present Value (PV): Basic concept

- The present value of a delayed payoff may be found by multiplying the payoff by a *discount factor* which is smaller than 1

- Let C_1 denote the expected payoff in one year from now. Then, the present value (PV) of the future payoff occurring one year from now is given by

$$\mathrm{PV}_1 = \underbrace{\frac{1}{1+r}}\, C_1$$

Discount factor, where r is the ***discount rate***, which is the reward that investors demand for accepting a delayed payment (in the next time period)

- The *discount rate* is typically calculated based on equivalent investment alternatives in the capital market (e.g. the interest rate of government securities for a safe investment) and can be called *rate of return*, *hurdle rate*, *opportunity cost of capital*

Net Present Value (NPV): Idealized example – safe investment

- Today, you decide to build a wind park, which costs 100,000 CHF and you expect to sell it in one year from now for 110,000 CHF
- The investment implies an expected future revenue, C_1 = 110,000 CHF
- Assume this revenue is a sure thing (i.e. you are certain that you can sell your wind park for the expected amount) and you can compare it with an investment in government securities. Suppose the securities offer a 4% interest, hence r = 0.04
- The present value of your future revenue (in one year from now) is thus

$$\mathrm{PV}_1 = \frac{1}{1+r} C_1 = \frac{1}{1+0.04} 110{,}000 = 105{,}769 \text{ CHF}$$

- However, this future revenue comes at the initial investment cost, I_0 = 100,000 CHF, which is a cash outflow (money spent) and, therefore, is accounted for with negative sign
- We define the ***net present value*** (NPV) of this investment as

$$\mathrm{NPV} = -I_0 + \frac{1}{1+r} C_1 = -100{,}000 + 105{,}769 = 5{,}769 \text{ CHF}$$

Net Present Value (NPV): Idealized example – risky investment

- Unrealistic assumption made above: The future payoff of 110,000 CHF is not a sure thing
- Second basic principle of finance: *a safe Swiss franc is worth more than a risky one*
- You could achieve 110,000 CHF with certainty in one year by buying today 105,769 CHF of government securities: you would invest in your wind park only for a cost smaller than this
- Not all investment are equally risky. Suppose that the project is as risky as investment in the stock market with r = 0.08. This is the discount rate you should use (equally risky securities)
- Now, the net present value (NPV) becomes

$$\mathrm{NPV} = -I_0 + \frac{1}{1+r} C_1 = -100{,}000 + \frac{1}{1+0.08} 110{,}000 = -100{,}000 + 101{,}852 = 1{,}852 \text{ CHF}$$

- If other investors agree with your forecast and with your assessment of risk, then today the wind park is worth 101,852 CHF. This is still a good investment, it makes a net contribution to value of 1,852 CHF, but not as good as if it was risk-free
- Overall, *a higher risk translates into a higher discount rate (hence a lower present value)*

Net Present Value (NPV): General expression (1)

- The concepts of present value (PV) and net present value (NPV) are to be expanded to cover the entire lifetime, T, of the investment
- Consider the wind park you have built at year t = 0 at the investment cost I_0
  - Instead of selling the park after one year, you sell the generated energy during the entire park lifetime, T
  - This implies T yearly payoffs during future years, and their corresponding present values:

$$\mathrm{PV}_1 = \frac{1}{1+r} C_1$$

$$\mathrm{PV}_2 = \underbrace{\frac{1}{1+r}}_{\text{Discount for 1st year}} \underbrace{\frac{1}{1+r}}_{\text{Discount for 2nd year}} C_2 = \underbrace{\left(\frac{1}{1+r}\right)^2}_{\text{Overall discount for payoff at year } t = 2} C_2$$

$$\vdots$$

$$\mathrm{PV}_T = \left(\frac{1}{1+r}\right)^T C_T$$

$$\boxed{\mathrm{PV} = \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^t C_t}$$

Present Value (PV): The power of discounting

- Present value of 100 in T years from now (Time horizon), with a discount rate r:

Discount rate [-] \ Time horizon [years]	5	10	20	40
0.01	95.1	90.5	82.0	67.2
0.025	88.4	78.1	61.0	37.2
0.05	78.4	61.4	37.7	14.2
0.1	62.1	38.6	14.9	2.2
0.2	40.2	16.2	2.6	0.1

- *The higher the discount rate, the lower the value* assigned to future costs/revenues in today's decisions

Net Present Value (NPV): General expression (2)

- The net present value (NPV) is given by the sum of all cash flows, i.e. the initial investment I_0 and the present values of all future revenues and expenditures:

$$\mathrm{NPV} = -I_0 + \mathrm{PV}_1 + \mathrm{PV}_2 + \cdots + \mathrm{PV}_T =$$

$$= -I_0 + \frac{1}{1+r} C_1 + \left(\frac{1}{1+r}\right)^2 C_2 + \cdots + \left(\frac{1}{1+r}\right)^T C_T$$

$$\Rightarrow \mathrm{NPV} = -I_0 + \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^t C_t$$

- The initial investment, I_0, is a negative number (cash outflows), whereas future cash flows C_t can be positive (revenue inflows) or negative (e.g. operation & maintenance costs, social/external costs)
- **NPV > 0** represents a good investment (it makes a net contribution to value)
- **NPV < 0** implies that an alternative investment would be more profitable

NPV and Internal Rate of Return (IRR)

- The Internal Rate of Return (IRR) is the discount rate that results into NPV equal to zero:

$$\mathrm{NPV} = -I_0 + \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^t C_t$$

$$\Rightarrow - I_0 + \sum_{t=1}^{T} \left(\frac{1}{1+\mathrm{IRR}}\right)^t C_t = 0$$

- The IRR is determined by solving the equation above
- Projects should be assessed as follows:
  - If projects are mutually exclusive, choose the project with highest value of NPV
  - If projects are independent, choose projects with NPV > 0 (i.e. IRR > r)
- From the perspective of energy systems modeling and optimization, NPV is most used with fixed values of discount rate (for private investments in western countries r = 4-6%)

After this lecture, you are able to …

- ✓ Thermodynamic KPIs for energy systems:
  - ✓ Cumulative energy demand (CED), related to LCA seen in Lecture 6
  - ✓ Energy conversion efficiency
  - ✓ Energy storage efficiency (round-trip efficiency vs. self-discharge efficiency)

- Economic KPIs for energy systems:
  - ✓ Net present value (NPV)
  - ✓ Internal rate of return (IRR)
  - Levelized cost of energy (LCOE)
  - Total annual cost (TAC)

Levelized cost of energy (LCOE): Basic concept

- The concepts of present value (PV) and net present value (NPV) can be applied to the costs (cash outflows) of a power generation plant to quantify the levelized cost of energy (LCOE)
- The LCOE is the average revenue per unit of energy generated that is required to recover the costs of building and operating a generation plant during its lifetime
- The LCOE
  - is defined as the average present cost of energy generation for a generation plant over its lifetime
  - is calculated as the ratio between all the discounted costs over the lifetime of the generation plant divided by a discounted sum of the energy delivered
  - is used to compare / rank different energy generation technologies on a consistent basis
  - has units EUR/MWh (or Rp./kWh, or equivalent)
- These costs typically include the investment cost, the operation and maintenance (O&M) costs, the fuel costs (not present for renewable energy generation plants) and other costs (e.g. CO_2 costs, disposal costs)

Levelized cost of energy (LCOE): General expression

- LCOE is the average energy price such that discounted revenues (left) equal discounted costs (right):

$$\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^{t} \mathrm{LCOE}\, E_t = \sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^{t} (I_t + O_t + F_t + X_t)$$

$$\Rightarrow \mathrm{LCOE} = \frac{\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^{t} (I_t + O_t + F_t + X_t)}{\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^{t} E_t}$$

where,

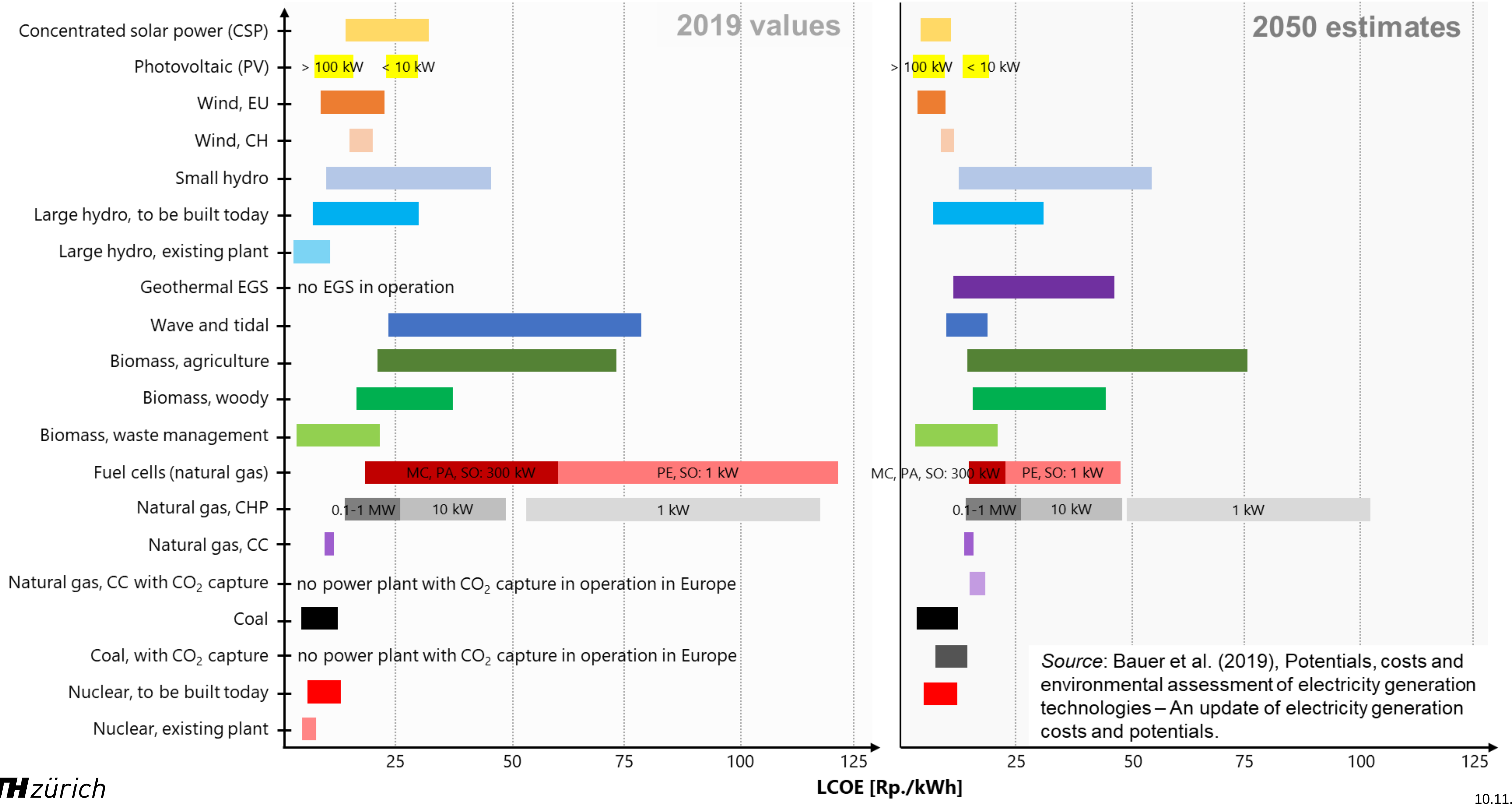
- I_t is the investment cost at year t (typically, present only at year t = 0)
- O_t is the operation and maintenance (O&M) cost at year t (present only at year t > 0)
- F_t is the fuel price at year t (present only at year t > 0)
- X_t are other costs, such as CO_2 or disposal costs (can be present from t = 0 onward)
- E_t is the energy generated at year t (present only at year t > 0)

Levelized cost of energy (LCOE): Practical considerations

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^t (I_t + O_t + F_t + X_t)}{\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^t E_t}$$

- Contrary to NPV, here costs take a positive value (since only cash outflows are considered)
- Capital investment and O&M costs are the most relevant terms for renewable energy sources
- Fuel costs are the most relevant term for fossil-based system, and are not present for renewable energy sources
- Fuel costs are related to GHG emissions during the system operation (minimizing GHG emissions is connected to minimizing fuel costs)
- The LCOE of a generation plant can be compared against grid energy prices
- Comparing the LCOE of renewable energy and fossil-based technologies requires accounting for environmental externalities (included in the term X_t)

Levelized cost of energy (LCOE)



Source: Bauer et al. (2019), Potentials, costs and environmental assessment of electricity generation technologies – An update of electricity generation costs and potentials.

After this lecture, you are able to …

- ✓ Thermodynamic KPIs for energy systems:
  - ✓ Cumulative energy demand (CED), related to LCA seen in Lecture 6
  - ✓ Energy conversion efficiency
  - ✓ Energy storage efficiency (round-trip efficiency vs. self-discharge efficiency)

- Economic KPIs for energy systems:
  - ✓ Net present value (NPV)
  - ✓ Internal rate of return (IRR)
  - ✓ Levelized cost of energy (LCOE)
  - Total annual cost (TAC)

Total annual cost (TAC): Basic concept

- The LCOE is widely used to compare the economic performance of single energy generation technologies
- When investigating integrated energy system, their optimal design and their optimal operation (see Lecture 9), different metrics are adopted
- One of these metrics is the total annual cost (TAC), which is based on the following considerations:
  - The operation of integrated energy systems is often analyzed over time horizons of one year (sufficient to capture daily and seasonal system dynamics)
  - The investment required for installing integrated energy systems should be reported on the same time basis (i.e. the fraction of that investment concerning one year)
- The concepts of PV and NPV can be applied to the investment cost of integrated energy systems to quantify the total annual cost (TAC)
- When computing the TAC, the time index essentially disappears

Total annual cost (TAC): Investment annualization (1)

- Consider a wind park with capacity 100 kW characterized by
  - I = 1,000 CHF/kW
  - O = 20 CHF/kW/year
- At first sight, the investment cost, I, seems much larger than the O&M cost, O
- However, the O&M cost is paid every year, whereas the investment cost covers the entire lifetime of the wind park, T
- The annualized value of the investment cost, I_{AV}, can be determined from the expression of the present value (PV), which connects it to the current investment, I

$$I = I_{\text{AV}} \sum_{t=1}^{T} \left(\frac{1}{1+r} \right)^t =$$

$$= I_{\text{AV}} \frac{1}{1+r} \underbrace{\sum_{t=0}^{T-1} \left(\frac{1}{1+r} \right)^t}_{} \longrightarrow = I_{\text{AV}} \frac{1}{1+r} \underbrace{\left[\frac{1 - \left(\frac{1}{1+r} \right)^T}{1 - \frac{1}{1+r}} \right]}_{}$$

Geometric series

Total annual cost (TAC): Investment annualization (2)

- The annual value of the investment cost, I_{AV}, can be determined from the expression of the PV

$$I = I_{\mathrm{AV}} \frac{1}{1+r}\left[\frac{1-\left(\frac{1}{1+r}\right)^T}{1-\frac{1}{1+r}}\right] = I_{\mathrm{AV}} \frac{1-\left(\frac{1}{1+r}\right)^T}{r}$$

$$\Rightarrow I_{\mathrm{AV}} = I \underbrace{\frac{r}{1-\left(\frac{1}{1+r}\right)^T}}_{\text{annuity factor, } a}$$

- The expression of the PV is inverted to determine the annualized (future) value
- The annual value of the investment cost can be compared to the yearly O&M cost
- For the wind park above, considering T = 25 years and r = 0.05,
  - $I_{\mathrm{AV}} = aI$ = 71 CHF/kW/year ~ 7% of the overall present value
  - O = 20 CHF/kW/year

Total annual cost (TAC): General expression

- Overall, the TAC accounts for the annualized investment cost, the yearly O&M costs, the yearly fuel costs and the yearly revenues due to selling energy
- The time index disappears, as all terms refers to the yearly operation of the system

$$\mathrm{TAC} = I_{\mathrm{AV}} + O + \underbrace{p_{\mathrm{U}} U}_{\text{yearly fuel cost, } F} - \underbrace{p_{\mathrm{V}} V}_{\text{yearly energy revenue, } R}$$

- where,
  - I_{AV} is the annualized investment cost
  - O is the yearly operation and maintenance cost
  - p_{U} is the average yearly fuel price
  - U is yearly fuel input
  - p_{V} is the average yearly price of energy generated
  - V is the yearly energy generated

After this lecture, you are able to …

- ✓ Thermodynamic KPIs for energy systems:
  - ✓ Cumulative energy demand (CED), related to LCA seen in Lecture 6
  - ✓ Energy conversion efficiency
  - ✓ Energy storage efficiency (round-trip efficiency vs. self-discharge efficiency)

- ✓ Economic KPIs for energy systems:
  - ✓ Net present value (NPV)
  - ✓ Internal rate of return (IRR)
  - ✓ Levelized cost of energy (LCOE)
  - ✓ Total annual cost (TAC)

Summary on economic metrics

Indicator	Description	Formula	Decision criterion
NPV	Expected money to be earned by the investment at today's value	$\mathrm{NPV} = -I_0 + \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^t C_t$	Choose alternative with largest NPV (if NPV positive)
IRR	Discounted rate at which the investment has zero Net Present Value (NPV)	$-I_0 + \sum_{t=1}^{T} \left(\frac{1}{1+\mathrm{IRR}}\right)^t C_t = 0$	Choose alternative with largest IRR (if IRR > *r*)
LCOE	Average energy price at which future revenues and costs are equal	$\mathrm{LCOE} = \frac{\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^t (I_t + O_t + F_t + X_t)}{\sum_{t=0}^{T} \left(\frac{1}{1+r}\right)^t E_t}$	Choose technology with lowest LCOE
TAC	Total cost of the system referred to one year of operation	$\mathrm{TAC} = I_{\mathrm{AV}} + O + p_{\mathrm{U}} U - p_{\mathrm{V}} V$	Choose system with lowest TAC