13 Life-Cycle Assessment

- 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_2 emissions caused by electric vehicles through the CO_2 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

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

so we have

$$\tilde{\boldsymbol{y}} = (800\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 36\,\mathrm{kg},\ 15\,000\,\mathrm{l})'.$$

Example: Gasoline vehicle (ctnd)

2. Total CO_2 emissions

Defining e_1 to be the CO_2 emissions in kg (e_2 could be NO_x, e_3 PM and so on), we have

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

with the row vector

$$\boldsymbol{C}_{\mathrm{CO_2}} = (C_{1j}) = (4,\ 30,\ 2,\ 2,\ 20,\ 2.7\,\mathrm{kg/l}).$$

The last emission factor $C_{16} = C_{16}^{\mathrm{w2t}} + C_{16}^{\mathrm{t2w}}$ is the sum of two contributions:

- **Well-to-tank (w2t)** emissions of the production chain mining $\rightarrow$ transport to refinery $\rightarrow$ refining process $\rightarrow$ transport to the gas station: $C_{16}^{\mathrm{w2t}} = 0.4\,\mathrm{kg/l}$,
- **Tank-to-wheel (t2w)** emissions dictated by the chemistry during the actual combustion: $C_{16}^{\mathrm{t2w}} = 2.3\,\mathrm{kg/l}$ (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:

$$\tilde{\boldsymbol{y}} = (800\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 600\,\mathrm{kg},\ 50\,000\,\mathrm{kWh})'.$$

- The last changed repository items lead to a new CO_2 emission factors vector

$$\boldsymbol{C}_{CO_2} = (4,\ 30,\ 2,\ 2,\ 20,\ 0.45\,\mathrm{kg/kWh}).$$

  - 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_2 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_2 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_2emissions 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

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

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: *Ablassbriefe*] /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_2 emissions. Discuss why PV energy still has a nonzero CO_2 footprint and how to calculate the PV CO_2 emission factor. Use LCA arguments and assume a steady state.

(i) Get information about the usable lifetime τ,
(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., $W_{\text{el}} = 0.12\,\tau P_{\text{max}}$
(iii) Get the production and recycling emissions C of your PV including the connection to the electric grid and calculate the CO_2 footprint $e_{\text{PV}} = C/W_{\text{el}}$ [kg/kWh].

13.2. Econometric Input-Output LCA

See the German script, Chapter 5.3.