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.

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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 C**:

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

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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
- $\tilde{y}_4 = 50\,\mathrm{kg}$ rubber
- $\tilde{y}_5 = 36\,\mathrm{kg}$ lead (three starter batteries à 12 kg)
- $\tilde{y}_6 = 15\,000\,\mathrm{l}$ gazoline (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 → transport to refinery → refining process → 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).

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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:

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

- This leads to the new CO_2 emission factors vector

$$C_{CO_2} = (4,\ 30,\ 2,\ 2,\ 20,\ 0.45\,\text{kg/kWh}).$$

  - The Li driving batteries are expensive to produce and there is much controversy in extimating their overall emission factor C_{15}
  - The enery emission factor is based, e.g., on the present (2019) German energy mix emitting 450 g CO_2 per kWh of electrical energy at the socket

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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 * 0.45 kg/kWh=9 kg. The ICV vehicle emits directly and indirectly 6 l * 2.7 kg/l=16.2 kg. So, the BEV "wins" when considering the direct and indirect emissions in the driving phase alone.

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

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

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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/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 trickky).

? 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, it is about 10 % of the installed power P_{max}) and calculate the total electric energy delivered, e.g., $W_{el} = 0.1\,\tau P_{max}$

(iii) Get the production and recycling emissions C of your PV including the connection to the electric grid and calculate the CO_2 footprint $c_{PV} = C/W_{el}$ [kg/kWh].

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