Life cycle assessment (LCA)

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Outline

- What is LCA
- Why LCA
- Ideal characteristics of LCA
- LCA according to ISO standards
- LCA case study (floating wind power plant)
- Mathematical description of LCA
- Input output analysis (IOA)
- Hybrid LCA-IOA
Life Cycle Assessment (LCA) – definition

- A method created to assess products from environmental point of view with respect to their life cycle perspective
- Raw material extraction – processing – transport – production – use – end of life treatment
Life cycle of a product

Production → Packaging → Transport → Use → Disposal → Recycling → Extraction → Production
Why environment/nature?

- Human health
  - What we breath, eat, drink, noise, …

- Human made capital
  - Corrosion, ageing, …

- Nature
  - Ecosystem services
Ecosystem services

- Functions of ecosystems utilized by humans
- Difficult to substitute
- Depend on ecosystems

<table>
<thead>
<tr>
<th>ECOSYSTEM SERVICES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Provisioning</strong></td>
</tr>
<tr>
<td>FOOD</td>
</tr>
<tr>
<td>FRESH WATER</td>
</tr>
<tr>
<td>WOOD AND FIBER</td>
</tr>
<tr>
<td>FUEL</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td><strong>Supporting</strong></td>
</tr>
<tr>
<td>NUTRIENT CYCLING</td>
</tr>
<tr>
<td>SOIL FORMATION</td>
</tr>
<tr>
<td>PRIMARY PRODUCTION</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td><strong>Regulating</strong></td>
</tr>
<tr>
<td>CLIMATE REGULATION</td>
</tr>
<tr>
<td>FLOOD REGULATION</td>
</tr>
<tr>
<td>DISEASE REGULATION</td>
</tr>
<tr>
<td>WATER PURIFICATION</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td><strong>Cultural</strong></td>
</tr>
<tr>
<td>AESTHETIC</td>
</tr>
<tr>
<td>SPIRITUAL</td>
</tr>
<tr>
<td>EDUCATIONAL</td>
</tr>
<tr>
<td>RECREATIONAL</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

Why environment?

- ES are expensive to substitute
- Human activities lead to degradation of ES
- A tendency to optimize (decrease) human impact on the environment, the aim is to sustain human society and to maximize human welfare
Effort to minimize negative environmental impacts

- Clean up old damages
- Prevent new
  - Searching for alternatives
- Limited resources and willingness for change
- We need to know what is better from the environmental perspective
Fossil fueled cars versus electric cars – what is better?

• Ideal type of answer
  • Product A has environmental impact of X
  • Product B has environmental impact of Y
  • If $X > Y$, product B is better than product A and vice versa
Fossil fueled cars versus electric cars – what is better?

Gasoline car

- High emissions during operation
- Zero electricity consumption
- Fuel tank

Electric car

- Zero emissions during operation
- High electricity consumption
- Battery

Different requirements during operation and production, different additional products, different environmental consequences.

Direct comparison impossible and meaningless, necessity to consider the whole life cycle of the product.
Requirements for the comparison

- Complete product systems / system boundaries
- Unification of environmental stressors into one single number / a set of environmental categories
Ideal characteristics of LCA

- Clearly defined concept applicable to all types of products including services
- Coverage of all environmental impacts related to product’s life cycle
- Clear answer – one number as a final score
- The aim is to overcome shifts of environmental impacts across life cycle stages, time, regions and environmental areas
Life cycle assessment

Goal and scope definition

Inventory analysis

Impact assessment

Interpretation
Goal and scope definition

- Goal of the study
  - Intended audience
  - Why the study is conducted
- Scope of the study (product system definition)
  - System boundaries
  - Function and functional unit
  - Reference flow
  - Scenario of the product life cycle
  - Selection of impact categories and characterization models
Product function, functional unit

- The purpose of a product is its function
- For a comparison of different products it is necessary to quantify the function and express the results per one unit of the function
- For example: one minute of phone call for mobile phone
  - What is the functional unit for a washing machine, a car, a hand dryer, a pen, a transformer?
- Additional functions determine the set of alternatives
Life cycle scenario

- Assumptions about the products life cycle
  - Origin of materials (primary x secondary, region, …)
  - Transport during life cycle stages
  - How is the product used (how many times a week is the product used, how many functional units it will provide during the whole life time)
  - Maintenance, failure and repair
  - End of life treatment, recycling rate

- Often necessary to consider more options and make a composition according to assumed probability of appearance

- A set of processes which are part of the product’s life cycle is called “product system”
Impact on other processes

- How are other processes influenced by the studied product?
  - What is the source of electricity, which is consumed by the product? (e.g. in Norway 98% of electricity is supplied by hydro power plants and 2% by natural gas power plants)

- Attributional LCA assumes average values
- Consequential LCA considers marginal changes
System boundaries

- Inputs and outputs at the system boundary should be elementary flows
- Too broad, the system would cover the whole economy of the whole world
- Therefore, it is necessary to set up system boundaries
- Cut-off criteria: weight, environmental relevance
Reference flow

- How much of the primary product is needed to provide one functional unit
  - How much of the kettle
  - How much of electricity

- It is necessary to design a scenario for the product’s life cycle (how often will be the kettle used)
Choice of appropriate process

Process A

Process B

Process C

Process D

Product A

Product A

Product A

Product A

Distribution

Product A
Impact on other processes

- How are other processes influenced by the studied product?
  - What is the source of electricity, which is consumed by the product? (e.g. in Norway 98% of electricity is supplied by hydro power plants and 2% by natural gas power plants)

- Attributional LCA assumes average values

- Consequential LCA considers marginal changes
Choice of appropriate process

- Prospective = marginal = consequential
  - Marginal values, necessary to analyze causal relations between processes
- Retrospective = average = attributional
  - Average values – easier
- Example
  - Emissions from electricity generation in Norway
    (99 % hydro, 1 % natural gas)
  - Marginal: natural gas x average: hydro
Attributional x consequential

\[ f(x) \]

Attributional

Consequential
Allocation

- Product system has more useful outputs
  - One process has one or more by-products (not waste)
    - Example: meat, milk, leather for cattle raising – the product system cannot be split to end up with only one output
Allocation

- Partitioning the input and output flows of a process between two product systems
- It should be avoided
  - By dividing the process
  - Expanding the product system to include additional functions
- Where it cannot be avoided physical or economic relations can be used for partitioning
Recycling

- Recycled material is a by-product – allocation principals apply
- Often closed loop system assumed in which outputs replace inputs
  - Problem is a time horizon, the materials can be released for further used in 50 years or later
Inventory analysis (LCI)

- The compilation and quantification of inputs and outputs for a product throughout its life cycle
- The aim is to quantify all flows between the product system and its environment (= elementary flows)
- Data collected for unit processes
Product system
Unit process

Input flows → Unit process → Output flows

Intermediate flows

Input flows → Unit process → Output flows

Intermediate flows

Input flows → Unit process → Output flows
Inventory analysis

- Data?
- Direct collection often impossible
- Process databases, the most widespread is Ecoinvent (about 4000 processes)
- Literature: many LCA studies already published (ABB, Vestas)
- Input output analysis (hybrid LCA)
- Qualified estimate
# Inventory analysis – results

<table>
<thead>
<tr>
<th>Compound</th>
<th>Medium</th>
<th>Unit</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acenaphthene</td>
<td>Air</td>
<td>ng</td>
<td>48</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>Air</td>
<td>mg</td>
<td>14</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>Air</td>
<td>mg</td>
<td>142</td>
</tr>
<tr>
<td>Acetone</td>
<td>Air</td>
<td>mg</td>
<td>17</td>
</tr>
<tr>
<td>Acrolein</td>
<td>Air</td>
<td>μg</td>
<td>9</td>
</tr>
<tr>
<td>Aldehydes, unspecified</td>
<td>Air</td>
<td>mg</td>
<td>1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Air</td>
<td>g</td>
<td>133</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Air</td>
<td>g</td>
<td>53</td>
</tr>
<tr>
<td>Ammonium carbonate</td>
<td>Air</td>
<td>μg</td>
<td>15</td>
</tr>
<tr>
<td>Antimony</td>
<td>Air</td>
<td>mg</td>
<td>128</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Air</td>
<td>g</td>
<td>1</td>
</tr>
</tbody>
</table>
Impact assessment

- The aim is to convert the results of LCI to a manageable number of indicators
- Elementary flows grouped according to the character of their impact
- Main areas of protection
  - Human health
  - Ecosystems
  - Resources
Impact assessment

Mandatory elements

Selection of impact categories, category indicator and characterization models

Assignment of LCI result (classification)

Calculation of category indicator results (characterization)

Category indicator results, LCIA results (LCIA profile)
Impact assessment – optional elements

- Normalization – calculation of the magnitude of category indicator results relative to reference information
- Grouping
- Weighting
- Subjective values
Impact assessment – endpoint and midpoint indicators

Source: Hauschild, 2005
Impact aggregation

- Inventory
  - Concentration Changes
  - Impact Category
  - Category Indicators
  - Respiratory
  - Cancer
  - Cataract
  - Infectious
  - Thermal /cold stress
  - Natural Disasters
  - Human health
  - DALY
  - Social welfare
  - Yen

- Areas of Protection Indicators
- Single Indicator
- Human life
- Human health
- Single indicator
- Yen

- Benzene
  - Chemicals in air
  - Urban air pollution
  - Human toxicity
  - Ecotoxicity
  - Ozone layer depletion
  - Climate change
  - Acidification
  - Eutrophication
  - Photochemical ozone creation
  - Resource consumption
  - Land use
  - Land use

- TCDD
  - Chemicals in water

- Lead
  - Chemicals in soil

- HCFCs
  - Stratospheric ODS

- CO₂
  - GHGs in air

- SOx
  - Acid deposition

- NOx
  - DO consumption

- Total N
- Total P

- NMVOC
  - Oxidants in air

- Copper ore use
- Oil use
- Waste quantity
- Land use

Source: Pennington et al., 2004
Example: Global warming

- Emisions of CO2, CH4 a N2O

\[
GWP_{x,T} = \frac{\int_0^T a_x \times [x(t)] dt}{\int_0^T a_r \times [r(t)] dt}
\]

<table>
<thead>
<tr>
<th>kg</th>
<th>Characterisation factor (GWP100)</th>
<th>kg CO2eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>N\textsubscript{2}O</td>
<td>10</td>
<td>298</td>
</tr>
<tr>
<td>CH4</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>
Problems related to LCIA

- Too difficult and demanding to create own characterization models and to determine characterization factors
- It is necessary to utilize existing LCIA method with defined categories and characterization factors
- Site specific characterization factors for local and regional problems
Example of LCIA method – Ecoindicator

- Human health (unit DALY = Disability adjusted life years);
- Ecosystems (unit PDF.m²yr = Potentially disappeared fraction of species);
- Resources depletion (MJ surplus)
- Supports a single indicator, unit Pt (point)
- Possibility to control weighting coefficients
## CML 2000

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Impact category</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abiotic depletion (ADP)</td>
<td>kg Sb eq</td>
</tr>
<tr>
<td>Global</td>
<td>Global warming (GWP100)</td>
<td>kg CO₂ eq</td>
</tr>
<tr>
<td></td>
<td>Ozone layer depletion (ODP)</td>
<td>kg CFC-11 eq</td>
</tr>
<tr>
<td>Regional</td>
<td>Human toxicity (HTP)</td>
<td>kg 1,4-DB eq</td>
</tr>
<tr>
<td></td>
<td>Fresh water aquatic ecotoxicity (FWAT)</td>
<td>kg 1,4-DB eq</td>
</tr>
<tr>
<td></td>
<td>Marine aquatic ecotoxicity (MAT)</td>
<td>kg 1,4-DB eq</td>
</tr>
<tr>
<td></td>
<td>Terrestrial ecotoxicity (TE)</td>
<td>kg 1,4-DB eq</td>
</tr>
<tr>
<td></td>
<td>Photochemical oxidation</td>
<td>kg C₂H₄ eq</td>
</tr>
<tr>
<td></td>
<td>Acidification</td>
<td>kg SO₂ eq</td>
</tr>
<tr>
<td></td>
<td>Eutrophication</td>
<td>kg PO₄--- eq</td>
</tr>
</tbody>
</table>
Normalization

- Expressing environmental impacts as a ratio of reference environmental impact
- Example: average impact of one EU citizen in one year
- Subjective value choice > the results have to be presented also before this step
Weighting

- Aggregation of more impact categories and calculation of one indicator
- Different relevance of different categories > weights have to be chosen
- Aggregation of different indicators into one is always a problem
  - Aggregation of pears and apples
    - Weight
    - Number of pieces
    - Economic value (price)
    - Sugar content
    - Vitamin C content
    - Always subjective preference
- Subjective value choice
Sensitivity analysis

- What if scenarios > change in uncertain values, change in life cycle scenario
  - Change in supplier which will result in higher transport distance
  - A fridge will be used in warmer environment
  - The reliability will be lower
  - The life span will be longer
  - The electricity mix will be different

- It shows how the results are sensitive to different assumptions and aspects of the product system

- It possible to identify the issues which should be controlled during the life cycle and during the production phase
Uncertainty analysis

- Almost no data is exact
- It is possible to assume statistical distribution and standard deviation
- Uncertainty analysis shows the uncertainty of the results due to uncertainty in the data
- Monte Carlo analysis
  - The system is analyzed many times with different input data (1000 - 10000)
  - Data are generated according to statistical distribution
  - If two product systems are compared, it is possible to generate the same input data at once and to minimize the uncertainty of the comparison
Interpretation

● Evaluation and check of LCA study
  – Complteteness
  – Consistency
  – Sensitivity analysis
  – Uncertainty analysis
  – Data quality analysis
  – Presentation of results
  – Peer review
Use of LCA

- Product development and improvement
- Strategic planning
- Public policy making
- Marketing
- …
Use of LCA

- Product development and improvement
- Strategic planning
- Public policy making
- Marketing
- …
Limitations of LCA

- Not all environmental areas represented
- Generality and linearity
- Cannot act as a single method
  - E.g. Rebound effect
Energy payback time

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy requirements (MJ primary / m2 modul)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon winning and purification</td>
<td>2200</td>
</tr>
<tr>
<td>Silicon wafer manufacturing</td>
<td>1000</td>
</tr>
<tr>
<td>Module manufacturing</td>
<td>300</td>
</tr>
<tr>
<td>Module encapsulation materials</td>
<td>200</td>
</tr>
<tr>
<td>Other equipment</td>
<td>500</td>
</tr>
<tr>
<td>Aluminum frame</td>
<td>400</td>
</tr>
<tr>
<td>Total</td>
<td>4600</td>
</tr>
</tbody>
</table>

Panel efficiency: 17%
Efficiency of electricity conversion: 75%
Solar radiation energy: 1100 kWh / m²rok
## Energy payback time

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Panel efficiency: 17 %  
Efficiency of electricity conversion: 75 %  
Solar radiation energy: 1100 kWh / m² rok
Software tools

- Too many data > difficult to manage
- Connection of own data with databases
- Other features (sensitivity analysis, uncertainty analysis)
- SimaPro (www.pre.nl)
- GaBi (www.gabi-software.com)
- BOUSTEAD
- CMLCA
- Umberto
Mathematical description of LCA

How much coal is used to produce 1 ton of steel in the entire life cycle?
$x_1 = y_1 + \frac{50}{1000} x_2$

$x_2 = y_2 + \frac{200}{500} x_1 + \frac{100}{1000} x_2$

<table>
<thead>
<tr>
<th>Process</th>
<th>Steel</th>
<th>Coal</th>
<th>$y$</th>
<th>$x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply</td>
<td>Steel</td>
<td>0</td>
<td>50</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>200</td>
<td>100</td>
<td>700</td>
</tr>
</tbody>
</table>

$$
\begin{pmatrix}
  x_1 \\
  x_2
\end{pmatrix} =
\begin{pmatrix}
  z_{11} & z_{12} \\
  z_{21} & z_{22}
\end{pmatrix} +
\begin{pmatrix}
  y_1 \\
  y_2
\end{pmatrix}
$$

$x = Z \cdot 1 + y$

$1 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$
Mathematical description of LCA

Define technology coefficient matrix $A$ as:

$$A = Z \cdot \hat{x}^{-1}$$

$$Z = A \cdot \hat{x}$$

$x = Z \cdot \mathbf{1} + y \quad \rightarrow \quad x = A \cdot x + y$

where $a_{ij} = z_{ij}/x_j$

$x_1 = y_1 + (50/1000) \cdot x_2$

$x_2 = y_2 + (200/500) \cdot x_1 + (100/1000) \cdot x_2$
\[ x = A \cdot x + y \]

- Two ways for solve this problem:
  - Indefinite series: \[ x = y + Ay + A^2y + A^3y + \ldots + A^n y \]
  - Direct solution (Leontief inverse matrix):
    \[
    x = (I - A)^{-1} \cdot y
    \]
    (I is an identity matrix)

- This is a model of the production system, \( y \) can be replaced by any output of the product system, which we want to analyze
Inventory analysis (elementary flows)

- Matrix $F$, which elements represent emissions and other elementary flows of all processes per unit of their output.

<table>
<thead>
<tr>
<th>Process</th>
<th>Extraction (…/1 t)</th>
<th>Production (…/1 ks)</th>
<th>Use (…/1 functional unit)</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission of CO$_2$ (kg/…)</td>
<td>$f_{11}$</td>
<td>$f_{12}$</td>
<td>$f_{13}$</td>
<td>$f_{1...}$</td>
</tr>
<tr>
<td>Emission of CH$_4$ (kg/…)</td>
<td>$f_{21}$</td>
<td>$f_{22}$</td>
<td>$f_{23}$</td>
<td>$f_{2...}$</td>
</tr>
<tr>
<td>...</td>
<td>$f_{...1}$</td>
<td>$f_{...2}$</td>
<td>$f_{...3}$</td>
<td>$f_{...}$</td>
</tr>
</tbody>
</table>

- Total elementary flows of all processes can be expressed as a vector $e$:

\[
e = F \cdot x
\]
\[
e = F \cdot \text{inv}(I - A) \cdot y
\]
Impact assessment

- The characterization factors can be placed in a matrix/table for each emission and impact category:

<table>
<thead>
<tr>
<th>Characterization factors for impact category</th>
<th>Emission 1</th>
<th>Emission 2</th>
<th>Emission …</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$c_{11}$</td>
<td>$c_{12}$</td>
<td>$c_{1…}$</td>
</tr>
<tr>
<td>2</td>
<td>$c_{21}$</td>
<td>$c_{22}$</td>
<td>$c_{1…}$</td>
</tr>
<tr>
<td>…</td>
<td>$c_{…1}$</td>
<td>$c_{…1}$</td>
<td>$c_{……}$</td>
</tr>
</tbody>
</table>

- Impact assessment in matrix algebra:
  $$d = C \cdot e$$
Normalization and weighting

- It is possible to continue similarly in normalization and weighting procedures.
- Definition of normalizing vector \( \mathbf{n} \).
- Definition of weighting coefficient vector \( \mathbf{w} \).

\[
\mathbf{m} = \text{diag}(\mathbf{n}) \cdot \mathbf{d}
\]

\[
\mathbf{v} = \mathbf{w} \cdot \mathbf{m}
\]

- \( \mathbf{m} \) is a vector of normalized results and \( \mathbf{v} \) is a single value result of the LCA study.
Analysis of the LCA results

- Elementary flows of individual processes:
  \[ E_{\text{pro}} = F \cdot \text{diag}(x) \]

- Impact of individual processes:
  \[ D_{\text{pro}} = C \cdot E_{\text{pro}} = C \cdot F \cdot \text{diag}(x) \]

- Impact of individual elementary flows
  \[ D_{\text{pro}} = C \cdot E_{\text{pro}} = C \cdot F \cdot \text{diag}(x) \]
Input output analysis (IOA)

- A macroeconomic tool based on monitoring monetary flows among economic sectors
- The basic element is an input output table, which is usually created from supply and use tables
## Use table

<table>
<thead>
<tr>
<th>Product</th>
<th>Sector 1</th>
<th>...</th>
<th>Sector n</th>
<th>Final demand</th>
<th>Total use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td></td>
<td></td>
<td></td>
<td>y₁</td>
<td>t₁</td>
</tr>
<tr>
<td>...</td>
<td>Use matrix $U$</td>
<td></td>
<td></td>
<td>y₂</td>
<td>t₂</td>
</tr>
<tr>
<td>Product n</td>
<td></td>
<td></td>
<td></td>
<td>yₙ</td>
<td>tₙ</td>
</tr>
<tr>
<td>Value added</td>
<td></td>
<td></td>
<td></td>
<td>VA</td>
<td></td>
</tr>
</tbody>
</table>
## Supply table

<table>
<thead>
<tr>
<th>Sector</th>
<th>Sector 1</th>
<th>…</th>
<th>Sector n</th>
<th>Total domestic production</th>
<th>Imports</th>
<th>Total supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td></td>
<td></td>
<td></td>
<td>$\sum$ row = $q_1$</td>
<td>$p_1$</td>
<td>$x_1$</td>
</tr>
<tr>
<td>…</td>
<td>Matice dodávky $M$</td>
<td></td>
<td></td>
<td>$\sum$ row = $q_{\ldots}$</td>
<td>$p_{\ldots}$</td>
<td>$x_{\ldots}$</td>
</tr>
<tr>
<td>Product n</td>
<td></td>
<td></td>
<td></td>
<td>$\sum$ row = $q_n$</td>
<td>$p_n$</td>
<td>$x_n$</td>
</tr>
<tr>
<td>Total sectoral production</td>
<td>$\sum$ column = $g_1$</td>
<td>$\sum$ column = $g_{\ldots}$</td>
<td>$\sum$ column = $g_n$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Assumption: $t = x$ (total supply of product is equal to total demand)

Complication: by-products
Symmetric input output table

- „Product by product“
  - All products of one sector are produced with the same structure of inputs (industry technology assumption)
  - Each product is produced using the same technology regardless the production sector (product technology assumption)

- „Sector by sector“
  - Each product has fixed sales structure
  - Each sector has its own fixed sales structure regardless the products on the output
## Technology coefficient matrix

<table>
<thead>
<tr>
<th>Product</th>
<th>↓ demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td>Product 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>supply</th>
<th>Product 1</th>
<th>Product 2</th>
<th>Product n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product n</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A matrix
Leontief inverse

- Total product flow induced by particular final demand can be expressed as:

\[ x = (I - A)^{-1} \cdot y \]
Environmental extension

<table>
<thead>
<tr>
<th>Elementary flows</th>
<th>Sector 1</th>
<th>Sector …</th>
<th>Sector n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>$f_{11}$</td>
<td>$f_{1\ldots}$</td>
<td>$f_{1n}$</td>
</tr>
<tr>
<td>Natural gas</td>
<td>$f_{21}$</td>
<td>$f_{2\ldots}$</td>
<td>$f_{2n}$</td>
</tr>
<tr>
<td>…</td>
<td>$f_{\ldots 1}$</td>
<td>$f_{\ldots}$</td>
<td>$f_{\ldots n}$</td>
</tr>
</tbody>
</table>

\[ e = F \cdot x \]
Applications

- Elementary flows induced by final demand of a set of product $y$

\[ e = F \cdot \text{inv}(I - A) \cdot y \]

- Elementary flows on a macro level:
  - Comparison of elementary flows induced by international trade
Hybrid LCA

- Combination of LCA and environmentally extended IOA

\[
A = \begin{bmatrix}
A_{ff} & A_{fb} \\
A_{bf} & A_{bb}
\end{bmatrix}
\]

- Problem to be avoided> „double counting“
LCA case study: floating wind power plant

- To evaluate whether additional environmental burdens can be rebalanced or even offset by better wind conditions
- To compare environmental impact with other electricity sources
- => we do not care about money (smb. else does)
- => typical task for LCA (the entire life cycle has to be assess)
LCA case study

- **Goal and scope definition**
  - To evaluate whether additional environmental burdens can be rebalanced or even offset by better wind conditions
  - Energy payback time of floating wind power plant

- **Function and functional unit**
  - To supply electricity to power grid
  - 1 MJ of electricity supplied to power grid

- **Process LCA, average technology data**
Popis elektrárny

Technical life-time  20 - 30 years
Windmills in a farm  40
Distance from a coast  50 km
Average load  53%
Nominal power  5 MW
System boundaries

Transform station

170 kV

30 kV

Sea / land

Electrical grid

System boundaries
Inventory analysis

- Data from producers and suppliers
- Life cycle process inventory database Ecoinvent
- Input output analysis used to estimate missing data from cable production and installation since no better data was available
Tower

- 1000 tons of low alloyed steel
- 5 tons of high alloyed steel
- Sheet rolling and welding
- Transport: 500 km by truck and 1500 km by boat
- Ecoinvent as a data source
Transformer station

- Modelled as a tower with ballast and mooring
- Transformer based on data provided by ABB: EPD of similar transformer
Final assembly and erection

- The most detailed and reliable data (directly from Sway)
- Pumping water into the tower (300 – 600 tons, height 15 m) and out (70 m)
- Lifting 2000 – 3000 tons of olivine stones up to 15 m
- One day operation of special crane (consumption of 300 litres of petrol and 1 litre of lubricant oil per hour)
Maintenance

- Regular inspections 3 times a year
- Each windmill transported once in a lifetime to a near coast inspection
- 2 windmills replaced during the operation of the windfarm
Cable production and installation

- Input output analysis
- We know material composition and the price of individual processes
- Norwegian input output analysis used (environmental extension of airborne emissions)

\[ e = F \cdot (I - A)^{-1} \cdot y \]

<table>
<thead>
<tr>
<th>Economic sector</th>
<th>Final demand ( y ) (NOK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of plastic</td>
<td>(-1.47 \times 10^6)</td>
</tr>
<tr>
<td>Production of steel</td>
<td>(-6.09 \times 10^6)</td>
</tr>
<tr>
<td>Production of precious metals</td>
<td>(-4.2 \times 10^7)</td>
</tr>
<tr>
<td>Machinery production</td>
<td>(4 \times 10^8)</td>
</tr>
</tbody>
</table>
End of life treatment

- Transport
- Dismantling
- Transport, disposal, and recycling of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Recycling rate (%)</th>
<th>Recycled amount (tons/windmill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>90</td>
<td>922</td>
</tr>
<tr>
<td>Copper</td>
<td>90</td>
<td>21</td>
</tr>
<tr>
<td>Gravel</td>
<td>80</td>
<td>2100</td>
</tr>
<tr>
<td>Material</td>
<td>Amount/power plant</td>
<td>Unit</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------</td>
<td>------</td>
</tr>
<tr>
<td>Steel, low alloyed</td>
<td>1.41E+06</td>
<td>kg</td>
</tr>
<tr>
<td>Steel, high alloyed&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.25E+03</td>
<td>kg</td>
</tr>
<tr>
<td>Gravel</td>
<td>3.23E+06</td>
<td>kg</td>
</tr>
<tr>
<td>Copper</td>
<td>5.85E+04</td>
<td>kg</td>
</tr>
<tr>
<td>Lubricating oil</td>
<td>7.51E+04</td>
<td>kg</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.25E+03</td>
<td>kg</td>
</tr>
<tr>
<td>Chromium steel</td>
<td>1.35E+05</td>
<td>kg</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>5.21E+04</td>
<td>kg</td>
</tr>
<tr>
<td>Lead</td>
<td>1.29E+04</td>
<td>kg</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>1.45E+04</td>
<td>kg</td>
</tr>
<tr>
<td>Cast iron</td>
<td>6.91E+04</td>
<td>kg</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>9.22E+03</td>
<td>kg</td>
</tr>
<tr>
<td>Electro steel&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.75E+03</td>
<td>kg</td>
</tr>
<tr>
<td>Epoxy resin&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.44E+03</td>
<td>kg</td>
</tr>
<tr>
<td>Logs&lt;sup&gt;b&lt;/sup&gt; (wood)</td>
<td>3.60E+02</td>
<td>kg</td>
</tr>
<tr>
<td>Synthetic rubber</td>
<td>2.63E+02</td>
<td>kg</td>
</tr>
<tr>
<td>Ceramics&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.39E+01</td>
<td>kg</td>
</tr>
<tr>
<td>Tin</td>
<td>1.31E+00</td>
<td>kg</td>
</tr>
</tbody>
</table>

*Transport*

<table>
<thead>
<tr>
<th>Transport</th>
<th>Amount/power plant</th>
<th>Unit</th>
<th>Amount/1 MJ</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck transport (lorry 40 tons)</td>
<td>8.76E+05</td>
<td>tkm</td>
<td>5.28E-04</td>
<td>tkm</td>
</tr>
<tr>
<td>Transport barge</td>
<td>3.60E+06</td>
<td>tkm</td>
<td>2.17E-03</td>
<td>tkm</td>
</tr>
<tr>
<td>Train transport</td>
<td>5.81E+05</td>
<td>tkm</td>
<td>3.50E-04</td>
<td>tkm</td>
</tr>
<tr>
<td>Transport helicopter (time)</td>
<td>7.00E+02</td>
<td>h</td>
<td>4.22E-07</td>
<td>h</td>
</tr>
<tr>
<td>Transport helicopter</td>
<td>1.00E+02</td>
<td>p</td>
<td>6.03E-08</td>
<td>p</td>
</tr>
<tr>
<td>(take off and land)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Impact assessment

- CML 2000
- Cumulative energy demand
## Results

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Impact / MJ</th>
<th>Unit</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abiotic depletion</td>
<td>2.5.10^{-5}</td>
<td>kg Sb eq</td>
<td>1.5.10^{-14}</td>
</tr>
<tr>
<td>Global warming potential (GWP100)</td>
<td>3.5.10^{-3}</td>
<td>kg CO₂ eq</td>
<td>1.4.10^{-14}</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP)</td>
<td>2.1.10^{-10}</td>
<td>kg CFC-11 eq</td>
<td>2.2.10^{-16}</td>
</tr>
<tr>
<td>Human ecotoxicity</td>
<td>2.2.10^{-2}</td>
<td>kg 1,4-DB eq</td>
<td>1.2.10^{-13}</td>
</tr>
<tr>
<td>Fresh water aquatic ecotoxicity</td>
<td>3.0.10^{-3}</td>
<td>kg 1,4-DB eq</td>
<td>4.0.10^{-13}</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>2.9.10^{0}</td>
<td>kg 1,4-DB eq</td>
<td>9.0.10^{-13}</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>6.7.10^{-5}</td>
<td>kg 1,4-DB eq</td>
<td>7.3.10^{-14}</td>
</tr>
<tr>
<td>Photochemical oxidation</td>
<td>1.7.10^{-6}</td>
<td>kg C₂H₄</td>
<td>9.3.10^{-15}</td>
</tr>
<tr>
<td>Acidification</td>
<td>3.1.10^{-5}</td>
<td>kg SO₂ eq</td>
<td>4.6.10^{-14}</td>
</tr>
<tr>
<td>Eutrofication</td>
<td>3.2.10^{-6}</td>
<td>kg PO₄³⁻ eq</td>
<td>6.4.10^{-15}</td>
</tr>
</tbody>
</table>

- Energy payback time about 5 months
Comparison with selected power plants

- Abiotic depletion
- Global warming (GWP100)
- Ozone layer depletion (ODP)
- Human toxicity
- Fresh water aquatic ecotoxicity
- Marine aquatic ecotoxicity
- Terrestrial ecotoxicity
- Photochemical oxidation
- Acidification
- Eutrophication

The diagram compares different environmental impacts for natural gas, wind power plant, and floating concept. The impacts include:

- Abiotic depletion
- Global warming (GWP100)
- Ozone layer depletion (ODP)
- Human toxicity
- Fresh water aquatic ecotoxicity
- Marine aquatic ecotoxicity
- Terrestrial ecotoxicity
- Photochemical oxidation
- Acidification
- Eutrophication
Interpretation

● In comparison to near coast offshore power plant the floating wind power plant has:
  – Lower environmental impact in categories of: global warming, abiotic depletion
  – Similar impact in categories of fresh water ecotoxicity
  – Higher impact in other categories

● Higher material requirements can be rebalanced by higher amount of electricity supplied to the grid due to better wind conditions
That’s all from my side...

- Any questions are welcome
- Do not hesitate to contact me via e-mail: jan.weinzettel@czp.cuni.cz
Literature

Electric vehicles

- http://www.youtube.com/watch?v=YKTdNoI0le8