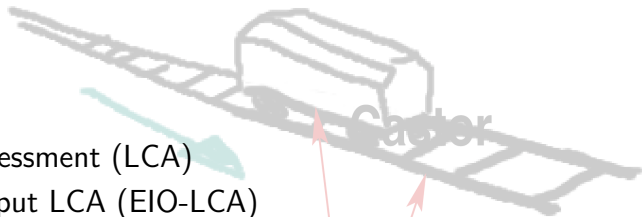
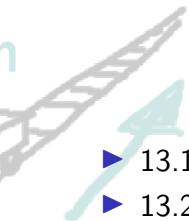
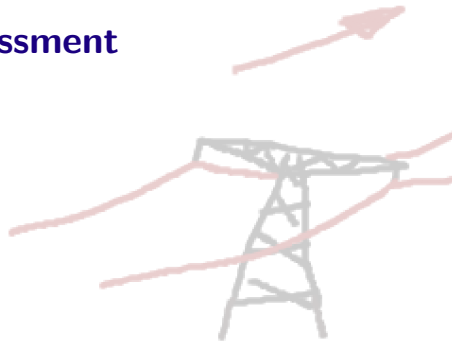


## 13 Life-Cycle Assessment

~~CO<sub>2</sub>~~



Factor

- ▶ 13.1. Classical Life-Cycle Assessment (LCA)
- ▶ 13.2. Econometric Input-Output LCA (EIO-LCA)

## 13.1. Life-Cycle Assessment (LCA): Motivation

- ▶ The IOM reflects a *snapshot* of *all products* of a national economy in the *steady state*
- ▶ Sometimes, it is more instructive or relevant to consider *the total lifetime* of a *single product* in a *time dependent way* by assessing production, operation, and destruction/recycling of this product.
- ▶ This is formalized by the methods of **Life-Cycle Assessment (LCA)** (German: **Ökobilanz**).
- ▶ However, LCA only considers first-order indirect effects, e.g., CO<sub>2</sub> emissions caused by electric vehicles through the CO<sub>2</sub> footprint of electricity production
- ▶ The class of **Econometric Input-Output (EIO) LCA models** combines both approaches.

## The standard LCA procedure

1. Define the life phases of the product in question:
  - ▶ production
  - ▶ operation/usage
  - ▶ destruction/recycling.
2. For each life phase, calculate the amount of needed materials/energy resulting in the **life-cycle inventory**  $\tilde{y}_j$  for product category  $j$  (the tilde denotes that the product is given in physical units such as kg or kWh rather than in €).
3. The total emissions  $e_i$  of pollutant  $i$  during the life time is obtained using the **emission factor matrix**  $\mathbf{C}$  :

$$e_i = \sum_j C_{ij} \tilde{y}_j$$

where the emission factor  $C_{ij}$  gives the units of pollutant  $i$  caused by one unit of product  $j$  (including the production chain).

## Example: Gasoline vehicle

Gasoline and Diesel vehicles are two examples of **internal combustion vehicles (ICV)**

### 1. Life-cycle inventory

- ▶  $\tilde{y}_1 = 800$  kg steel (900 kg at production time, 80 kg spare parts during lifetime, 20 % emission-neutral recycling contribution),
- ▶  $\tilde{y}_2 = 60$  kg aluminum (100 kg production, 40 % of it can be recycled without additional emissions)
- ▶  $\tilde{y}_3 = 100$  kg plastic (40 % of which can be recycled)
- ▶  $\tilde{y}_4 = 80$  kg rubber (25 % of which can be recycled)
- ▶  $\tilde{y}_5 = 36$  kg lead (three starter batteries à 12 kg)
- ▶  $\tilde{y}_6 = 15\,000$  l gasoline (250 000 km at 6 l/100 km during lifetime)

so we have

$$\tilde{\mathbf{y}} = (800 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 36 \text{ kg}, 15\,000 \text{ l})'$$

## Example: Gasoline vehicle (ctnd)

### 2. Total CO<sub>2</sub> emissions

Defining  $e_1$  to be the CO<sub>2</sub> emissions in kg ( $e_2$  could be NO<sub>x</sub>,  $e_3$  PM and so on), we have

$$e_1 = \sum_{j=1}^6 C_{1j} \tilde{y}_j$$

with the row vector

$$C_{\text{CO}_2} = (C_{1j}) = (4, 30, 2, 2, 20, 2.7 \text{ kg/l}).$$

The last emission factor  $C_{16} = C_{16}^{\text{w}2\text{t}} + C_{16}^{\text{t}2\text{w}}$  is the sum of two contributions:

- ▶ **Well-to-tank (w2t)** emissions of the production chain mining → transport to refinery → refining process → transport to the gas station:  $C_{16}^{\text{w}2\text{t}} = 0.4 \text{ kg/l}$ ,
- ▶ **Tank-to-wheel (t2w)** emissions dictated by the chemistry during the actual combustion:  $C_{16}^{\text{t}2\text{w}} = 2.3 \text{ kg/l}$  (it would be 2.7 kg/l for Diesel, i.e., the total w2w emissions of gasoline are about the t2w emissions when burning Diesel).

## Example 2: Battery-electric vehicle (BEV)

- ▶ The **Life-cycle inventory** of steel, aluminum, rubber, plastic etc is comparable to that of the ICVs.
- ▶ The starter batteries are replaced by the Lithium driving batteries ( $2 \times 300$  kg) and the gasoline is replaced by the needed electrical energy, typically 20 kWh per 100 km:

$$\tilde{\mathbf{y}} = (800 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 60 \text{ kg}, 600 \text{ kg}, 50\,000 \text{ kWh})'$$

- ▶ The last changed repository items lead to a new CO<sub>2</sub> emission factors vector

$$\mathbf{C}_{\text{CO}_2} = (4, 30, 2, 2, 20, 0.45 \text{ kg/kWh}).$$

- ▶ The Li driving batteries are expensive to produce and there is much controversy in estimating their overall emission factor  $C_{15}$
- ▶ The energy emission factor is based, e.g., on the present (2023) German energy mix emitting 400 g CO<sub>2</sub> per kWh of electrical energy at the socket

## Questions on LCA

- ? Is it possible to check, at a glance, whether the example BEV emits less CO<sub>2</sub> per km than the example ICV *when considering the driving phase alone*?
- ! Per 100 km, the BEV indirectly emits 20 kWh \* 0.4 kg/kWh=8 kg. The ICV vehicle emits directly and indirectly 6 l \* 2.7 kg/l=16.2 kg. So, the BEV CO<sub>2</sub>emissions per kilometer are about half that of the ICE (internal combustion engine, gasoline) vehicle.

However, the BEV production emissions are significantly higher. Furthermore, less than ideal efficiencies when charging/discharging have not been considered.

- ? How would you proceed to calculate the *break-even* mileage beyond which a BEV is more environmentally friendly (“green”) than the ICV?
- ! We saw that the *driving* emissions  $C'$  per kilometer  $x$  for the ICV are higher compared to the BEV. In contrast, it is the other way round for the *fixed* emissions  $C^0$  due to production/disposal/recycling. So, just calculate the break-even kilometrage  $x_c$  by the equation

$$C_{\text{BEV}}^0 + C'_{\text{BEV}}x_c = C_{\text{ICV}}^0 + C'_{\text{ICV}}x_c$$

## Questions on LCA (ctnd.)

- ? Give the two most important factors influencing the total LCA emissions of battery-electric vehicles.
- (i) The energy mix of the used electricity (this is tricky! particularly, you cannot save your soul by paying indulgences [ger: *Ablässbriefe*] /ordering “green” electricity)
  - (ii) The production and disposal/recycling emissions of the battery and whether you need more than one battery during lifetime (to research this is even more tricky).
- ? A common saying states that *the Sun does not issue invoices* nor does the production of electric energy by photovoltaic (PV) elements entail any direct CO<sub>2</sub> emissions. Discuss why PV energy still has a nonzero CO<sub>2</sub> footprint and how to calculate the PV CO<sub>2</sub> emission factor. Use LCA arguments and assume a steady state.
- (i) Get information about the usable lifetime  $\tau$ ,
  - (ii) Check the climate where you want to install your PV and determine the average power (in Germany, this so-called *availability* is about 12 % of the installed power  $P_{\max}$ ) and calculate the total electric energy delivered, e.g.,  $W_{\text{el}} = 0.12 \tau P_{\max}$
  - (iii) Get the production and recycling emissions  $C$  of your PV including the connection to the electric grid and calculate the CO<sub>2</sub> footprint  $e_{\text{PV}} = C/W_{\text{el}}$  [kg/kWh].



## 13.2. Econometric Input-Output LCA

See the [German script, Chapter 5.3](#).