VPPC 2014
Vehicle Power and Propulsion Conference
October 27-30, 2014 – Coimbra, Portugal
"Spreading E-Mobility Everywhere"

VPPC Tutorial:

How to understand and perform Life Cycle Assessment of electric vehicles

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Outline of the tutorial

TOPIC 1	**Introduction in LCA**	
15:00-16:15	• Introduction in LCA methodology; • Application of LCA. • LCA structure: WTW and LCA; • How to read studies and how to interpret? • Lessons learned from literature on LCA of BEV;	
	(Coffee) Break 16:15-16:30	
TOPIC 2	**Overview current LCA Studies on electric vehicle concepts**	
16:30-16:45	• Overview of LCA results	
TOPIC 3	**Key Issues: LCA of electric vehicles**	
16:45- 17:50	• General framework; • Production; • Use stage; • End-of-Life; • Range-based vehicle LCA.	
TOPIC 4	**Summary, conclusion and discussions**	
17:50-18:00	• Wrap up of tutorial and main conclusions; • Discussion.	

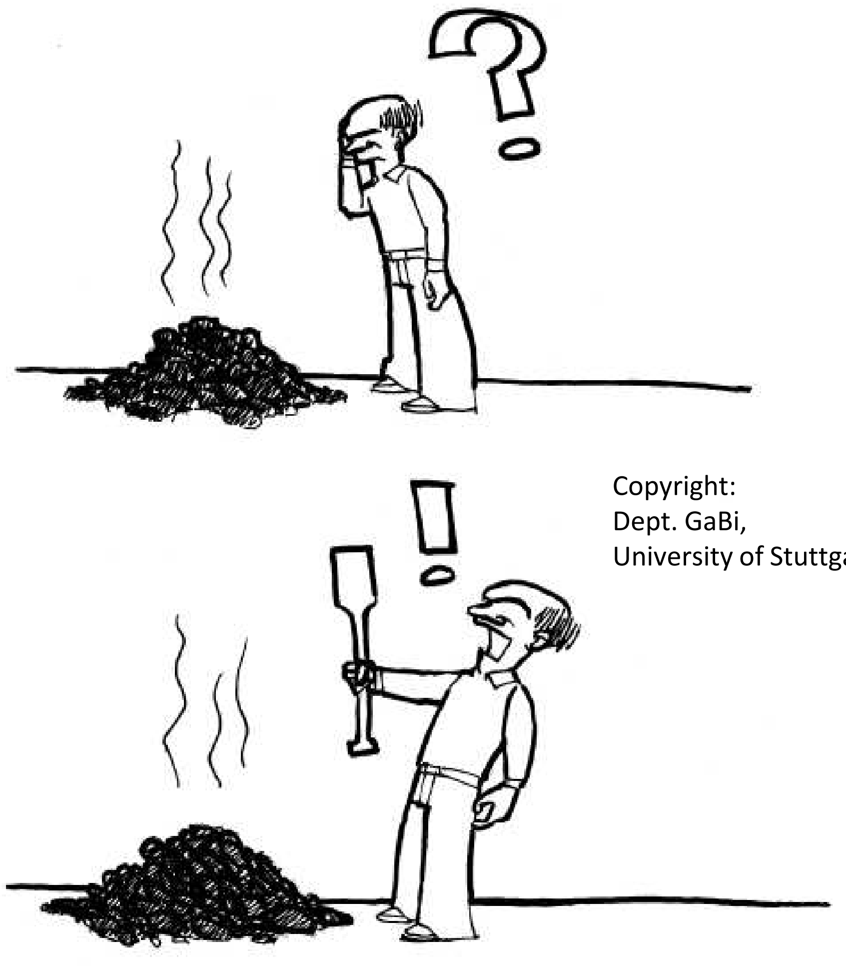
TOPIC 1: Introduction in LCA

- Introduction in LCA methodology
- Applications of LCA
- Sustainability-LCA

Methodology of Life Cycle Assessment (LCA) – life cycle thinking

Avoid...

...solving a problem...



Methodology of Life Cycle Assessment (LCA) – life cycle thinking

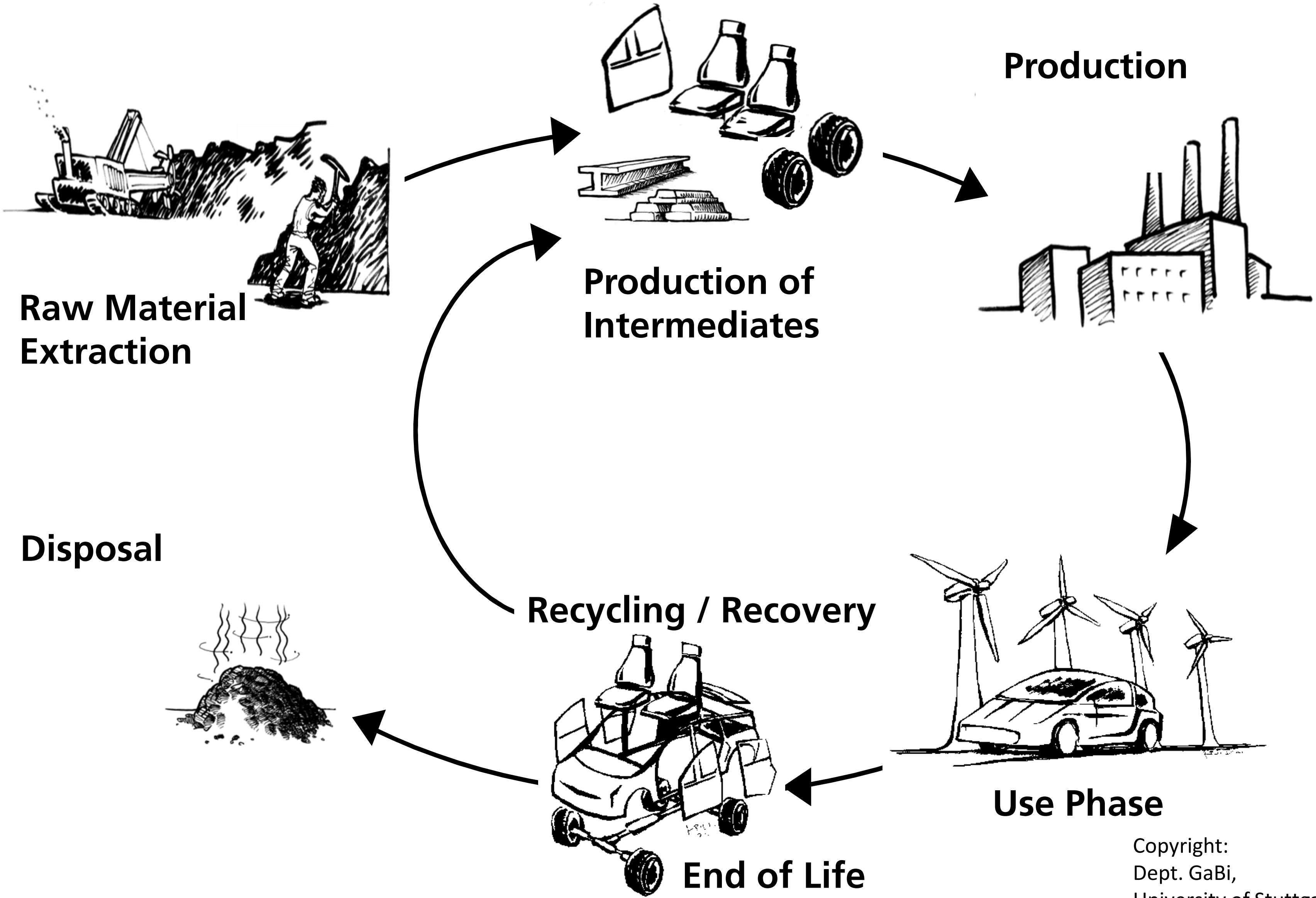
Avoid...

...solving a problem...

... by creating

a problem.

Methodology of Life Cycle Assessment (LCA) – life cycle thinking



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Methodology of Life Cycle Assessment (LCA) – What is LCA

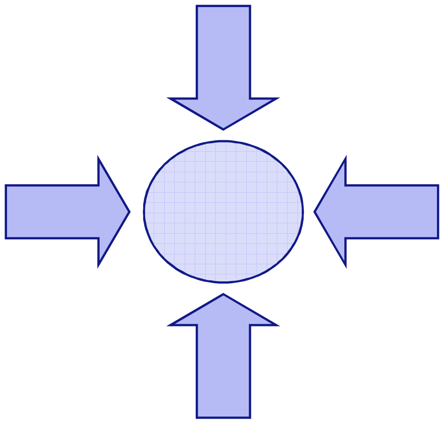
LCA ?

Definition of Life Cycle Assessment (ISO 14040):

> “LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle“

Internal Benefits from LCA

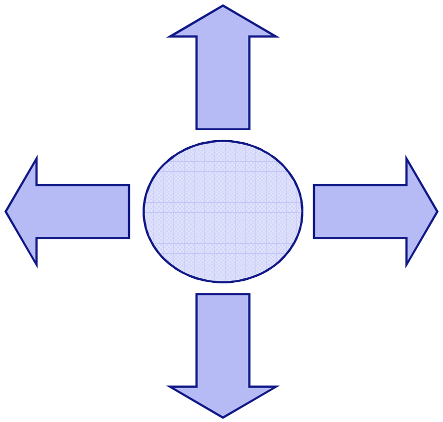
Internal benefit



- Detection of strategic risks and environmental issues
- Identification of relevant steps in the complete life cycle of products
- Development of sustainable products based on environmental information
- Support in fulfilling laws and restrictions
- Improvement of motivation of employees
- Support in environmental management systems (i.e. EMAS II)

External Benefits from LCA

External benefit



- Enhancement of communication to politics and authorities
- Improvement of image due to ecological considerations
- Supporting environmental innovations and decrease of environmental impacts
- Competitive advantage by inclusion of environmental aspects
- International standardized approach (ISO 14040 and ISO 14044)
  ➔ International and public acceptance

Methodology of LCA – ISO 14040 and 14044

ISO 14040:

Principles and framework of LCA

EUROPÄISCHE NORM
EUROPEAN STANDARD
NORME EUROPÉENNE

EN ISO 14040

Juli 2006/July 2006

ICS 13.020.10; 13.020.60

Ersatz für/Supersedes EN ISO 14040:1997, EN ISO 14041:1998, EN ISO 14042:2000, EN ISO 14043:2000

Zweisprachige Fassung – Bilingual version

Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006)

Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006)

Management environnemental – Analyse du cycle de vie – Principes et cadre (ISO 14040:2006)

Diese Europäische Norm wurde vom CEN am 19. Juni 2006 angenommen.

Die CEN- Mitglieder sind gehalten, die CEN/CENELEC-Geschäftsordnung zu erfüllen, in der die Bedingungen festgelegt sind, unter denen dieser Europäischen Norm ohne jede Änderung der Status einer nationalen Norm zu geben ist. Auf dem letzten Stand befindliche Listen dieser nationalen Normen mit ihren bibliographischen Angaben sind beim Management-Zentrum oder bei jedem CEN- Mitglied auf Anfrage erhältlich.

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Management-Zentrum: rue de Stassart, 36 B- 1050 Brüssel
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Ref. Nr./Ref. No. EN ISO 14040:2006 D/E

ISO 14044:

Requirements and guidelines

EUROPÄISCHE NORM
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EN ISO 14044

Juli 2006/July 2006

ICS 13.020.60; 13.020.10

Ersatz für/Supersedes EN ISO 14040:1997, EN ISO 14041:1998, EN ISO 14042:2000, EN ISO 14043:2000

Zweisprachige Fassung – Bilingual version

Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044:2006)

Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006)

Management environnemental – Analyse du cycle de vie – Exigences et lignes directrices (ISO 14044:2006)

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Ref. Nr./Ref. No. EN ISO 14044:2006 D/E

LCA according to ISO 14040 and 14044

1. Goal and scope of the study
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation
5. Reporting
6. Critical review (optional)

LCA according to ISO 14040 and 14044
1. Goal and scope of the study

- Goal of the study
    - intended applications
    - reasons for carrying out the study
    - intended audience
- Scope of the study
    - **function of the system**
    - **functional unit**
    - description of the system
    - **system boundaries**
    - allocation procedures
    - impact categories and the impact model
    - data requirements
    - data assumptions
    - limitations
    - data quality requirements
    - peer review
    - the type of reporting

LCA according to ISO 14040 and 14044
1. Goal and scope of the study

ISO 14040: function, functional unit and reference flow

- System can have a variety of possible functions
- Function depends on goal and scope of the LCA
- Functional unit defines the quantification of specified functions of the product and is used to create a reference to which input and output flows are related to
- Necessary in order to compare results of LCA
- Determination of reference flow in each product system to fulfil the system's intended function

LCA according to ISO 14040 and 14044
1. Goal and scope of the study

DIN ISO 14040 definitions:

→ The functional unit is the quantified performance of a product system for use as a reference unit

→ The reference flow is the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit

→ The LCA is a relative approach, which is built around a functional unit. This functional unit defines what is to be examined. All subsequent analyzes are then based on this functional unit, because all inputs and outputs in the life cycle and, consequently, the impact assessment profile are related to the functional unit

LCA according to ISO 14040 and 14044
1. Goal and scope of the study

Function, functional unit and reference flow – EXAMPLE

- Function of drying hands: assessment for paper towels as well as for an air drying system

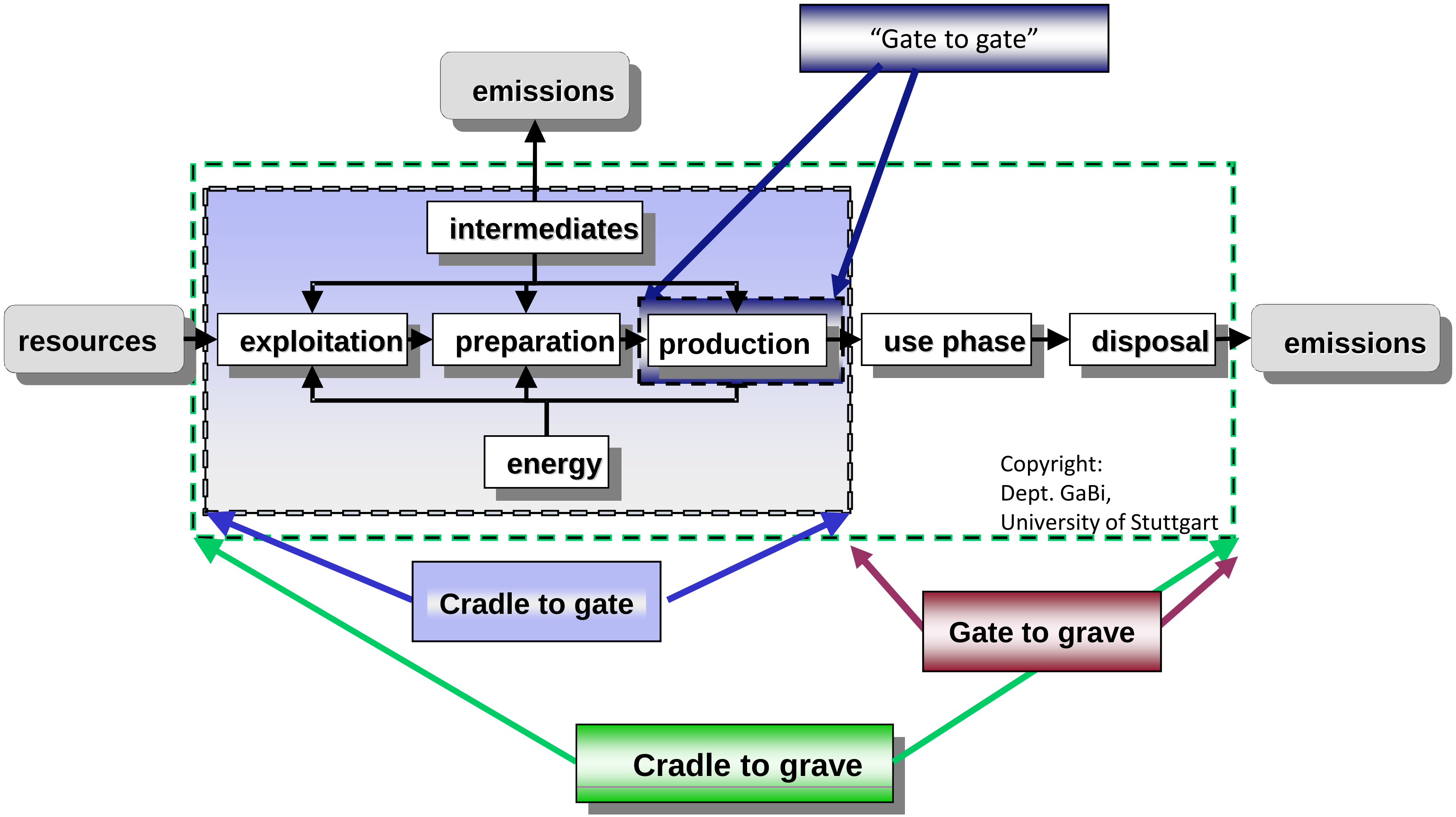
→ selected functional unit can be expressed as the number of dried hand pairs (for both systems identical)

- Reference flow could be the average mass of paper respectively the average volume of hot air
- For both systems it is possible to create a life cycle inventory of inputs and outputs on the basis of the reference flows

→ In case of paper towels, the LCI would be based on the consumed paper. In case of air dryer it would be based on the need of the volume of hot air for drying of hands

LCA according to ISO 14040 and 14044
1. Goal and scope of the study

Definition of system boundaries



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LCA according to ISO 14040 and 14044
2. Life cycle inventory analysis (LCI)

2. **Life cycle inventory analysis (LCI)**

→ Data collection

→ Description of the inventory

3. Life cycle impact assessment (LCIA)

→ Classification (by impact categories)

→ Characterization

→ Normalization (or weighting)

4. Interpretaion

→ Evaluation and discussion

5. Reporting

6. Critical review

→ optional

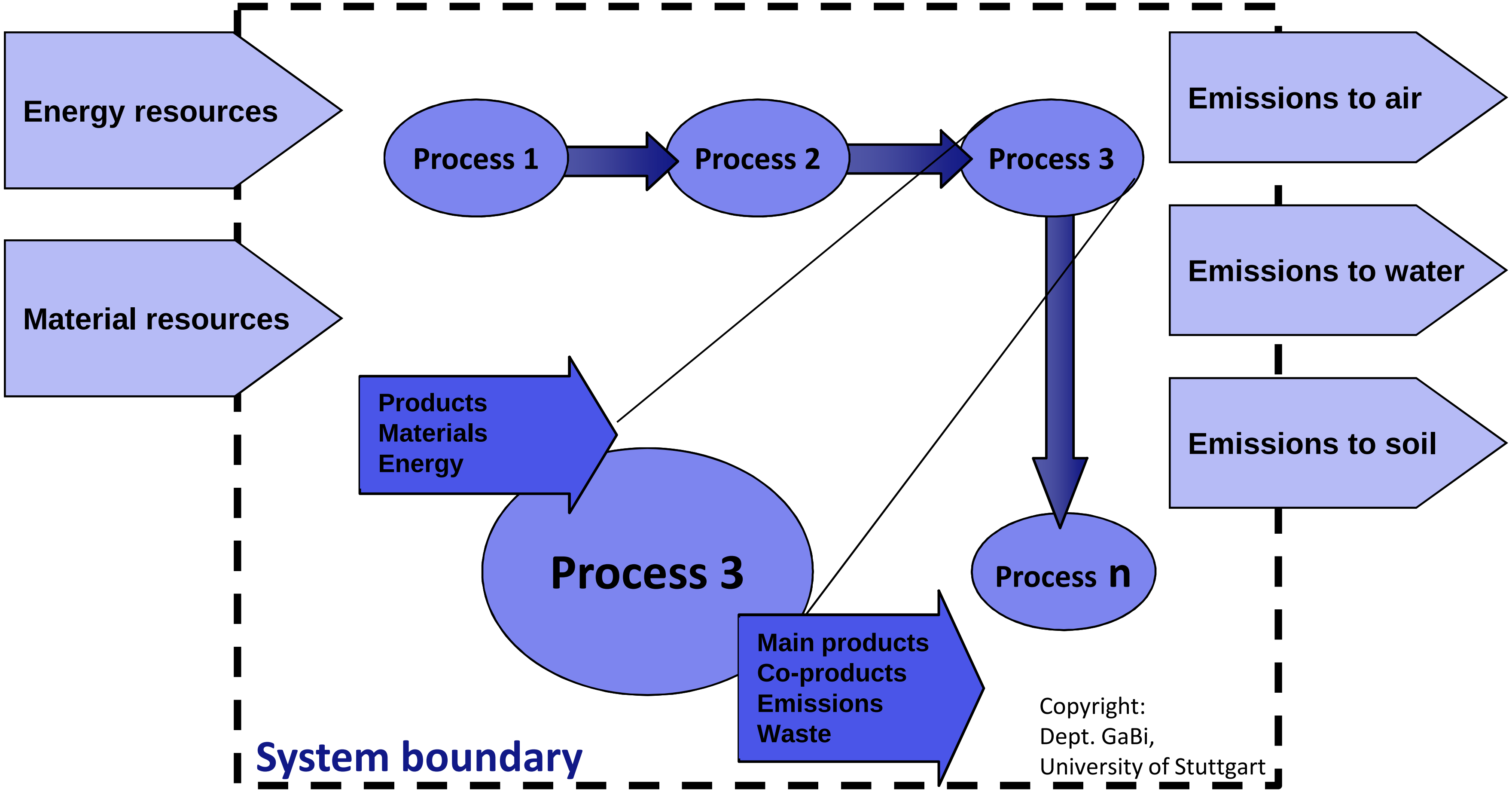
LCA according to ISO 14040 and 14044
2. Life cycle inventory analysis (LCI)

Definition of life cycle inventory analysis from ISO 14044:

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle"

LCA according to ISO 14040 and 14044
2. Life cycle inventory analysis (LCI)

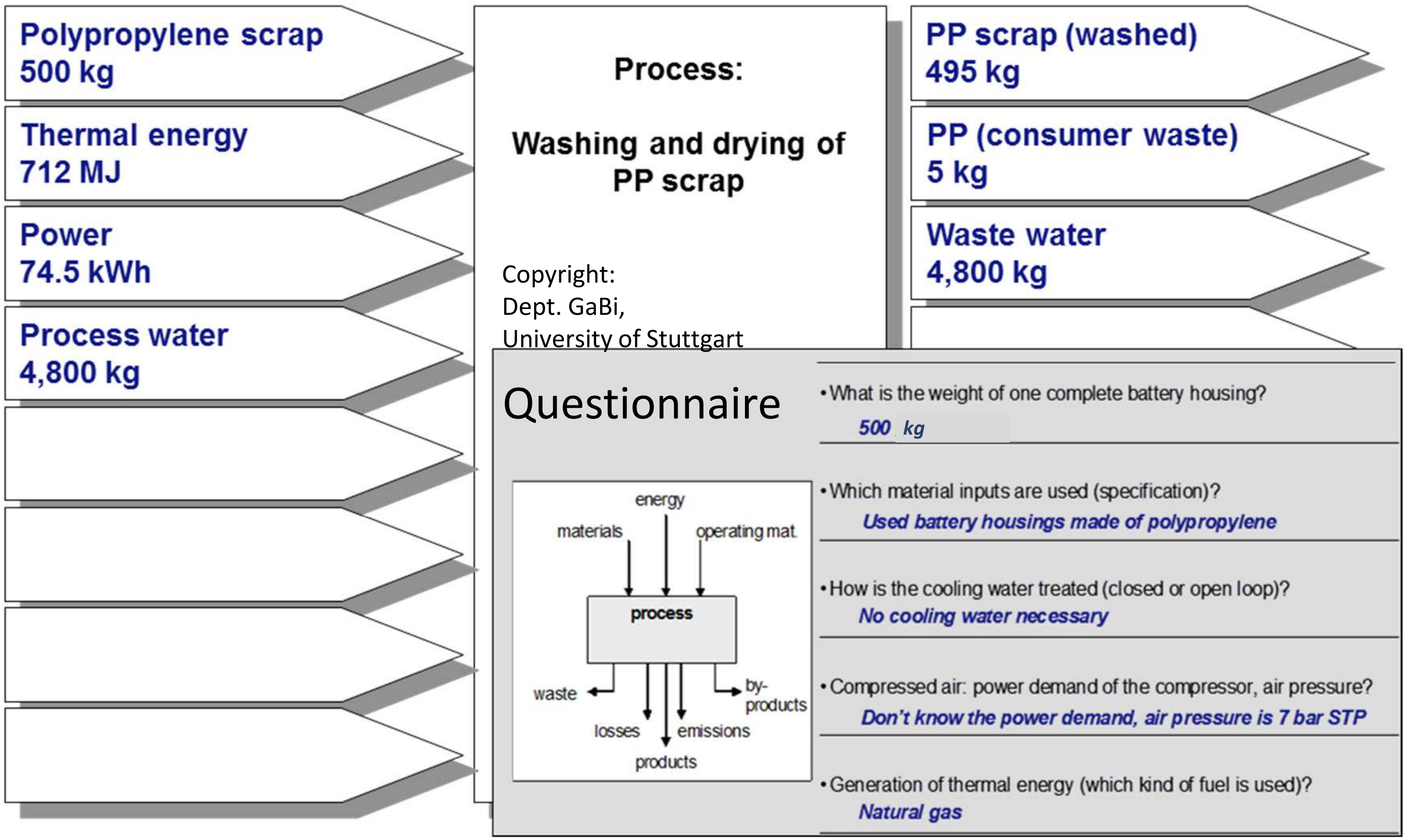
LCI-modeling of a system within an LCA



LCA according to ISO 14040 and 14044
2. Life cycle inventory analysis (LCI)

Modeling of a system within an LCA – Example

Input: **Output:**



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LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

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   - → Evaluation and discussion

5. Reporting

6. Critical review
   - → optional

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Definition of Life cycle impact assessment from ISO 14044:

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product"

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Research institutions involved in the development of commonly used impact assessment methods

- **CML 2001 Method:** Institute of Environmental Sciences, Leiden University, Netherlands
- **ReCiPe LCA methodology:** RIVM (National Institute of Public Health and Environmental Protection), CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft
- **Eco-Indicator 99:** PRé Consultants
- **IPPC:** Intergovernmental Panel on Climate Change

Etc.

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

ILCD Recommendations:
Impact categories (mid- and end-point)

- **Climate Change:**
  - Mid-point: GWP IPCC 2007
  - End-point: no mature method
- **Resource Depletion:**
  - Mid-point (scarcity): ADP CML
  - Mid-point (water): Swiss Ecoscarcity (water)
  - End-point: no mature method
- **Human Toxicity:**
  - Mid-point: USEtox
  - End-point: DALYs by Huijbregts et al. (2005a)
- **Eutrophication:**
  - Mid-point (terrestrial): Accumulated Exceedance (Seppälä 2006)
  - Mid-point (aquatic): EUTREND ReCiPe
  - End-point: no mature method
- **...**

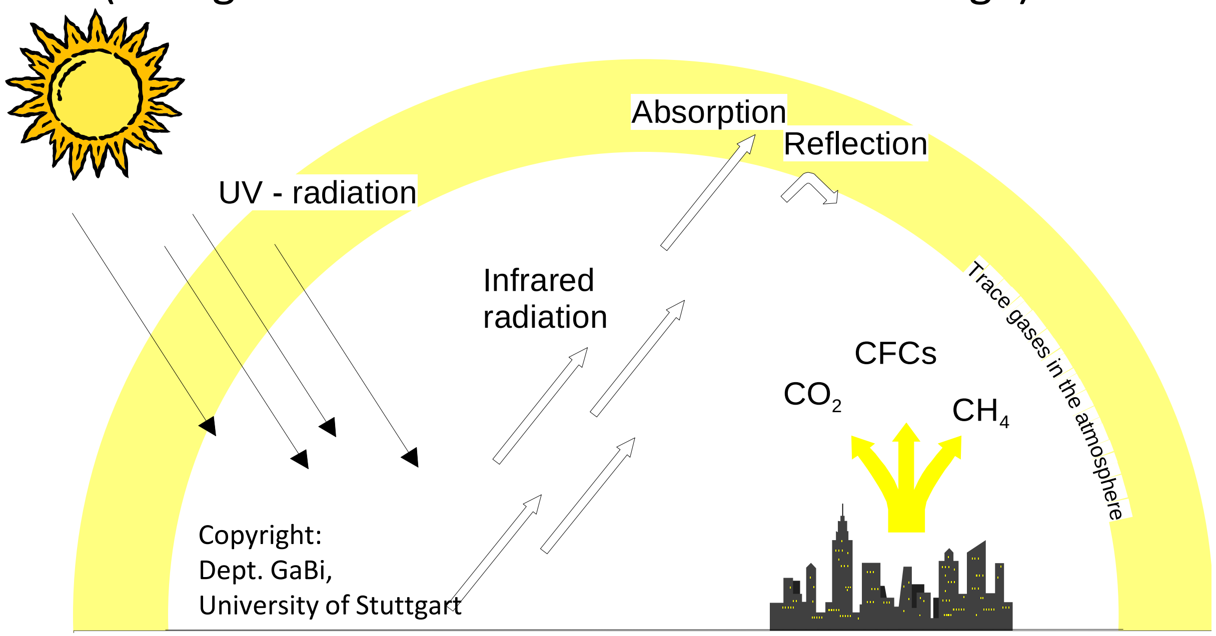
Many different institutions involved in developing methods and characterization factors

http://eplca.jrc.ec.europa.eu/uploads/ILCD-Recommendation-of-methods-for-LCIA-def.pdf

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Impact categories – Global Warming Potential (GWP)

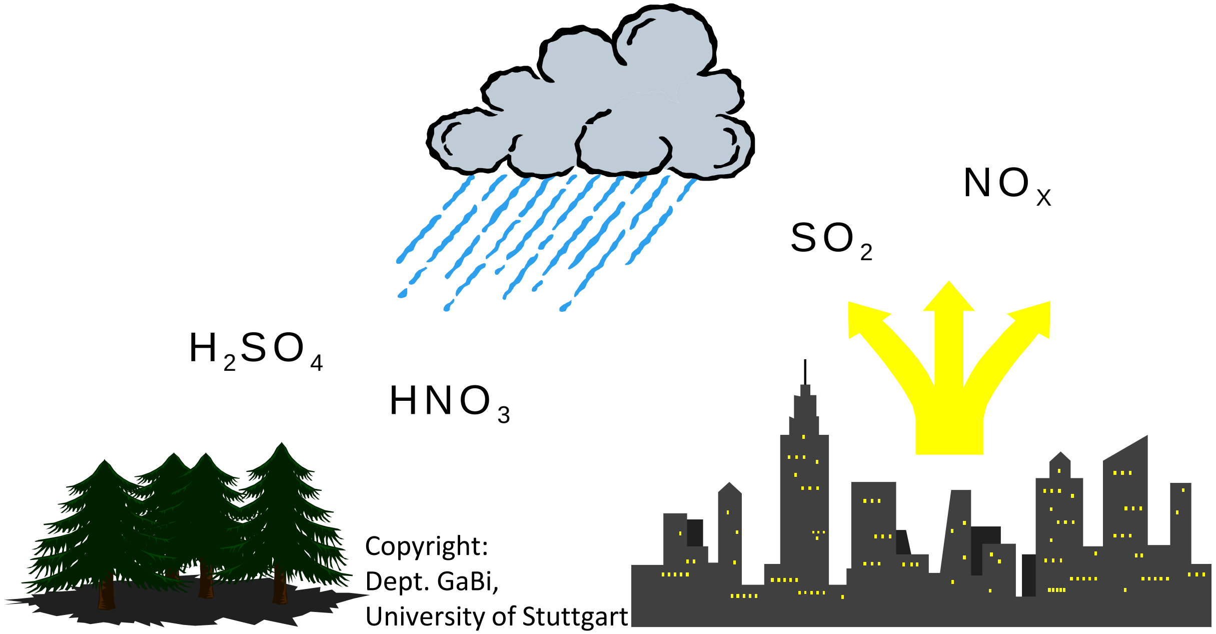
- **Effect:** Increased warming of the troposphere due to anthropogenic greenhouse gases e.g. from the burning of fossil fuels.
- **Reference Substance:** Carbon Dioxide (CO2)
- **Reference Unit:** kg CO2 Equivalent
- **Source:** IPCC (Intergovernmental Panel on Climatic Change)



LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Impact categories – Acidification Potential (AP)

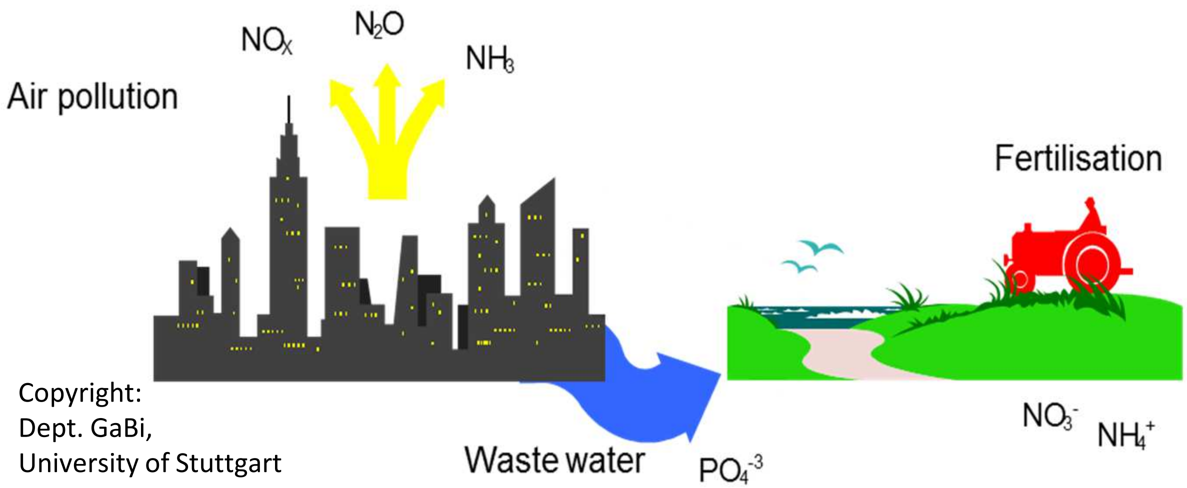
- **Effect:** Increase in the pH-value of precipitation due to the wash-out of acidifying gases e.g. Sulphur dioxide (SO2) and Nitrogen oxides (NOx).
- **Reference Substance:** Sulphur dioxide (SO2)
- **Reference Unit:** kg SO2 Equivalent
- **Source:** CML, (Heijungs, Centrum voor Milieukunde Leiden), 1992



LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Impact categories – Eutrophication Potential (EP)

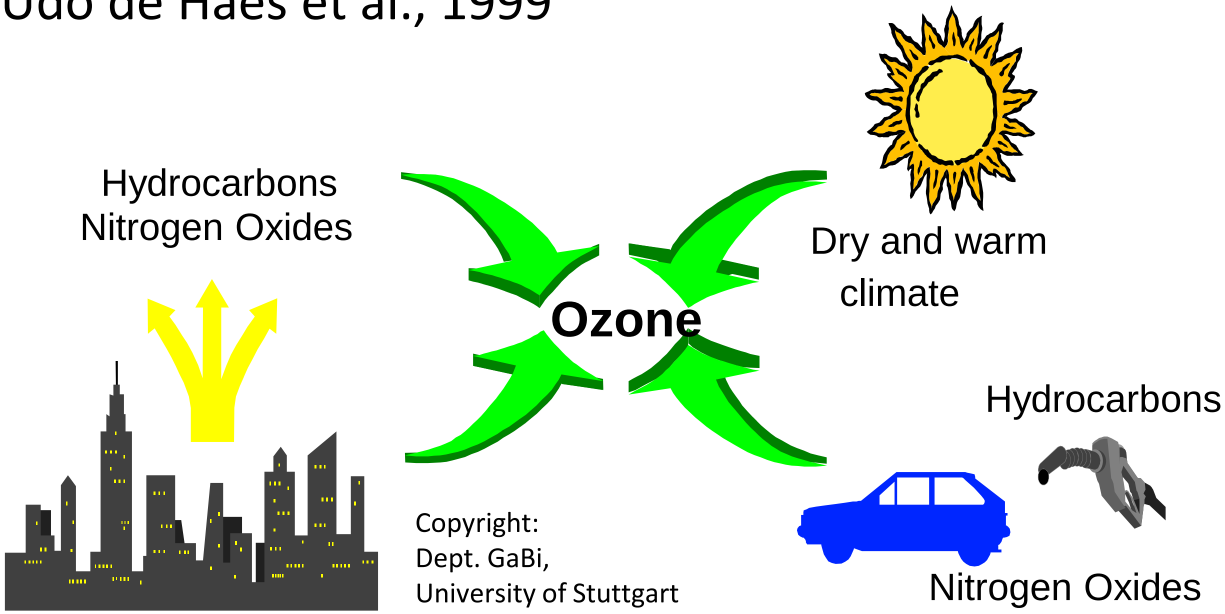
- **Effect:** Excessive nutrient input into water and land from substances such as phosphorus und nitrogen from agriculture, combustion processes and effluents.
- **Reference Substance:** Phosphate (PO4-)
- **Reference Unit:** kg PO4 Equivalent
- **Source:** CML, (Heijungs, Centrum voor Milieukunde Leiden), 1992



LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Impact categories – Photochemical Ozone Creation Potential (POCP)

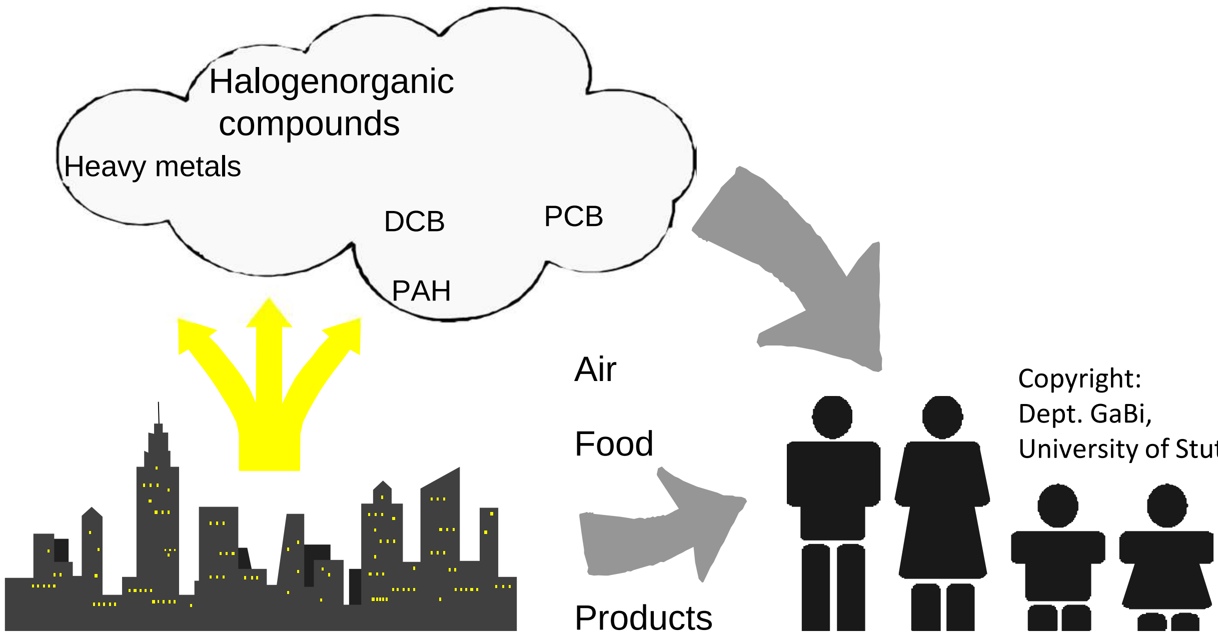
- **Effect:** Formation of low level ozone by sunlight instigating the photochemical reaction of nitrogen oxides with hydrocarbons and volatile organic compounds (VOC)
- **Reference Substance:** Ethylene (C2H4)
- **Reference Unit:** kg C2H4 Equivalent
- **Source:** Udo de Haes et al., 1999



LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Impact categories – Human Toxicity Potential (HTP)

- **Effect:** Continuous toxicological impact on humans (arbitrary estimation)
- **Reference Substance:** 1,4-Di-chloro-benzene (DCB, C6H4Cl2)
- **Reference Unit:** kg DCB - Equivalent
- **Source:** CML (Centrum voor Milieukunde Leiden); RIVM (National Institute of Public Health and Environmental Protection)



LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Global, regional and local impact assessment categories

Global Criteria
- Resource depletion
- Global Warming Potenzial (GWP)
- Ozone Depletion Potential (ODP)

Regional Criteria
- Acidification Potential (AP)
- Land use

Local Criteria
- Human and Eco Toxicity Potential (HTP / AETP / TETP)
- Eutrophication Potential (EP)
- Photochemical Oxidant Creation Potential (POCP)

Other Criteria
- Disturbances (Noise, odor, demand on land fill sites)

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Steps of life cycle impact assessment:

1. Classification:	Assignment of LCI results which are exclusive to one impact category and identification of LCI results which relate to more than one impact category.
2. Characterization:	Conversion of LCI results to common units and the aggregation of the converted results within the impact category by the use of characterization factors
3. Normalization (optional step):	Calculation of the magnitude of the category indicator results relative to reference value(s) Comparison with the reference quantity.

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Classification and characterization

Life Cycle Inventory value	*	GWP Factor	=	Impact potential
24 kg CO_2	*	1	=	24 [kg CO_2-equivalent]
2 kg CH_4	*	25	=	50 [kg CO_2-equivalent]
...	*	...	=	...
			Total:	74 [kg CO_2-equivalent]

1 kg of CH_4 emission is equivalent to 25 kg of CO_2 emission

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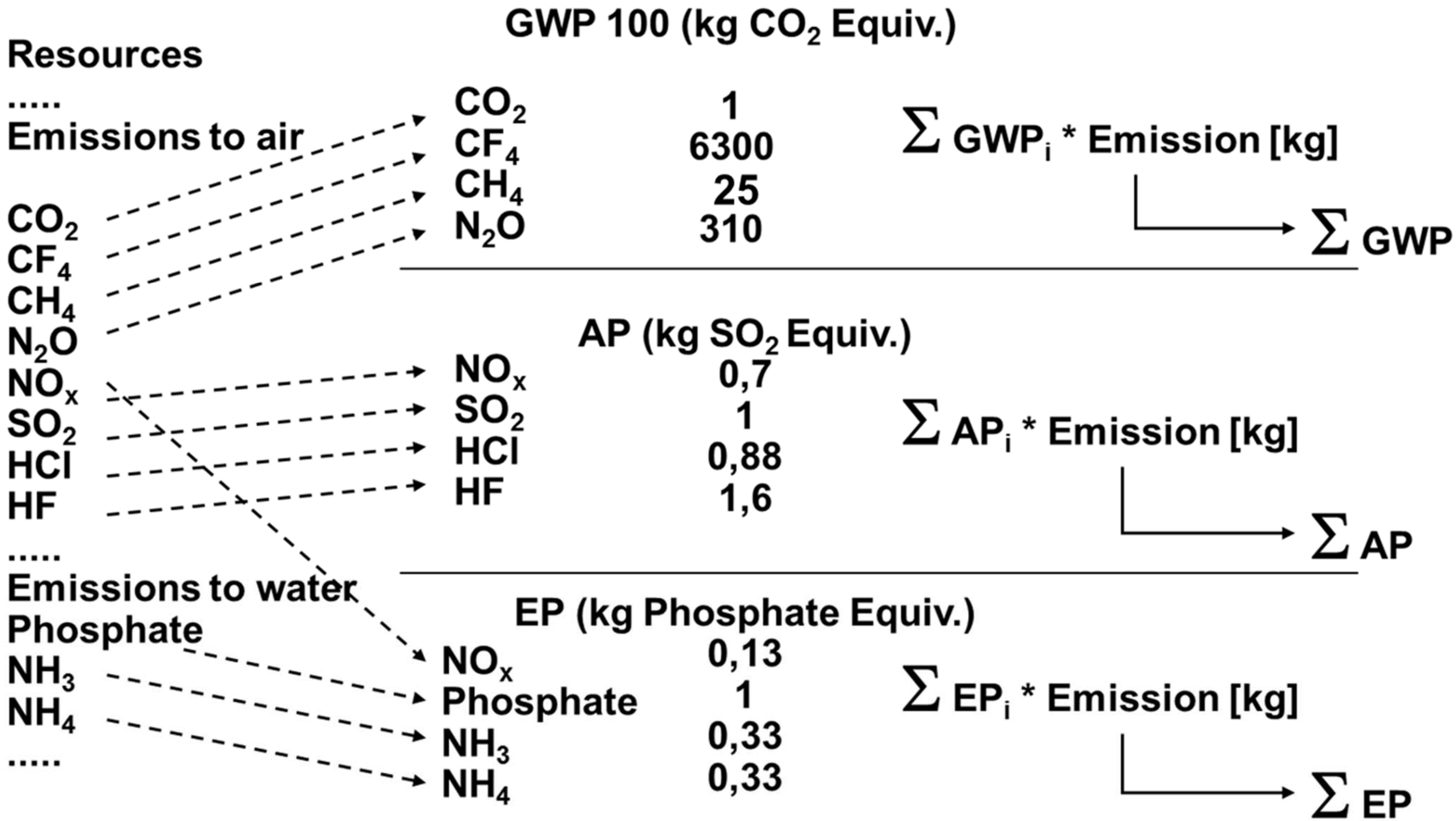
LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Classification and characterization



The shown characterization factors are not state of the art, current values may differ.

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LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Classification and characterization

Global warming potential (GWP 100 years)				
Emission	kg CO2-Äqv.		Emission	kg CO2-Äqv.
Carbon dioxide (CO2)	1		R 22 (chlorodifluoromethane)	1700
Trichloromethane (chloroform)	5		R 142b (chlorodifluoroethane)	2000
Dichloromethane (methylene chloride)	9		R 125 (pentafluoroethane)	3200
Methane (CH4)	25		R 227ea (septifluoropropane)	3300
R 123 (dichlorotrifluoroethane)	93		R 11 (trichlorfluormethane)	4000
Trichloroethane	110		R 143a (trifluoroethane)	4400
R 152a (difluoroethane)	140		R 113 (trichlorofluoroethane)	5000
R 225ca (dichloropentafluoropropane)	170		Halone (1301)	5600
R 143 (trifluoroethane)	290		Tetrafluoromethane	6300
Laughing gas (dinitrogen monoxide)	310		R 236fa (hexafluoropropane)	8000
R 124 (chlorotetrafluoroethane)	480		R 12 (dichlorodifluoromethane)	8500
R 225cb (dichloropentafluoropentane)	530		R 115 (chloropentafluoroethane)	9300
R 32 (trifluoroethane)	580		R 114 (dichlorotetrafluoroethane)	9300
R 245ca (pentafluoropropane)	610		R 13 (chlorotrifluoromethane)	11700
R 141b (dichloro-1-fluoroethane)	630		R 23 (trifluoromethane)	12100
R 134a (tetrafluoroethane)	1300		R 116 (hexafluoroethane)	12500
Carbon tetrachloride (tetrachloromethane)	1400		Sulphur hexafluoride (SF6)	23900
R 43-10 (decafluoropentane)	1600		...	

The shown characterization factors are not state of the art, current values may differ.

LCA according to ISO 14040 and 14044
3. Life cycle impact assessment (LCIA)

Normalization (optional step)

$$\frac{GWP_{\text{example system}}}{\text{Normalization factor GWP Germany}} \longrightarrow \frac{67 \ [\text{kg } CO_2\text{-equivalent}]}{1{,}218 \times 10^{12} \ [\text{kg } CO_2\text{-equivalent}]}$$

Normalized GWP: **$5{,}501 \times 10^{-11}$** [-]

- By the use of normalization impact potentials are set in relation to the total impact potential within a reference system (e.g. Europe).
- The result is dimensionless
- Impact potentials get comparable

LCA according to ISO 14040 and 14044
Interpretation, Reporting, Critical review

2. Life Cycle Inventory LCI
   → Data collection
   → Description of the inventory

3. Life cycle impact assessment (LCIA)
   → Classification (by impact categories)
   → Characterization
   → Normalization (or weighting)

4. **Interpretation**
   → Evaluation and discussion
5. **Reporting**
6. **Critical review**
   → optional

Interpretation, Report and critical review

4) Interpretation:

On the basis of the inventory results and the impact assessment the analysis and interpretation of the study is performed. These are the fundamentals for further discussions or system optimization.

5) Report:

Prerequisites of performing a Life Cycle Assessment are the definition and the specification of system boundaries as well as the description of the system investigated. To guarantee the traceability of the results obtained, a defined way of reporting is necessary.

6) Critical Review:

For internal projects this step is an optional one. If a study compares competitive products and will be published, a critical review of the study is compulsory.

Use in daily work:

Software systems and databases, guidelines

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Software Systems, Databases Guidelines

<u>European Platform on LCA</u>

- Resource Directory
  - 50+ tools
  - 30+ databases
  - LCA – Service providers
- International Reference Life Cycle Data System (ILCD)
  - Web-based data network
  - Entry-level and full compliance
  - Handbook

eplca.jrc.ec.europa.eu/

European Commission - Joint Research Centre
LCA Tools, Services and Data

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Software Systems, Databases Guidelines

Software systems with great variety in functionality

- Analysis options
  - Life Cycle Impact Assessment (LCIA)
  - Life Cycle Inventory (LCI)
  - Life Cycle Costing (LCC)
  - Design for Environment (DfE)
  - Material Flow Analysis (MFA)
  - …
- Automation
  - Bill-of-Material / Bill-of-Part Import
  - Hot-spot analysis
  - …
- Modelling options
  - Process models
  - Product models
  - Parameterisation
  - …
- Connectivity and Collaboration
  - Web-Access
  - Cloud – Database
  - Collaboration in distributed teams
  - …
- …

umberto® legep® GaBi Product Sustainability Performance ENDAMI SimaPro

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Software Systems, Databases Guidelines

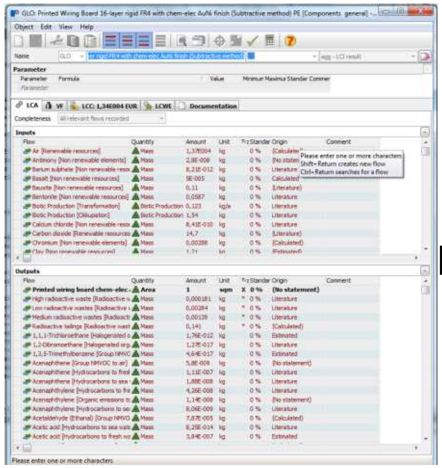
<u>Example: Software and database GaBi</u>

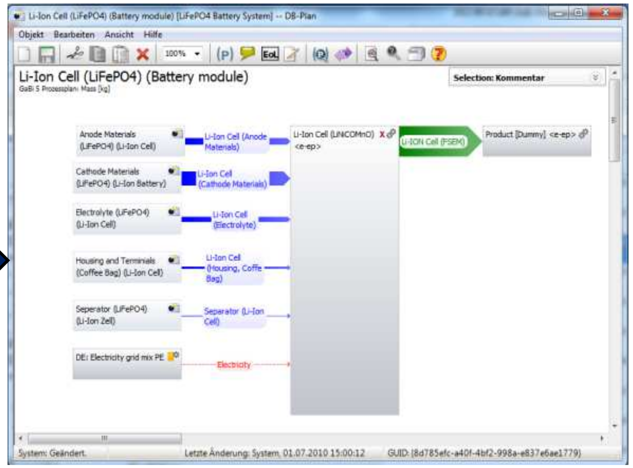
- Expert tool with manifold functionality
- Industry-based background data
- LCI-datasets for country specific energy provision, materials, products,…

Background LCI-datasets

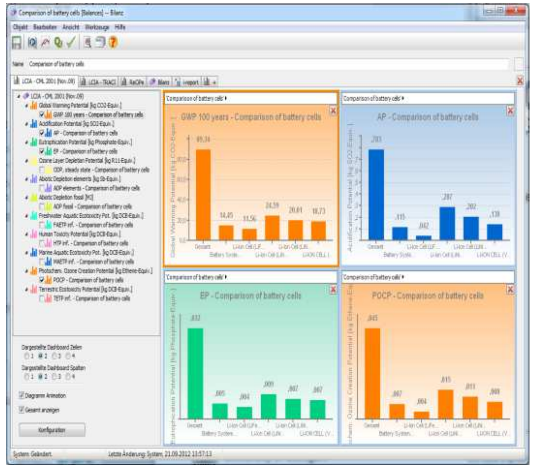
Process model

Result Analysis





Automatic LCI and Impact Computation



Database

Plan-Editor

Analyst/Scenario-Manager

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Software Systems, Databases Guidelines

European Platform on LCA

- Resource Directory
  - 50+ tools
  - 30+ databases
  - LCA – Service providers
- International Reference Life Cycle Data System (ILCD)
  - Web-based data network
  - Entry-level and full compliance
  - Handbook

eplca.jrc.ec.europa.eu/

European Commission - Joint Research Centre
LCA Tools, Services and Data

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Software Systems, Databases Guidelines

ILCD Compliance

- Data-Quality
  - Completeness
  - Representativeness (Technological, geographical, time-related)
  - Precision / Uncertainty
  - Methodological appropriateness and consistency
- Method
  - ISO 14040/14044
  - Differentiation by goal situations
- Nomenclature
  - Correctness and consistency of nomenclature and basic reference data (flows, processes, elementary flows, units, etc.)
  - Correctness and consistency of terminology (technical terms)
- Documentation (extent, form, format)
- Review

Handling of databases

- Compatibility database, software, LCIA-method
  - Format
  - Content
- Compatibility of different database systems
  - Avoid mixing of different databases
    - Remodel in master database
    - Appropriately similar dataset from master database
  - If unavoidable
    - ILCD Compliance?
    - Check and compare dataset documentation

Critical view on comparisons
Consistency & Interpretations

Functional-Unit

Does 1 kg of both materials really provide the same function?

System boundaries

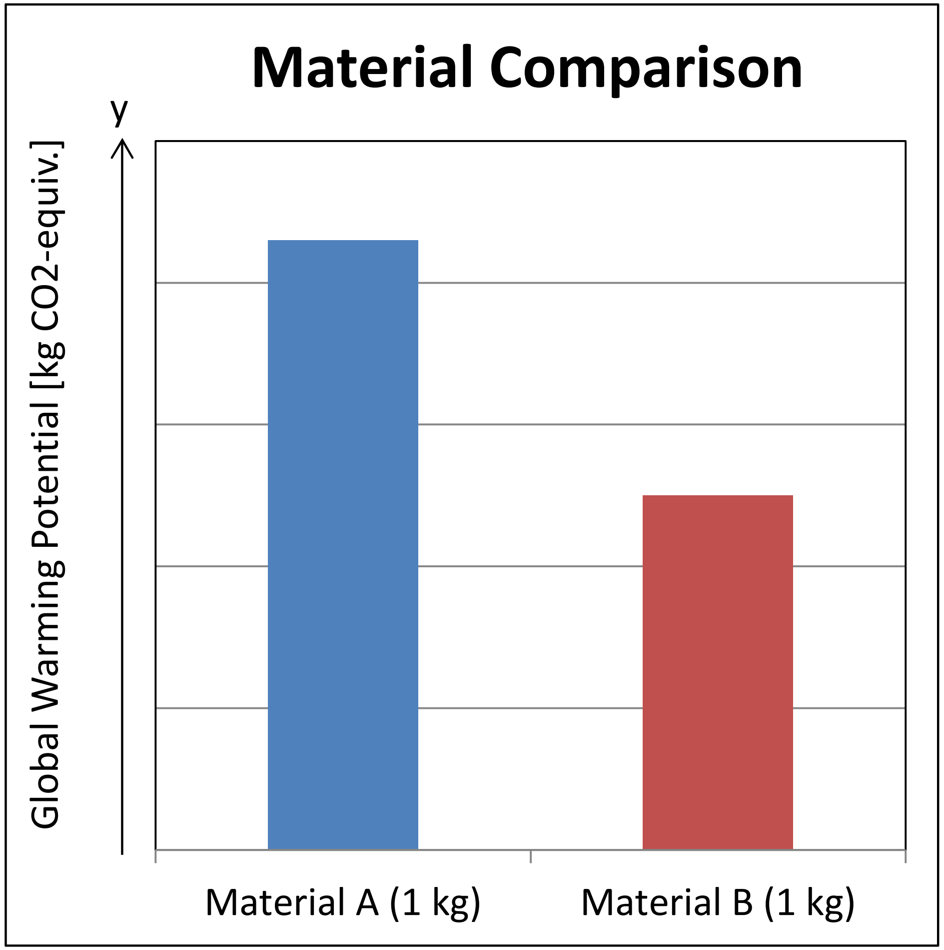
Which phases?

Cut-offs?

Allocation

Mass, economic, material properties?

Other



Summary

- European Platform on LCA
  - Resource directory
  - International Reference Life Cycle Data System (ILCD)
- Software-/database-systems with great variety in functionality
  - Differences in analysis options, modelling options, degree of automation, connectivity
  - Select what suits you best
- Consistency
  - ILCD Guidelines/Compliance
  - Critical areas for consistency: Mixing of databases, interpretation of results

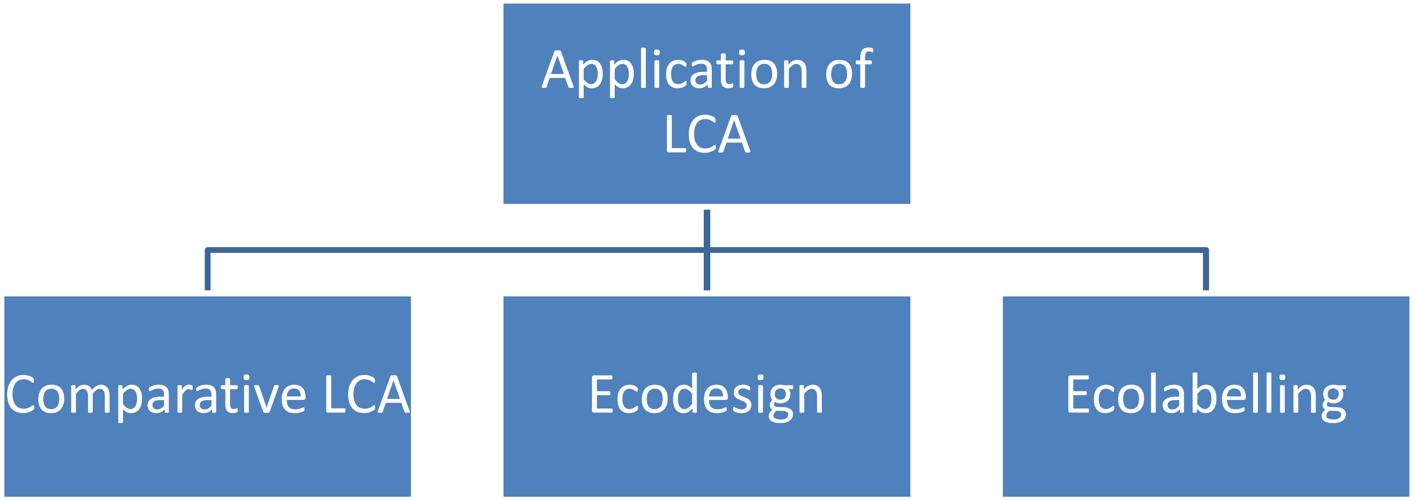
TOPIC 1: Introduction in LCA

- Introduction in LCA methodology
- Applications of LCA
- Sustainability LCA

Applications of LCA

- LCA can assist in:
  - Identifying opportunities to improve the environmental performance of products at various points in their life cycle
  - Informing decision-makers in industry, government or non-government organizations
  - Marketing (ecolabels, environmental product declaration, etc.)

ISO 14040:2006



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Applications of LCA
Comparative LCA

- LCA is a comparative tool of environmental impacts of products or systems

- Conditions for a comparative assessment
  - Meaningful and equivalent functional unit
  - Same system boundaries
  - Similar data quality

ceramic cup

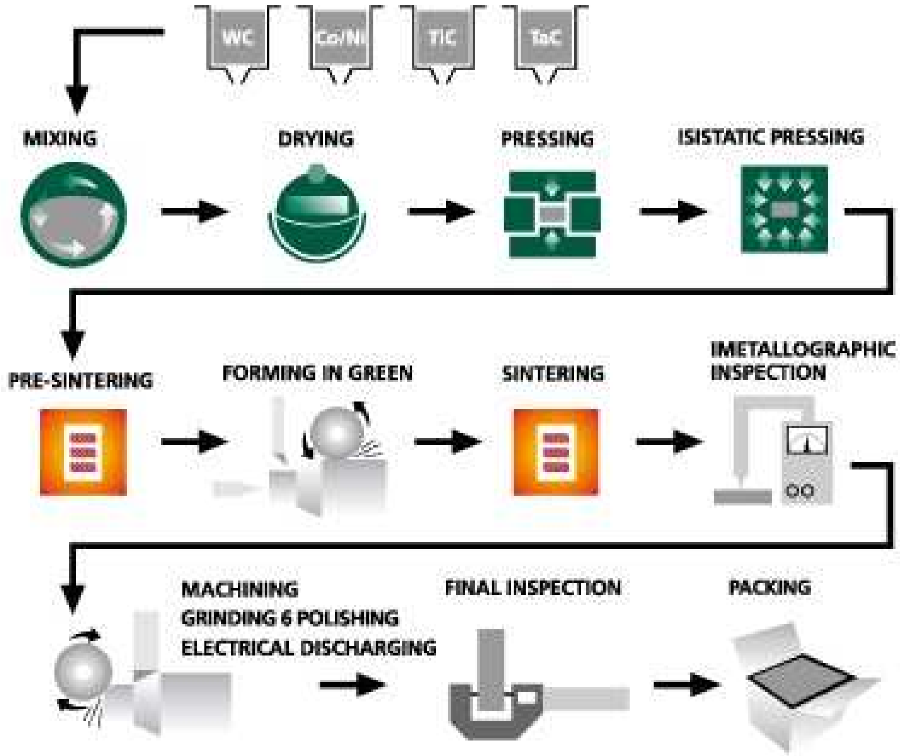
glass cup

plastic cup (reusable)

plastic cup

Applications of LCA
Comparative LCA

- Identify critical hotspots to improve and optimise the environmental performance of a product or system



Applications of LCA
Ecodesign

- Ecodesign: How can a product be optimised from an environmental point of view?

Ecodesign

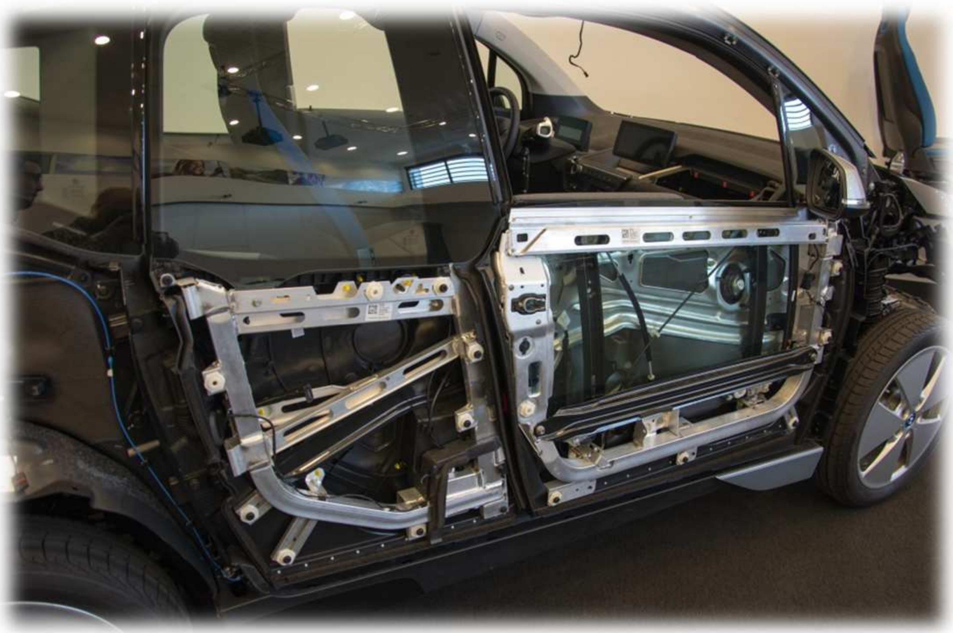
- Design products with minimised environmental impacts
- Include environmental issues into the process of **product development**
- Knowledge of a reference product and compare with possible improvement strategies
- → Design for environment (DfE), green product development and ecological design

Tools

- Developed independently from LCA
- Inclusion of simplified LCA in ecodesign tools, key environmental performance indicators (KEPI)
- 10 golden rules of ecodesign

Applications of LCA

Example: lightweighting BMW i3



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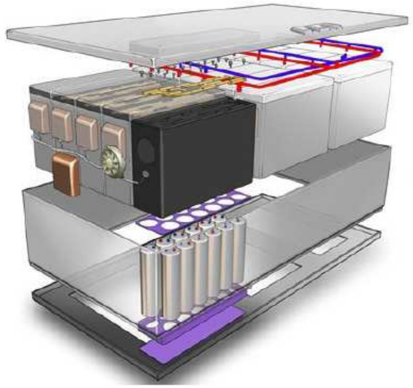
Applications of LCA
Examples of Ecodesign in European projects

Opera4fev

Ecodesign of operating energy rack for full electric vehicle

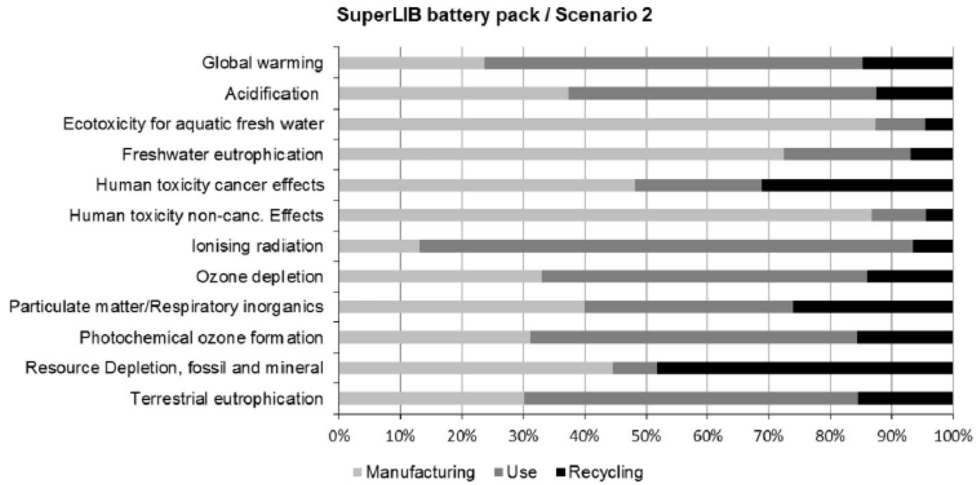
- KEPI of the design options
- LCA benchmark
- Quantifying environmental impact reduction



Sanfelix J., Messagie M., Coosemans T., Van Mierlo J. (2012)
Ecodesign of Operating Energy Rack for Full Electric Vehicles

SuperLib

Smart Battery Control System based on a Charge-equalization Circuit for an advanced Dual-Cell Battery for Electric Vehicles



Sanfélix, J., Messagie, M., Omar, N., Van Mierlo, J., Hennige, V. (2014)
Environmental performance of advanced hybrid energy storage systems for electric vehicle applications. Applied Energy

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Applications of LCA: Ecolabelling

- **Diversity of ecolabels**
  - More than 437 ecolabels in 25 industrial sectors in 197 nations (Ecolabel Index website)

- **Ecolabelling process**
  - Certification scheme → labeling process
  - Voluntary process

- **Communication tools**
  - Created for the consumers

Sergeant N., Messagie M., Boureima F., Timmermans J., Turcksin L., Macharis C., Van Mierlo J., (2012) Validation of the Well-to-Wheel approach in the Ecoscore methodology with Life Cycle Assessment for passenger cars, Urban Transport and the Environment in the 21st Century, Issue: XVIII, pp: 27 - 38, eds: J. W. S. Longhurst & C. A. Brebbia, published by: WIT press, published at: Ashurst Southampton SO40 7AA, UK, ISBN-ISSN: 1743-3509

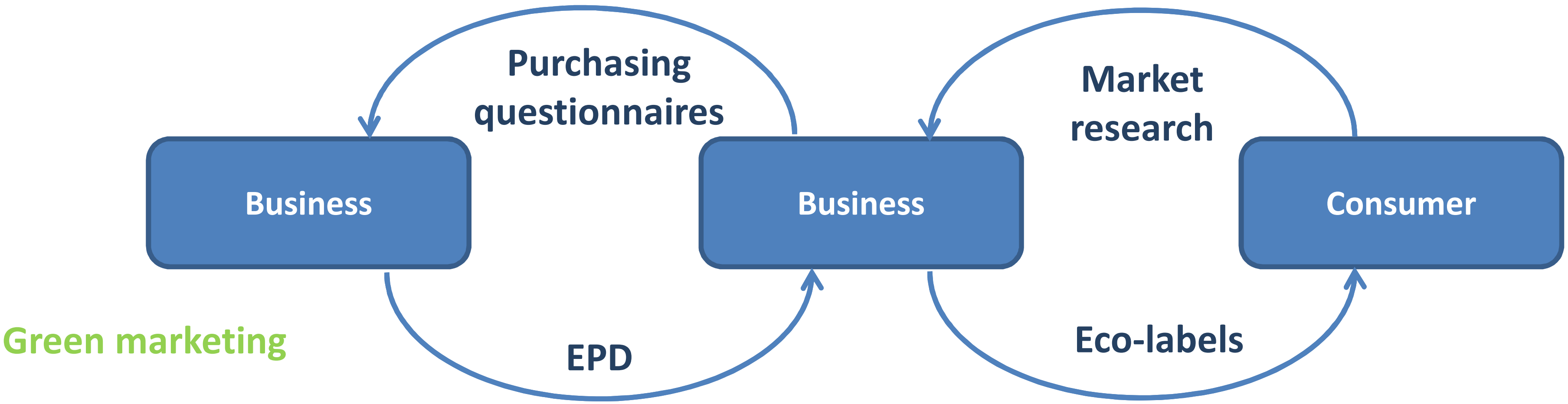
Applications of LCA: Ecolabelling

- **Type I**
  - Multi-attributes, based on a set of criteria, and verified by a third party
- **Type II**
  - Self-declared environmental claims by manufacturers or retailers without independent verification
- **Type III (EPD)**
  - Communicates product life cycle assessment (LCA) results, based on ISO 14040 series, verified by a third party

Ecolabelling - EPD

Definition

- Environmental product declaration (EPD)
- Standardised and LCA-based tool to communicate the environmental performance of a product
- Based on product category rules (PCRs)
- Provide category specific guidance for estimating and reporting product life cycle environmental impacts
- Mainly used for business-to-business communication



Applications of LCA
EPD

Standardised life cycle phases

Example for an EPD of a building product

Impact category	Unit (per m^3 MDF)	Total	A 1	A2	A3
Global warming	kg CO_2 equiv.	463.59	445.66	14.71	3.23
Ozone depletion	kg CFC 11 equiv.	5.36E-05	5,10E-05	2,32E-06	2,72E-07
Acidification	kg SO_2 equiv.	1,87	1,67	0,06	0,151
Eutrophication	kg $(PO4)^{3-}$ equiv.	0,62	0,56	0,015	0,040
Ozone creation	kg Ethene equiv.	0,22	0,14	0,002	0,081
Abiotic resource depletion	kg Sb equiv.	4,48	4,34	0,105	0,037

Standardised impact categories and methods

TOPIC 1: Introduction in LCA

- Introduction in LCA methodology
- Applications of LCA
- Sustainability LCA

Sustainability LCA: combining three dimensions

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Sustainability LCA: combining three dimensions

LCSA = e-LCA + s-LCA + LCC

- Different stage of development of the three methodologies
- Analyses can not be performed in parallel but together
- Comprehensive interpretation and conclusions

LCSA is a key assessment tool for more sustainable practices

Introduction to social-LCA

- A social impact (and potential impact) assessment technique
- Objective: to assess the social and socio-economic aspects of products and their potential **positive** and **negative** impacts
- Life cycle perspective: extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal [1]

Other references for s-LCA

- UNEP-SETAC - Life Cycle Initiative
  - *Guidelines for social life cycle assessment of products* (2009)
  - *Methodological sheets* (2010)
  - Currently the main reference documents for s-LCA of products

“Guidelines for social life cycle assessment of products”

IMPACT CATEGORIES	STAKEHOLDER CATEGORIES	SUBCATEGORIES OF IMPACT (Ex. “local community”)
Human rights	Workers	Delocalization and Migration
Working conditions	Consumers	Community Engagement
Health and safety	Local community	Cultural Heritage
Cultural heritage	Society	Respect of Indigenous Rights
Governance	Value chain actors	Local Employment
Socio-economic repercussions		Access to Immaterial Resources
		Access to Material Resources
		Safe and Healthy Living Conditions
		Secure Living Conditions
		Public Commitment to sust. issues
		Contribution to Economic develop.

“Methodological sheets”

Subcategory	Inventory indicators (generic/specific analysis)
Cultural Heritage	Cultural Heritage in Urgent Need of Safeguarding Prevalence of Racial Discrimination
Local Employment	Percentage of workforce hired locally Strength of policies on local hiring preferences Percentage of spending on locally-based suppliers

Main differences with e-LCA

- Use of impact subcategories classified by stakeholder and impact categories
- The increased importance of geographical location information for inventory and impact assessment in s-LCA
- The integration of management practices assessment in s-LCA
- The use of qualitative and semi-quantitative indicators and methods besides quantitative indicators
- The inclusion of subjective data, which can be the most relevant data to use
- The inclusion of positive impacts

Stages of s-LCA

- Goal and scope in s-LCA
  - Data type to be collected (generic, specific)
- Inventory analysis s-LCA
  - No standardized inventory indicators for s-LCA
  - Social inventory indicators must be specifically defined depending on the scope of the study
- Impact assessment in s-LCA
  - Impact categories and subcategories classified by stakeholders
  - Scoring inventory indicators after comparing to "performance reference points" (the exact effect of certain measures is not known)
- Interpretation
  - Reading results in combination (e-LCA, LCC) rather than summing them up

Applications of s-LCA

- Many publications about methodological issues
  - Definition of categories and subcategories of impact

- Very few case studies
  - Typical comparison: **developing - developed** country

Int J Life Cycle Assess (2011) 16:366–379
DOI 10.1007/s11367-011-0266-x

SOCIETAL LIFE CYCLE ASSESSMENT

A comparison of cut roses from Ecuador and the Netherlands

Juliane Franze · Andreas Ciroth

Received: 8 October 2009 / Accepted: 8 February 2011 / Published online: 1 March 2011

Abstract
Purpose There is a need to assess social impacts of products along the full life cycle, not only to be able to address the "social dimension" in sustainability, but also for potentially improving the circumstances of affected stakeholders. This paper presents a case study for a social life cycle assessment (S-LCA) based on the recently published "Guidelines for Social Life Cycle Assessment of Products" developed by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) working group. General aim is to "try out" the proposed method. The case study itself compares the impacts of rose production in Ecuador with the Netherlands. Furthermore, the objective is to identify differences and similarities in environmental and social life cycle modelling and both social and environmental hot spots in each of the life cycles.
Methods The study considers the production of rose blossoms and the cutting and packaging process in two fictitious companies in Ecuador and the Netherlands. Both rose bouquets are delivered to the European market and auctioned in Aalsmeer, the Netherlands. The social assessment is based on the UNEP/SETAC guidelines for S-LCA. Data are mainly obtained from governmental and non-governmental organisations. For the calculation of the environmental burden, a screening-type LCA is conducted, including midpoint impact assessment.
Results and discussion This paper asserts that rose production in Ecuador is associated with many negative social effects, e.g. child labour, unfair salary, or bad impairment to health. The rose production in the Netherlands has no obvious negative social impacts but rather ecological consequences. Responsible for this is the high-energy consumption of the greenhouses.
Conclusions Application of the UNEP/SETAC guidelines in case studies can be encouraged based on results of this case study. The consideration of different stakeholder groups with corresponding, very diverse themes allows a comprehensive analysis of the actual conditions. However, finding suitable indicators to measure the status of the subcategories may be challenging. Moreover, the case study shows that results can be completely different for the environmental and for the social dimension, so that it often will be needed to perform both assessments if a complete picture is required.
Recommendations and perspectives It will be interesting to apply the UNEP/SETAC approach of S-LCA to other products; products with a more complex life cycle will be a special challenge. As with any new method, getting experience on data collection and evaluation, building a data stock, integrating the method in software, and finding ways for effective communication of results are important steps until integrating S-LCA in routine, recognized decision support.

Keywords Ecuador · E-LCA · Rose production · S-LCA · Social impacts · The Netherlands

1 Introduction

The analysis of ecological impacts of products and processes increased in popularity in the last decades due to an arising awareness both in society and economy caused by global problems like climate change, extinction of species or ozone depletion. However, the consideration of a social dimension in life cycle assessment (LCA) is still in its infancy, despite social ills, which are often related to globalization, and which are not necessarily related to environmental impacts. Thus, there is a need to assess social impacts of products along the full life cycle, not only for being able to address the "social dimension" in sustainability, but also for potentially improving the circumstances for affected stakeholders.

Responsible editor: Thomas Swarr

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Applications of s-LCA: a case study

- Background information:
  - Roses: specific conditions: T, water consumption, fragility
  - Ecuador: perfect climate conditions
  - The Netherlands: fully automated greenhouses
- Scope: **environmental** and **social assessment**; only production and harvesting considered (disposal dismissed because of the lack of data)
- Functional unit: bouquet with 20 caulis
- Inventory analysis (CIA, ILO, Agri-info reports, Eurostat statistics, etc.)

Producing roses in Ecuador	**Producing roses in The Netherlands**
No labour contracts at the company	The right to form and join unions
Unequal opportunities for women	Policy for equal opportunities
Child labour is common	No cases of child labour in the company.
Payment <legal minimum wage	Payment amounts ≥ minimum wage
72 h/week-adults	38 h/week

Applications of s-LCA: a case study

- Impact assessment:

stakeholder group	subcategory	Ecuador: status	Ecuador: assessment	The Netherlands: status	The Netherlands: assessment
workers	freedom of association	is not existent; labour contracts are missing		is existent	
	discrimination	is existent		is not existent	
	child labour	is existent		is not existent	
	fair salary	is not existent: wages are far below national minimum wage		is existent: minimum wage is paid	
	working hours	72-84h/week		38h/week	
	forced labour	is not existent		is not existent	
	health and safety	is at risks		is at low risk	
	social benefits	are not provided		are provided	
supply chain actors	fair competition	is existent		is existent	
	promoting social responsibility	is not existent		is existent	
local community	indigenous rights	are harmed		not applicable	
	safe and healthy living conditions	are degraded		are harmed by pollution	
	local employment	is promoted		is not promoted	
society	contribution to economic development	is existent, but unfair allocation: contrasting impacts		is existent	
	corruption	is existent in company and is in addition promoted indirectly by unfair conditions		is not existent	
	technology development	is not promoted		is promoted	
	prevention of armed conflicts	is not promoted, but the company is not involved actively in armed conflicts		is existent	

Introduction to Life Cycle Cost

Estimate of all direct and indirect costs associated with an asset or acquisition over its entire life cycle

Messagie, M., Lebeau, K., Coosemans, T., Macharis, C., Van Mierlo, J. (2013) Environmental and Financial Evaluation of Passenger Vehicle Technologies in Belgium SUSTAINABILITY Volume: 5 Issue: 12 Pages: 5020-5033

Case study: electric vehicles

Methodology

Financial costs

- Purchase price
- Registration tax
- Governmental support
- Opportunity cost
- Depreciation cost

Fuel operating costs

- Fuel or electricity cost
- Taxes on fuel

Non-fuel operating costs

- Taxation
- Insurance
- Technical control
- Tyres
- Maintenance

Scope and assumptions

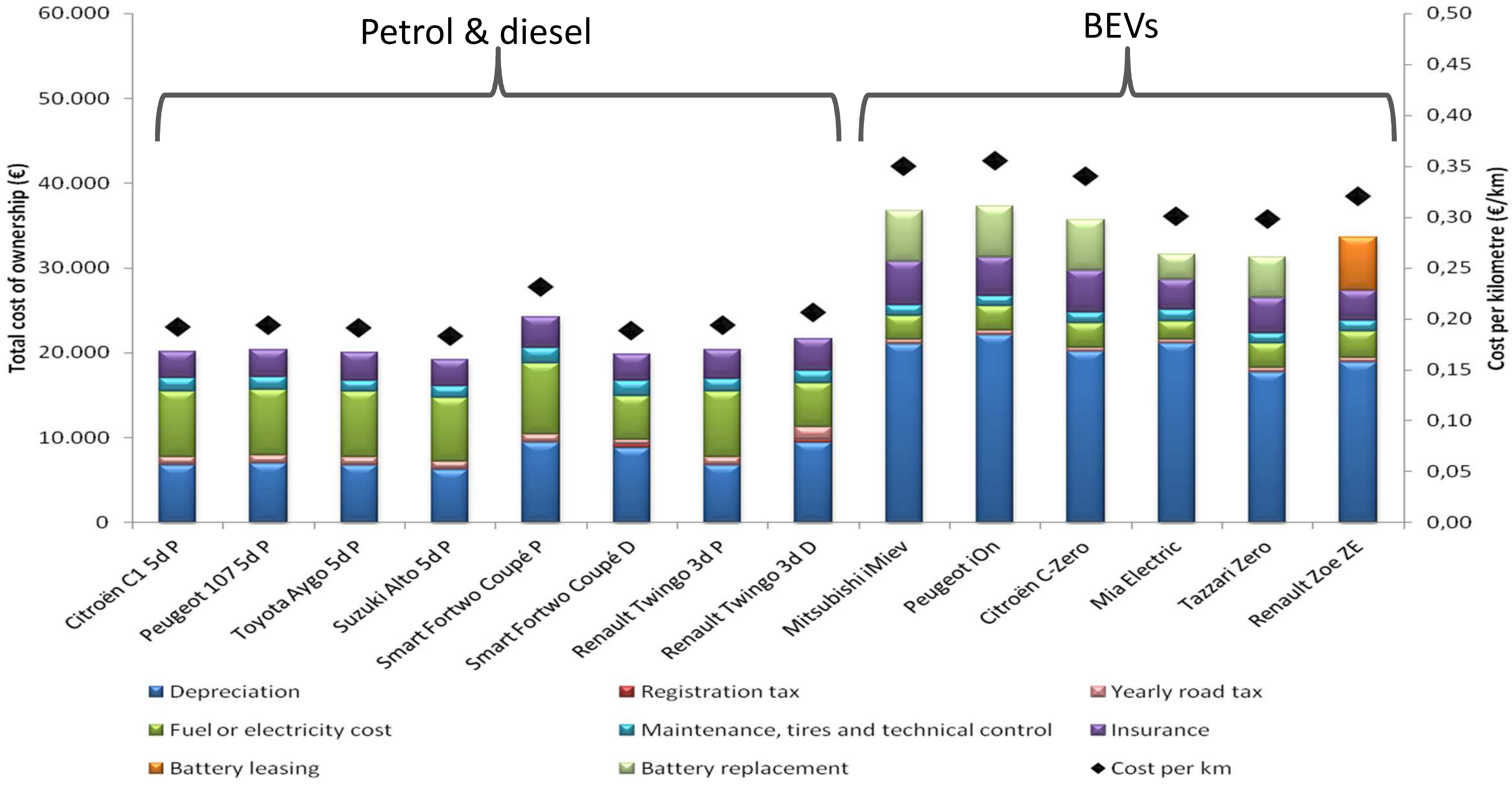
Scope

- Flanders, Belgium
- January 2013
- Three vehicle segments: small city, medium, premium

General assumptions

- 7 years
- 15,000 km/y
- 105,000 km total mileage
- Real discount rate: 1.18% (ECB, 2013)

Results for small city cars



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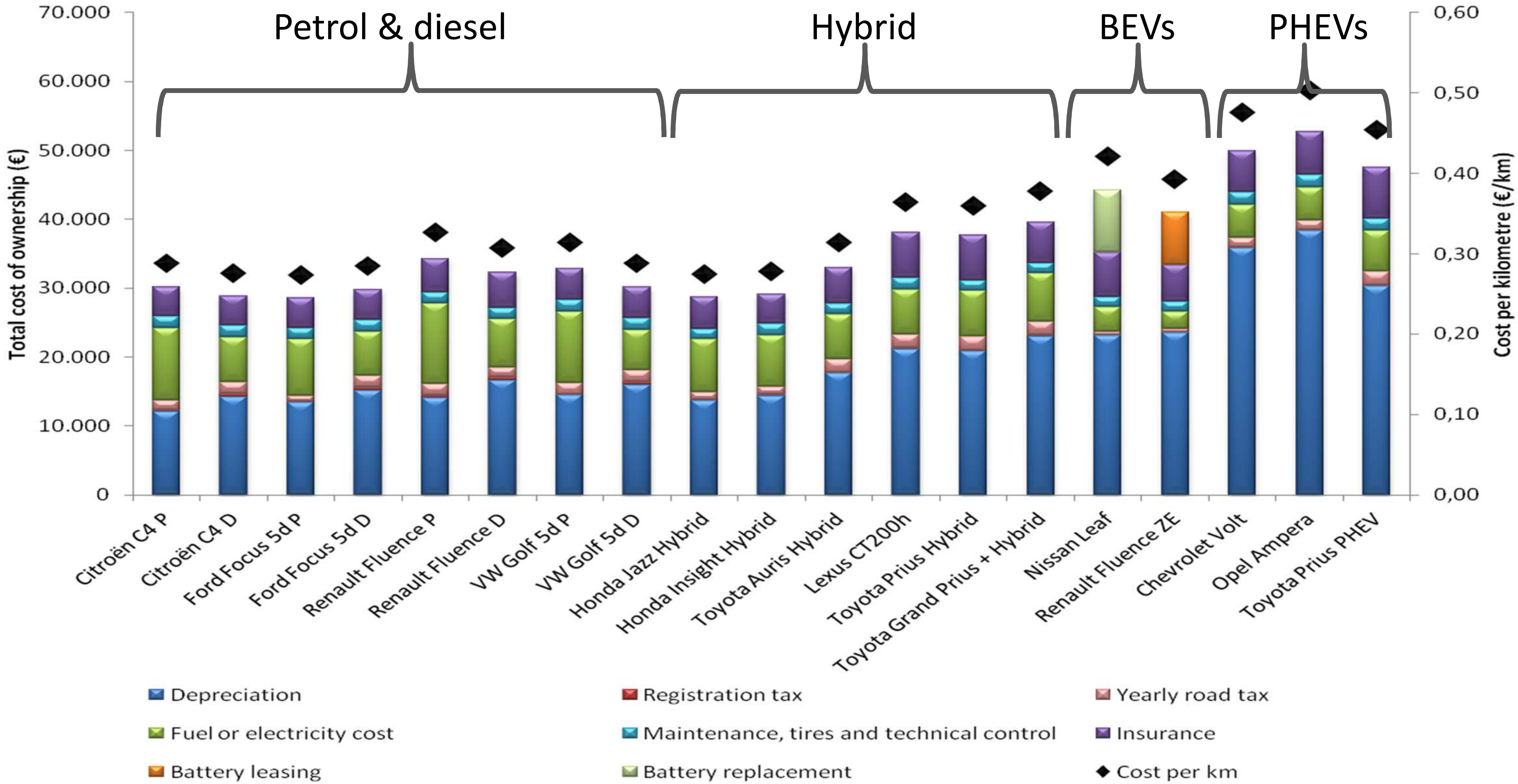
Results for medium cars



Messagie, M., Lebeau, K., Coosemans, T., Macharis, C., Van Mierlo, J. (2013) Environmental and Financial Evaluation of Passenger Vehicle Technologies in Belgium SUSTAINABILITY Volume: 5 Issue: 12 Pages: 5020-5033

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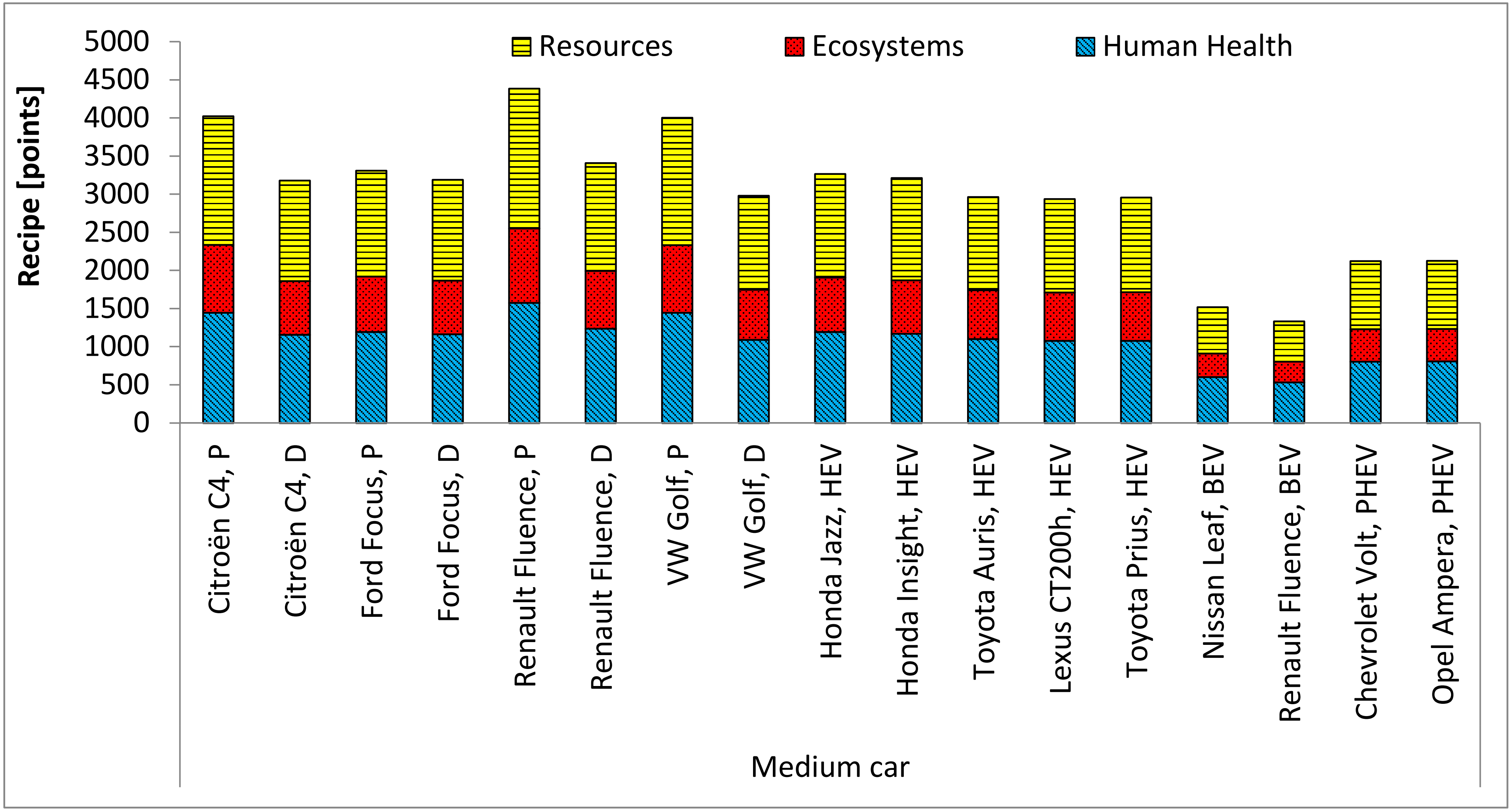
Environmental impacts – medium cars



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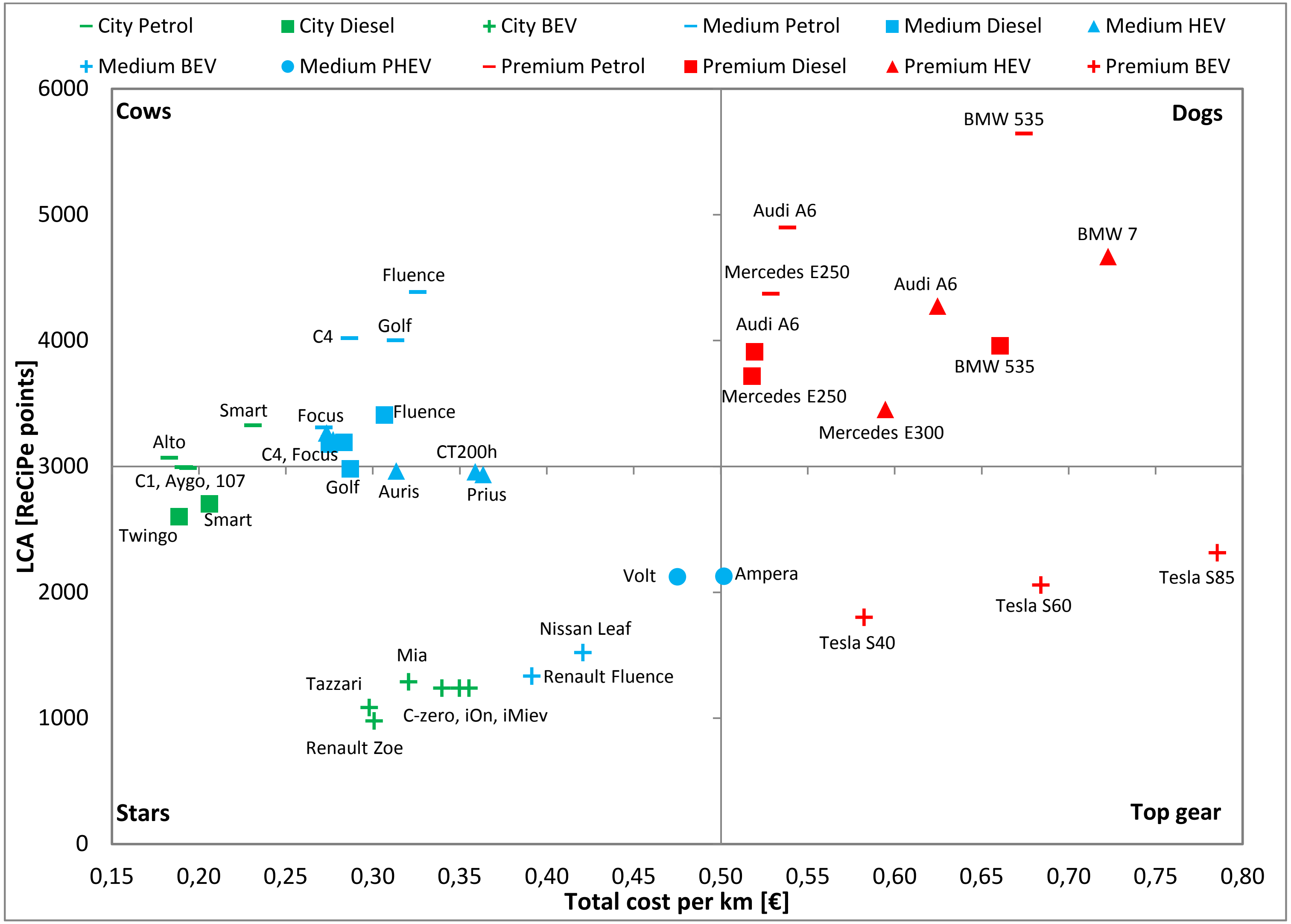
Eco-efficiency matrix:

Environmental and financial evaluation of vehicles



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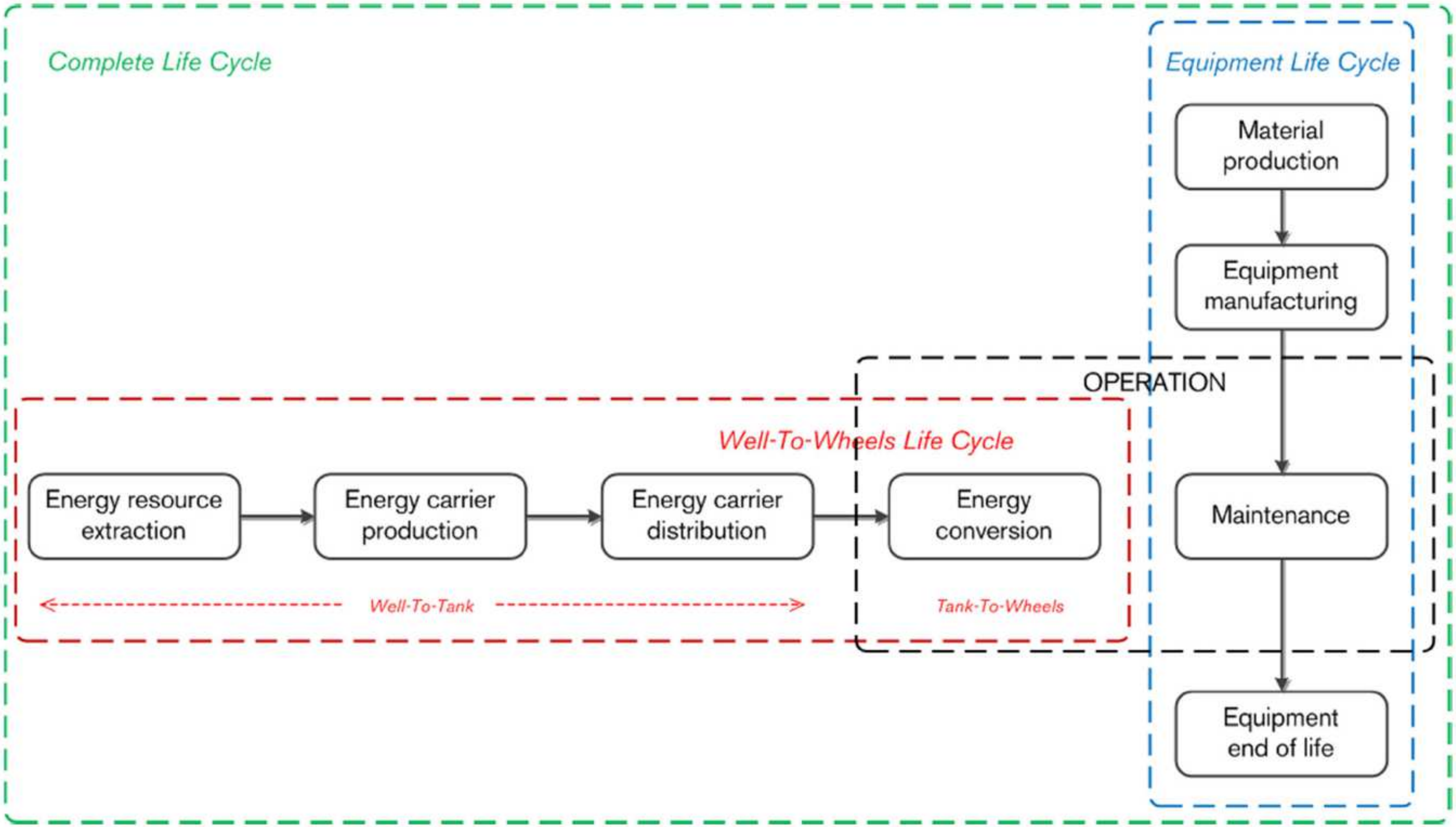
Case conclusions

- General results of TCO model
  - Small city: BEVs are very cost inefficient
  - Medium: BEVs with leasing are cost competitive with HEVs
  - Premium: BEVs are cost competitive (depending on battery capacity)
- Sensitivity analyses
  - Discount rate: small effect when high initial sales prices
  - Maintenance costs for BEVs: no/low impact
  - Annual mileage: BEVs are more sensitive
  - Ownership duration: BEVs are more sensitive
- Scenarios
  - Increased fuel prices
  - Decreased battery prices
  - Governmental subsidies

TOPIC 2: Overview current LCA Studies on electric vehicle concepts

- LCA structure: WTW and LCA;
- How to read studies and how to interpret?
- Overview of LCA results.

LCA structure
Life cycle stages: WTW and full LCA



Nordelöf, A., Messagie, M., Tillman, A., Söderman, M., Van Mierlo, J. (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess DOI 10.1007/s11367-014-0788-0

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LCA structure
Lessons learned from literature

- Well-to-Wheels (WTW)
  - Influence of driving modes
  - Influence of supplied energy
  - Degree of electricificationation
  - Especially used for analysis of climate change effects

- LCA
  - Other impact categories;
  - Material and component production
  - Comparison of vehicle size

Nordelöf, A., Messagie, M., Tillman, A., Söderman, M., Van Mierlo, J. (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess DOI 10.1007/s11367-014-0788-0

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TOPIC 2: Overview current LCA Studies on electric vehicle concepts

- LCA structure: WTW and LCA;
- How to read studies and how to interpret?
- Overview of LCA results.

Transparency and objectivity: to be made explicit during the reporting

Be aware of

- Goal and scope of the study
- Comparativeness of alternatives
- Functional unit

- Methodology, assumptions and data consistency
- Data quality of compared systems
- Identical parts of a system can be left out
- Scenarios shall be used (e.g. best and worst case)

Comparisons in LCA

Types

- System or process with same FU (e.g. different vehicles)
- Variants of a system (e,g. different materials for a car)
- Contribution analysis of specific system (e.g. production phase vs. use phase).
- A multi system type with different functions (e.g environmental impact of a person in countries A, B and C); producing in country A or in country B

Goal definition

- What is the objective of the study?
- What is the intended use of the results?
- Who is the target audience?
- Who is the commissioner?
- Who are the stakeholder and what are their interest and involvement?

- What is the functional unit?

Scope definition

- What are the system boundaries?
- What is the temporal and geographical scope of the study?

- What are the data quality targets?
- Who will review the report

How to read studies and how to interpret
Lessons learned from literature review

- Goal and scope definition
- Single values are not robust
- Electricity production
- Credibility of LCA

Messagie M., Macharis C., Van Mierlo J., Key outcomes from Life Cycle Assessment of vehicles, a state of the art literature review, World Electric Vehicle Journal

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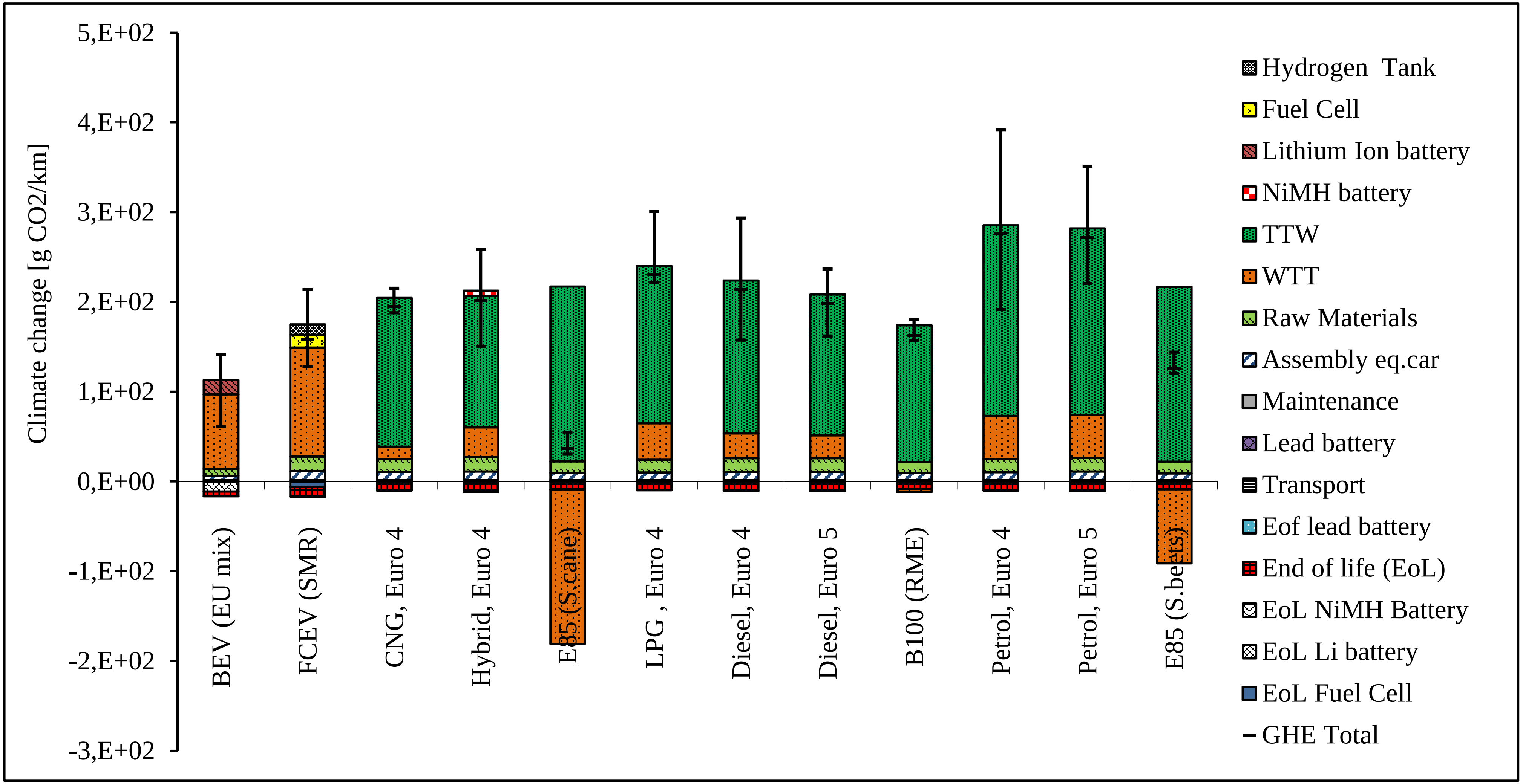
Single values are not robust



Messagie, M., Boureima, F., Coosemans, T., Macharis, C., Van Mierlo, J. (2014) A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. ENERGIES Volume: 7 Issue: 3 Pages: 1467-1482

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BREAK

Overview:

Current LCA studies on electric vehicle concepts

(Part 2: Results)

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Overview of LCA results – Current studies

- **FSEM:** Fraunhofer IBP, Dept. Life Cycle Engineering (GaBi), Stuttgart, Germany
- **UMBReLA:** Institute for Energy and Environmental Research (IFEU), Heidelberg, Germany
- **THELMA:** EMPA, Duebendorf, Switzerland

Focus of these studies:

Assessment of the environmental profile of different electric vehicle concepts and the future development of electricity supply

Overview of LCA results – Fraunhofer System Research for Electromobility (FSEM)

Goal of the FSEM is to provide an effective support for realizing a change to an „All-electric Economy“.

The FSEM (duration: 2009 - 2011) involved more than 30 Fraunhofer institutes, addressing topics along the whole value chain of E-Mobility, such as:

- Energy generation and infrastructures
- Interfaces between power grid and electric vehicles
- Energy storage
- New vehicle concepts / infrastructures
- Utilization- and metering concepts
- **Environmental assessment**
- Duration: 2009 - 2011

http://www.elektromobilitaet.fraunhofer.de/

Overview of LCA results – FSEM
Framework conditions: Scenario 2010-2020

- **Future development of the German power grid mix**
  - Increasing share of renewable energies based on BMU scenarios*
  - Dynamic adjustment of the environ. profile of the power grid mix
- **Battery System**
  - Battery lifetime from 8 years (2010) to 12 years (2020)
  - Energy density of cells: From 135 Wh/kg (2010) to 200 Wh/kg (2020) (optimistic)
- **Other**
  - Vehicle: Lifetime 12 years; mileage 14,300 km p.a. (171,600 km in total)
  - Energy consumption (EVs): Calculation model based on the ADAC EcoTest Cycle (incl. auxiliary users)
  - Combustion vehicles based on the scenarios of HBEFA 3.1
  - Fixed electric driving range (Battery improvements result in smaller layouts)
- **Used LCA software and database:**
  GaBi software with data from project partners, literature research (e.g. vehicle platform data for both electric and conventional vehicles from environmental commendations and certificates of automotive OEMs) and GaBi background data
- **Impact assessment method:** CML 2001 Method

*Power mix according to the lead scenarios of BMU Leitstudie 2009

Overview of LCA results – FSEM
Framework conditions: Regarded vehicles

2010 vehicle specifications	BEV* (mini class)	BEV* (compact class)	PHEV* Hybrid (compact class)
Battery system	Li-Ion ($LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$)		
Energy content battery [kWh]	20	40	14
PMSM motor [kW]	43	70	68
Gasoline ICE [kW]	-	-	41
Generator [kW]	-	-	41
Fuel tank [l]			40
Residual vehicle/ vehicle structure [kg]	736	1,115	1,115
Unladen weight vehicle [kg]	1,037	1,670	1,505
Energy consumption** [kWh/100 km]	18.7	22.9	20.4
Fuel consumption [l/ 100 km]	-	-	6.9

*Exemplary vehicle configurations, **Calculated based on ADAC EcoTest

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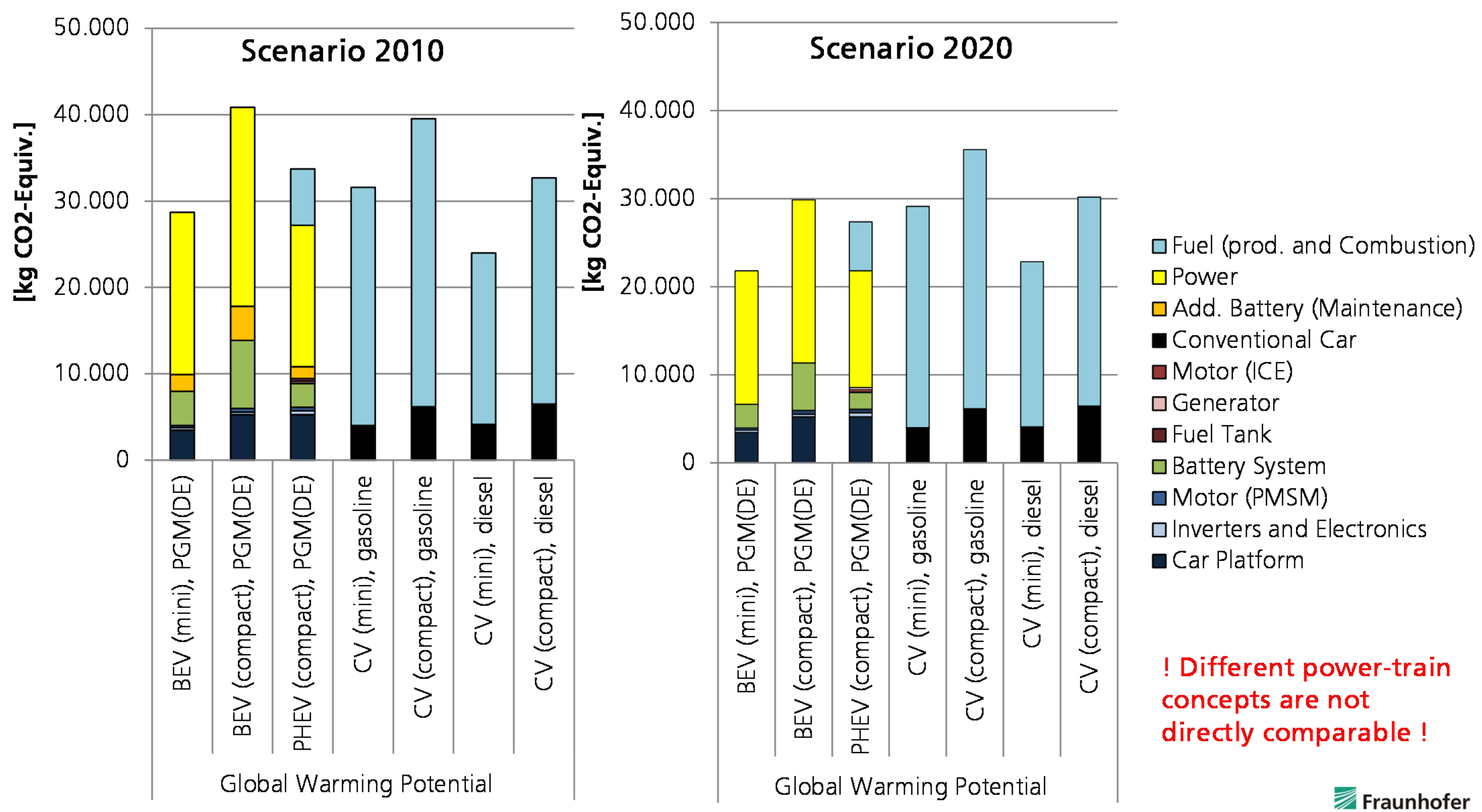
Overview of LCA results – FSEM
Framework conditions: Regarded vehicles

2010 vehicle specifications	Gasoline (mini class)	Gasoline (compact class)	Diesel (mini class)	Diesel (compact class)
Unladen weight vehicle [kg]*	850	1307	870	1369
Fuel consumption [l/100 km]**	5.9	7.1	3.8	5.1

* Average unladen vehicle weights of real mini class and compact class vehicles
** based on consumption values from HBEFA 3.1 (Euro 5 pollutant emissions are also from HBEFA 3.1)

Overview of LCA results – FSEM
Results: Global Warming Potential (2010-2020)
German Power mix



! Different power-train concepts are not directly comparable !

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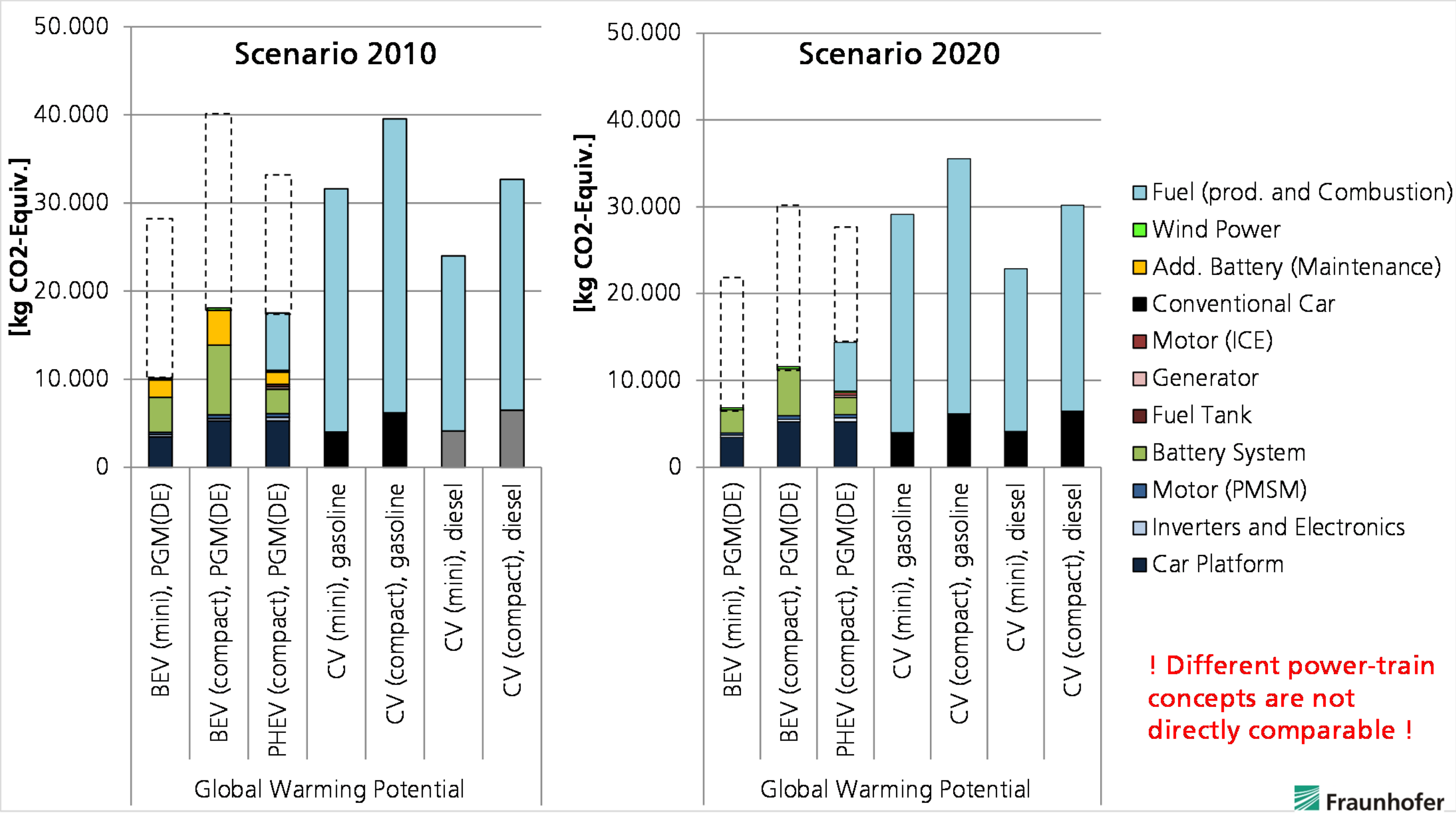
Overview of LCA results – FSEM
Results: Global Warming Potential (2010-2020)
Wind power



! Different power-train concepts are not directly comparable !

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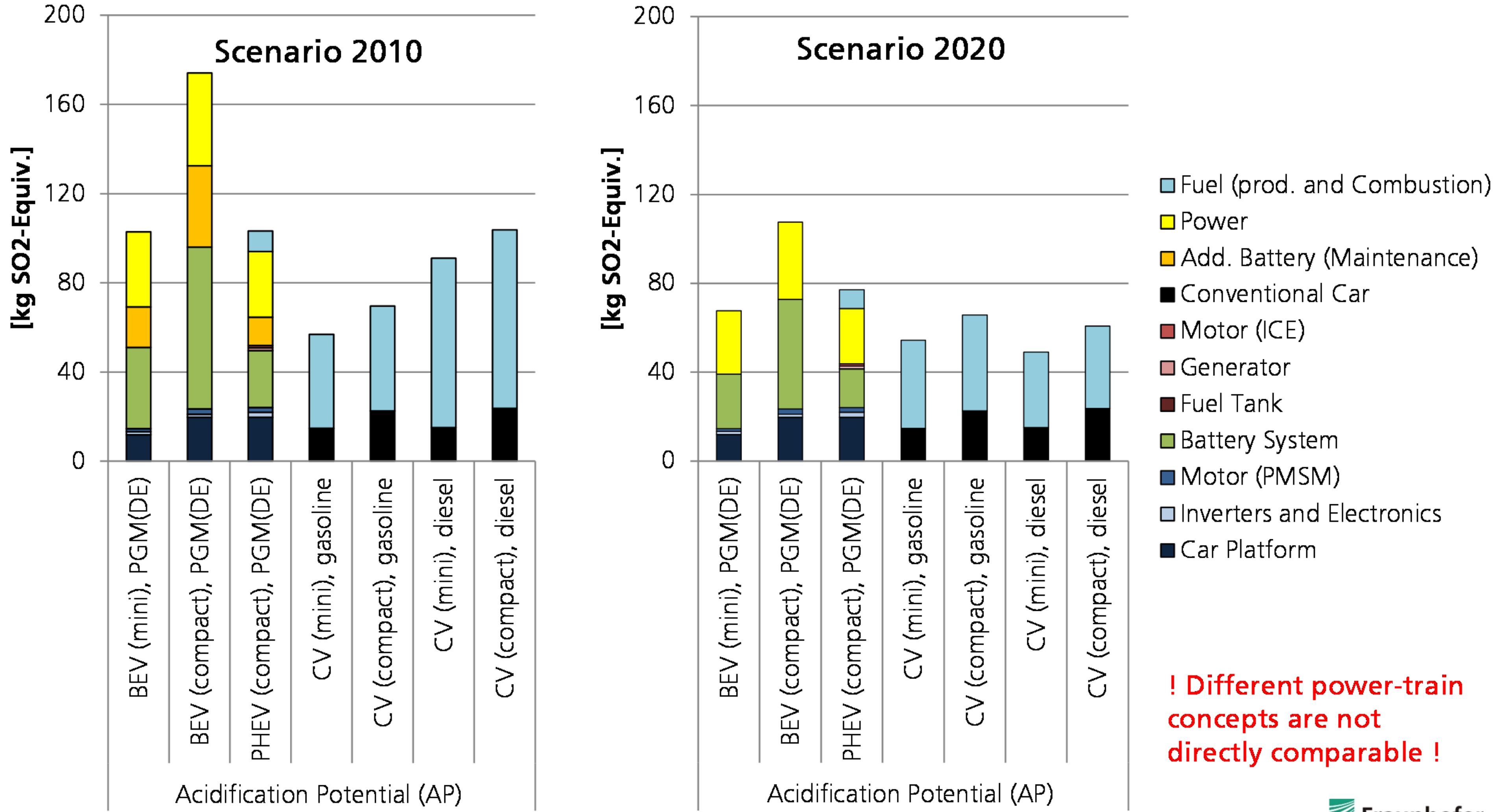
Overview of LCA results – FSEM
Results: Acidification Potential (2010-2020)
German Power mix



! Different power-train concepts are not directly comparable !

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Overview of LCA results – UMBReLa

The goal of UMBReLa concerning LCA is very similar to FSEM.

The project was conducted by Institute for Energy and Environmental Research (IFEU) in 2011. Addressed topics were:

- LCA of electric vehicle concepts
- Detailed scenarios of future developments of the electricity supply and possible electricity supply concepts
- Optimization potentials of the environmental profile from lightweight technologies
- Optimization potentials of the environmental profile by future changes of energy mix for vehicle production

http://www.emobil-umwelt.de

Overview of LCA results – UMBReLa

- **Future scenarios**
  - Three scenarios for 2030: conservative, moderate, innovative with differences in vehicle structure and energy density and lifetime of the battery
- **Battery System**
  - Battery lifetime of 8 years
  - Energy density of cells: From 100 Wh/kg (2010) to 200 Wh/kg (2030) (innovative scenario)
- **Other**
  - Vehicle: Lifetime 12 years, mileage depends on vehicle concept (e.g. city, standard, delivery vehicle): 120,000 km - 200,000 km
  - Energy consumption (EVs): LCA model eLCAr (Electric Car LCA), quality checked with real electric mobility fleet tests
  - Combustion vehicles based on TREMOD and HBEFA 3.1
- **Used LCA software and database:**
  UMBERTO software with data from LCA model eLCAr (Electric Car LCA) and Ecoinvent 2.2 background data
- **Impact assessment method:** Climate change according to IPCC 2007 method, the methods for other impact categories are not mentioned

Overview of LCA results – UMBReLa
Considered vehicle concepts and use profiles

	Size	Battery (kWh)*	Life cycle mileage (km)
City vehicle	small	18	120.000
Standard vehicle	small/middle/big	18/24/28	150.000
Delivery vehicle	big	28	200.000
Standard RE vehicle	middle	12	150.000
Intensive RE vehicle		14	200.000
			IFEU 2011

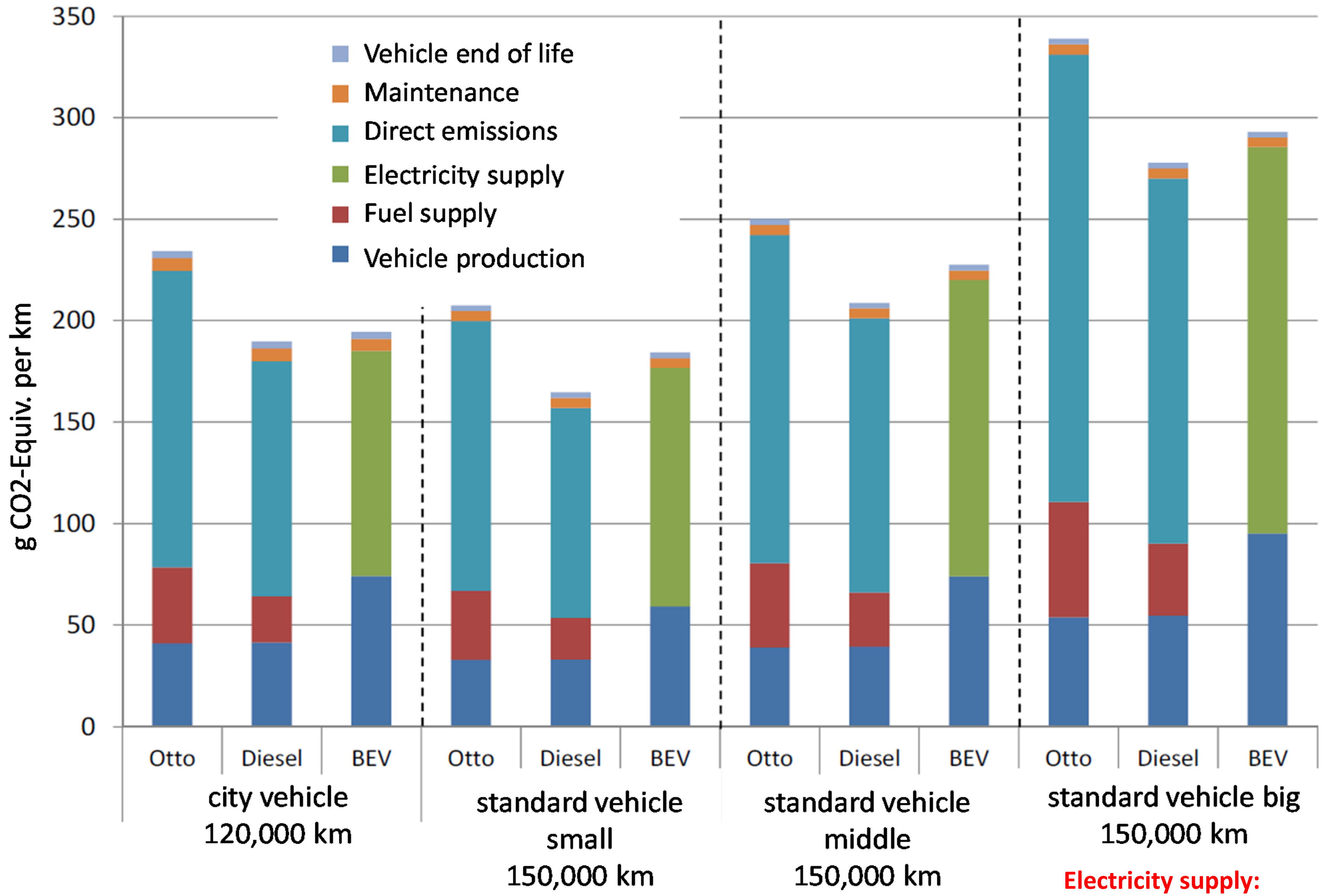
* 2010 are 1.5 batteries over the life cycle of the vehicle assumed

Overview of LCA results – UMBReLa
Scenario assumptions

2030 scenarios	Vehicle	Battery	Use
Conservative	German Electricity mix 2030 for manufacturing	energy density 100 Wh/kg	In each case slight improvement in the vehicle parameters and therefore of the energy consumption
Moderate	Additional Aluminium lightweight	energy density 150 Wh/kg*	
Innovative	Additional Downsizing	energy density 200 Wh/kg*	
			IFEU 2011

* Additionally enhanced battery lifetime: one battery over the full life of the vehicle

Overview of LCA results – UMBReLa
Global warming potential for different use profiles (2010)



Electricity supply:
German Power mix 2010

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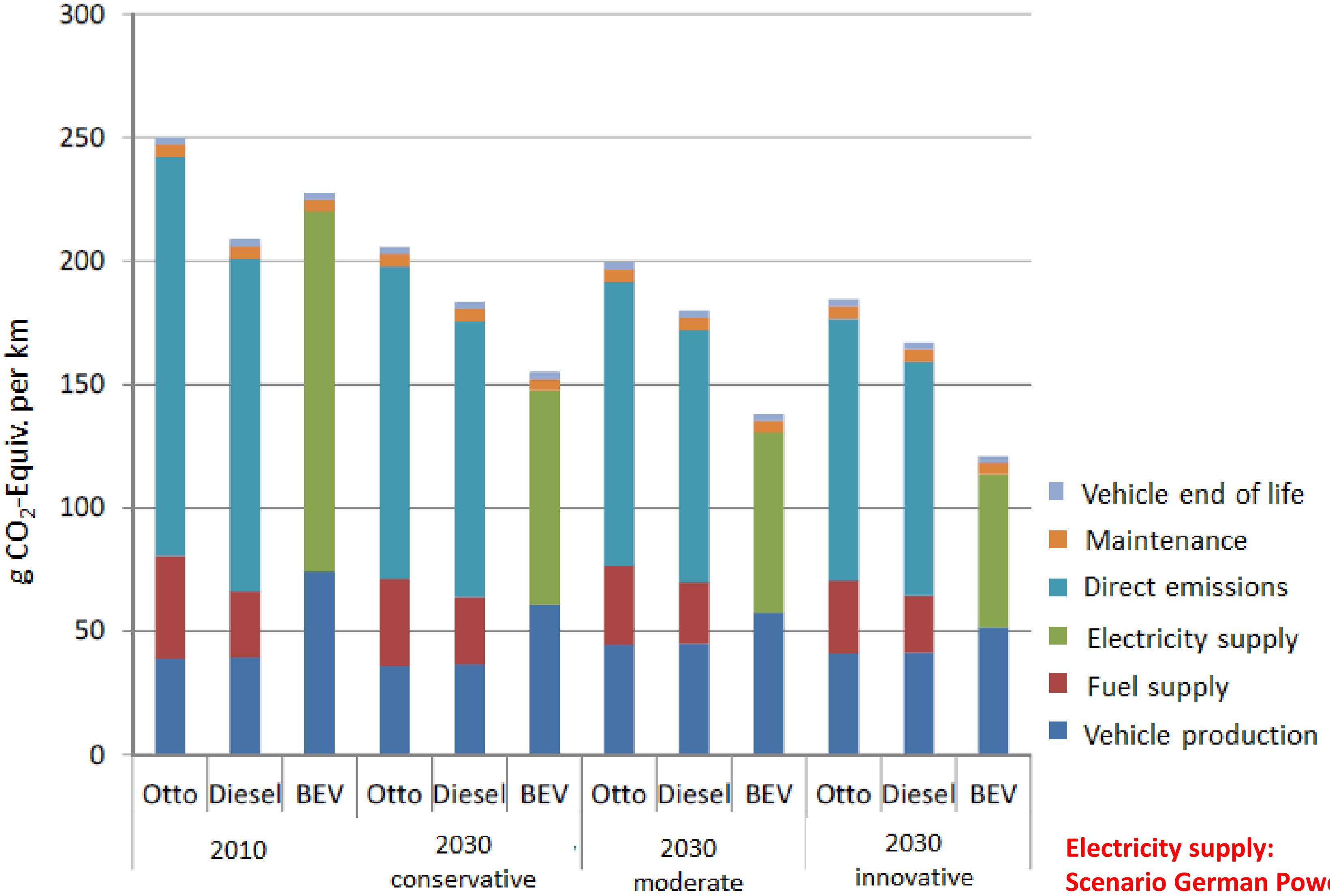
Overview of LCA results – UMBReLa
Global warming potential of middle class vehicles with different powertrains (Scenarios 2030)



Electricity supply:
Scenario German Power mix 2030

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Overview of LCA results – THELMA

- In the project THELMA two LCA studies concerning electric mobility were conducted by the Swiss Federal Laboratories for Materials Science and Technology (EMPA) and Paul Scherrer Institute (PSI) in 2010.
- The tutorial focuses on the LCA study of EMPA

http://www.thelma-emobility.net

Overview of LCA results – THELMA EMPA study

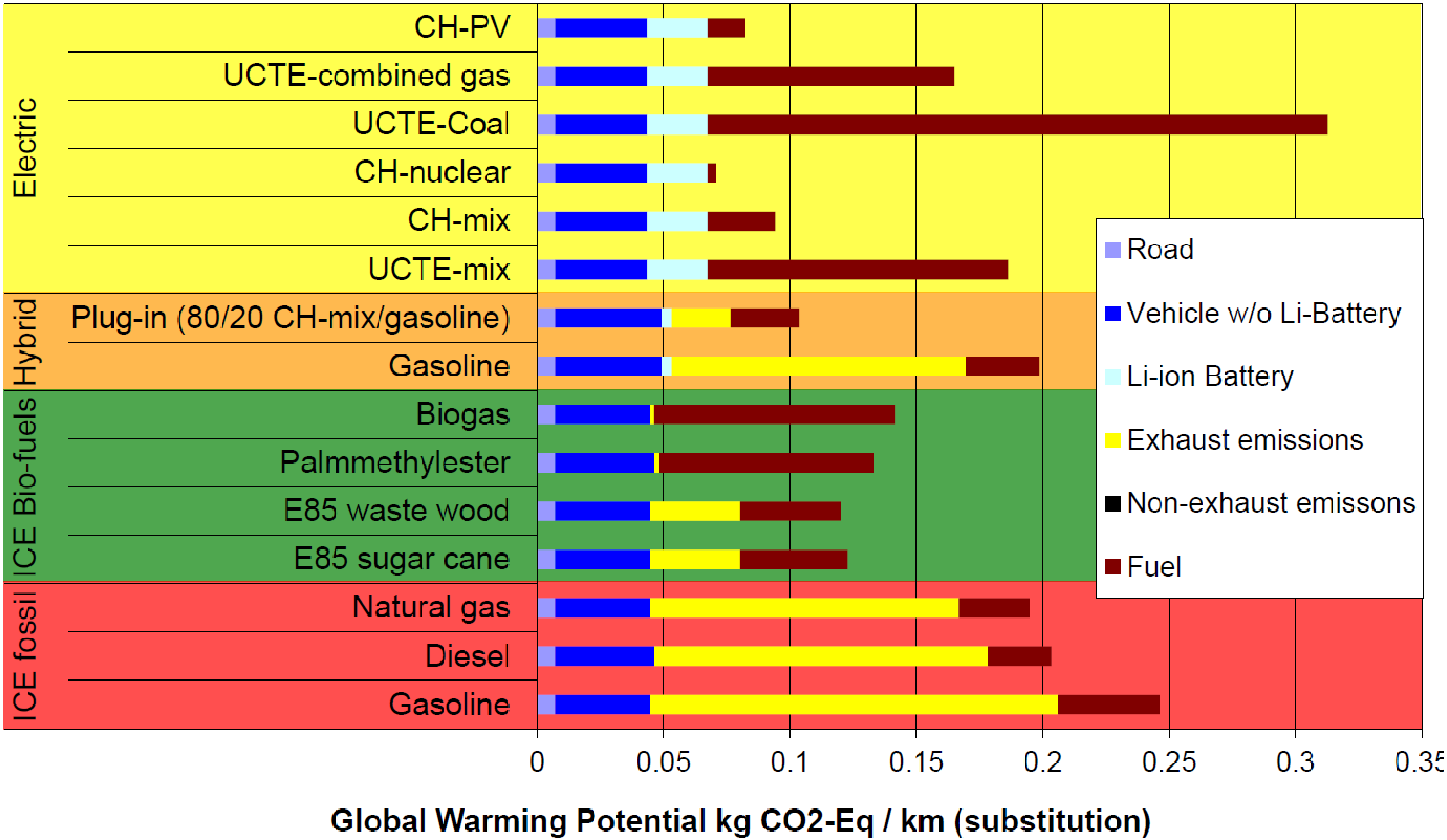
The goals of the EMPA study were:

- Compare driving in hypothetical near future BEVs with driving in modern (or near future) fossil or biofuel fuelled cars
- Representative cars for Golf class
- Provide background information to discuss the potential of electric mobility to improve environmental aspects of mobility
- Comparative LCA to be presented in public, including critical review

Overview of LCA results – THELMA EMPA study

- **Future scenarios**
  - Six electricity grid scenarios: mix CH, mix UCTE, nuclear power CH, combined gas power UCTE, coal UCTE, Photovoltaics CH
- **Battery System**
  - Energy density: 114 Wh/kg
  - Batteries are replaced in every second electric vehicle
- **Other**
  - Vehicle: Lifetime 12.7 years, mileage 150,000 km
  - Energy consumption (EVs): NEDC + real world addition (NEFZ +15%)
  - Combustion vehicles based on NEDC + real world addition (NEFZ +13%)
- **Used LCA software and database:**
  LCA data of vehicle platform Golf IV, electric drivetrain from BRUSA Elektronik AG, battery data from existing KOKAM battery, Ecoinvent v2.01 background data
- **Impact assessment method:** Three different categories of Ecoindicator 99 H including Climate change according to IPCC 2007 method

Overview of LCA results – THELMA EMPA study



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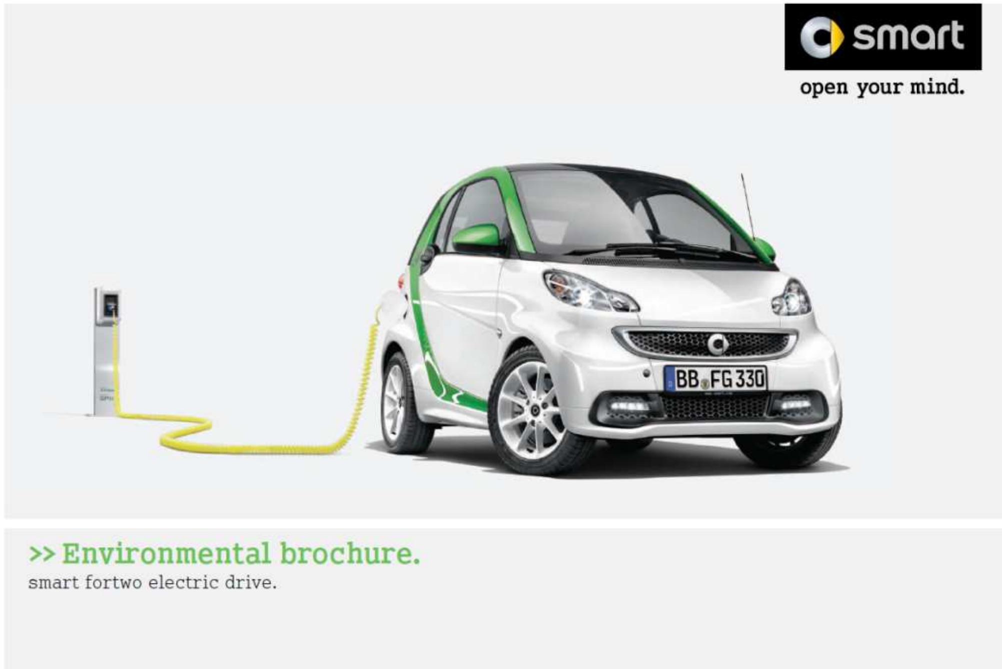
Overview of LCA results
Environmental commendations / certificates of OEMs

- Automobile manufacturers use the method of LCA as an instrument for quality assurance and the compliance with environmental targets
- Volkswagen und Mercedes-Benz regularly publish results in the form of environmental commendations (VW) or environmental certificates (Mercedes)
- Volkswagen and Mercedes-Benz both use GaBi software and background data from GaBi databases
- Environmental commendations / certificates of electric vehicles are already available and show comparisons with the conventional vehicle models

Overview of LCA results
Environmental commendations / certificates of OEMs



http://en.volkswagen.com/en/company/responsibility/environmental_commendations.html

http://www.daimler.com/dccom/0-5-1312394-1-1312442-1-0-0-0-0-0-8-0-0-0-0-0-0-0-0.html

Overview of LCA results
Conclusions

- Battery systems of electric vehicles strongly contribute to the environmental impacts of the production phase
- BEVs show a comparable magnitude of greenhouse gas emissions like current gasoline vehicles when the German electricity grid mix is used for charging
- By the use of additional renewable energies, e.g. wind power, the environmental impacts of electric vehicles can be reduced significantly and electric vehicles can contribute to a improvement of the environmental profile of individual transport
- High mileages during the use phase of electric vehicles are necessary because of significant higher impacts during production phase

Overview of LCA results
Relevant Indicators

- Power generation mix (share of renew. energies)
- Battery system: Technology, dimensioning and lifetime
- Production of required High-Tech materials (cobalt, graphite, rare earths, etc.)
- Vehicle and user specific driving profiles
- Total mileage

➢ Power train concepts are not directly comparable, as utilization profiles of vehicles might change

Key Issues:

LCA of electric vehicles

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Key issues: LCA of electric vehicles
Overview

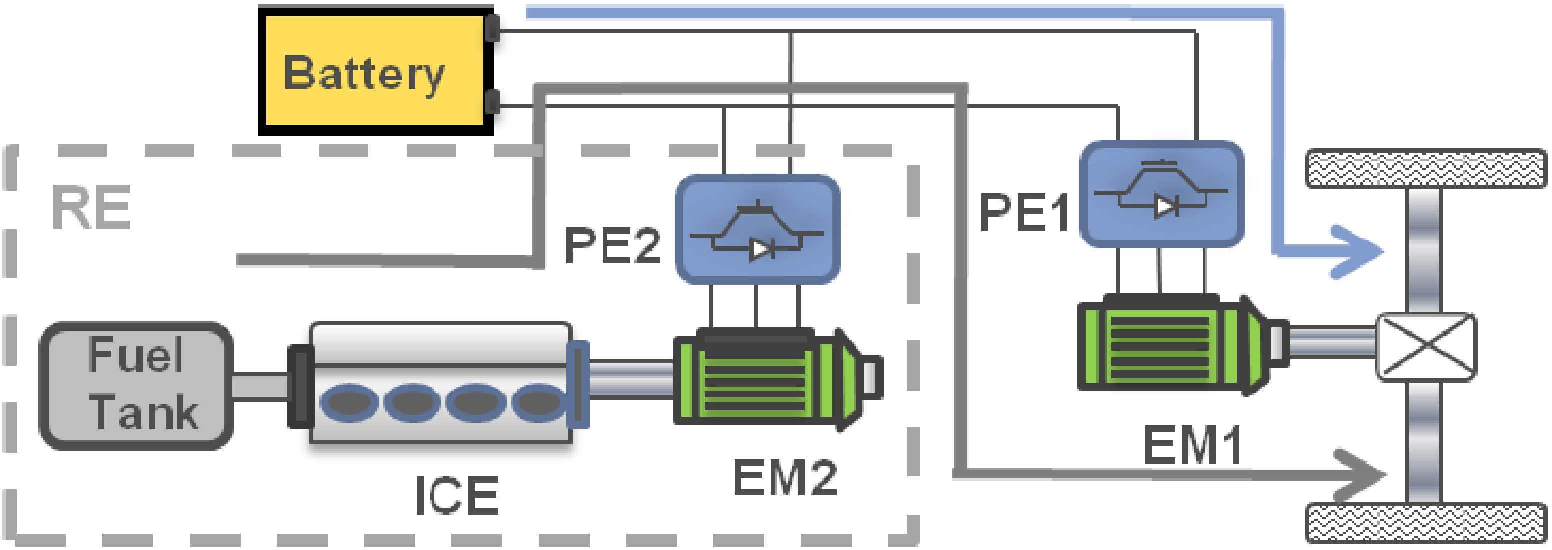
- **Production**
  - Key issues Power train concepts
  - LCA of Key Components
  - LCA of Battery Systems

  } using the example of EVREST project
- **Use phase**
  - Relevant parameters and requirements
  - Use patterns

  } using the example of EVREST project
  - Electricity grid mix: general requirements (Additional: Discussion of smart grid?)
- **End of life**
  - Approaches: avoidance, cut off, …
  - Issue battery recycling: Overview on current research (LiBRi, LithoRec, Argonne, SUBAT)
- **Range based vehicle LCA:** the need for uncertainty propagation when assessing the environmental performance of vehicles

EVREST project information

- EREV drivetrain architecture is based on a BEV topology with an additional energy source, the RE, which can supply electricity to the vehicle onboard network



EREV architecture, source: R. Derollepot (IFSTTAR-LTE) et al.: Optimizing components size of an Extended Range Electric Vehicle according to the use specifications

EVREST project information

www.evrest-project.org

EVREST – Electric Vehicle with Range Extender as a Sustainable Technology (project duration: 2012-2015)

- Main idea: How extended range electric vehicles (EREVs) could match the different usage patterns and what would be the acceptance and impacts of such a solution?
- Analyses of users' profiles and expectations based on databases from different European countries
- Optimized design from a technical, economic and **environmental** perspective
- Comparison of EREVs with BEVs and conventional vehicles with internal combustion engines (gasoline and diesel) on the basis of Life Cycle Assessment (LCA)

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Analyzed vehicles in EVREST

- Small vehicles (User profile: European cluster 2, yearly mileage 4877 km)

Vehicle	BEV	Small EREV
Motor power [kW]	47	47
Battery capacity [kWh]	16	9
RE power [kW]	-	19
Total weight [kg]	1200	1258
Vehicle lifetime [a]	12	12

- **Compact vehicles (User profile: European cluster 3, yearly mileage 12001 km)**

Vehicle	Gasoline	Diesel	Compact EREV
Motor power [kW]	87	87	**87**
Battery capacity [kWh]	-	-	**19**
RE power [kW]	-	-	**20**
Total weight [kg]	1470	1490	**1751**
Vehicle lifetime [a]	12	12	**12**

chosen example

EVREST: LCA according to ISO 14040 and 14044

1. Goal and scope of the study
   - Using the example of EVREST
2. Life cycle inventory analysis (LCI)
   - LCA modelling using the example of EVREST
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation
5. Reporting
6. Critical review (optional)

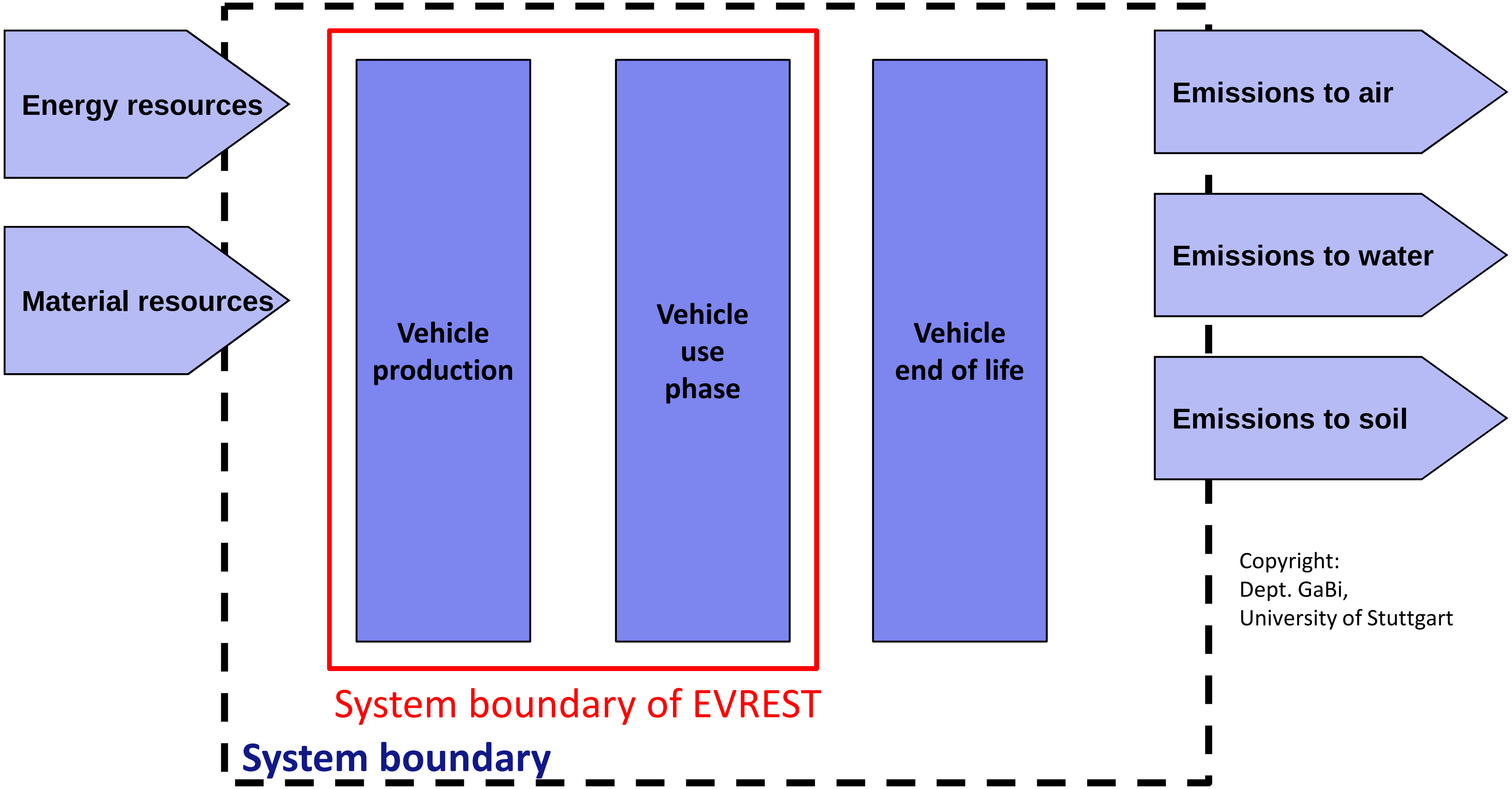
(Items 1–3: Focus of the tutorial)

EVREST: Goal and scope

- Functional unit:
  The function of the assessed product system is the transport of humans. The chosen functional unit is therefore determined as the transportation of humans over a distance of 58,524 km for small vehicles and **144,012 km for compact vehicles over 12 years vehicle operation**. **12 years is also the assumed lifetime of the vehicles.**
- System boundary:
  The vehicle life cycle stages production and use phase are taken into consideration. The production of the vehicles includes also the upstream processes for the provision of the used materials and energy. The use phase is mainly dominated by the fuel or electricity consumption (including fuel and energy supply). The end of life is not evaluated.
- Further items of goal and scope (e.g. LCIA methodology and types of impacts, data requirements etc.) have also to be defined

EVREST: Life cycle inventory analysis (LCI)

LCI-modeling of electric vehicles within an LCA



EVREST: Life cycle inventory analysis (LCI)

Data basis general:

- LCI data for material production and energy supply are based on the GaBi databases (e.g. electricity grid mixes, lithium supply etc.)
- The technical specifications of vehicle concepts (e.g. vehicle mass, power etc.) and use phase data is based on EVREST framework conditions

Production

EVREST: Life cycle inventory analysis (LCI) Production

Data basis and requirements for the production LCA model:

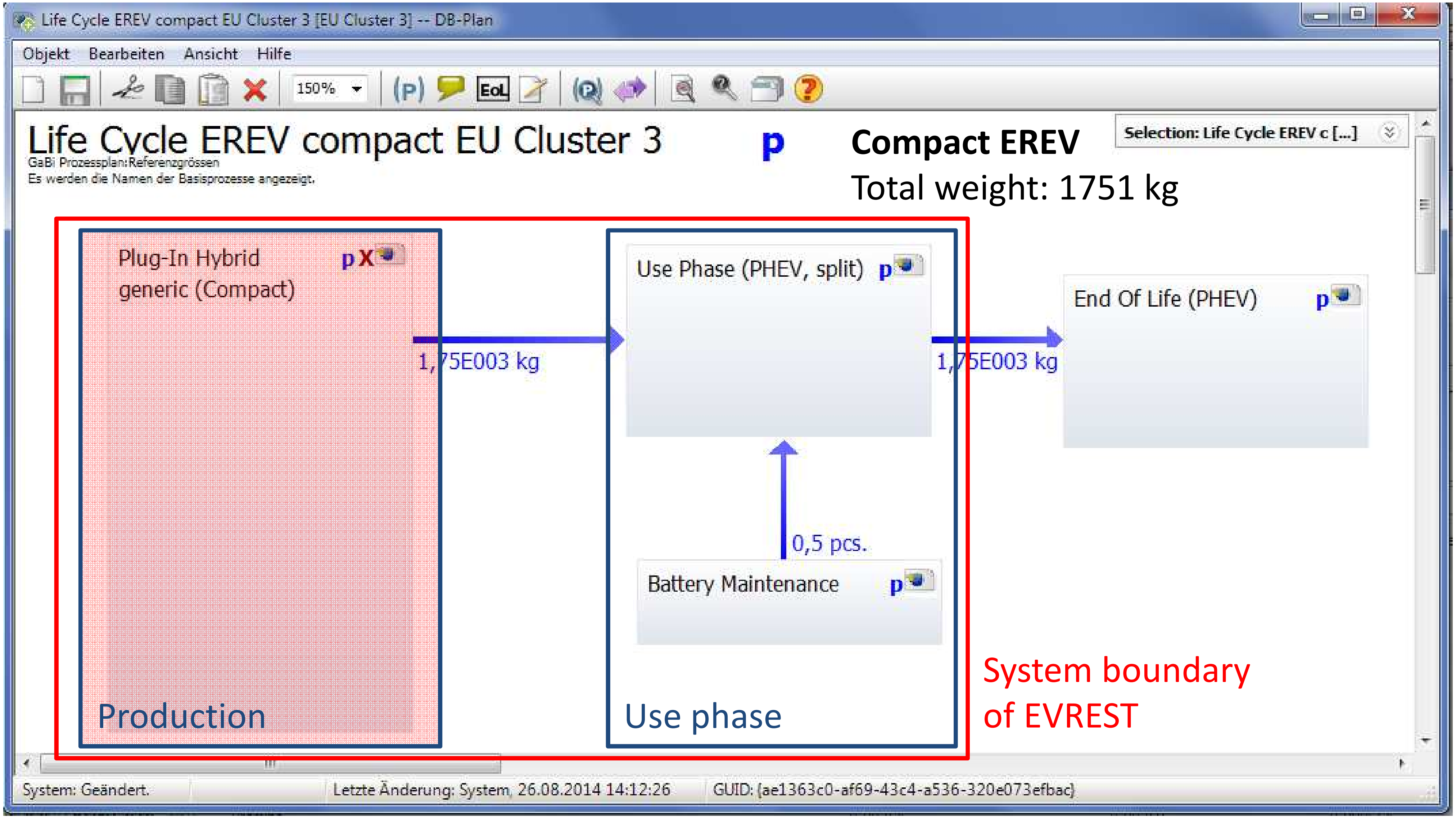
- Reference location of the vehicle production is Germany
- Environmental profiles of the conventional vehicles and the vehicle platforms are based on the material mix of comparable vehicles classes from environmental commendations / certificates from Daimler AG and Volkswagen AG (*Environmental Certificate A-Class; Environmental Certificate B-Class; Environmental commendation Golf)*
  ➔ scaled according to the vehicle and platform mass
- Electric motor is based on the material mix of a permanent magnet synchronous motor (PMSM) *(Swiss Federal Office of Energy SFOE)*
  ➔ scaled by the weight-to-power ratio
- The configuration and technical specifications of the battery system are based on internal data of the EVREST project

EVREST: Life cycle inventory analysis (LCI) Production

Data basis and requirements for the production LCA model:

- Currently only few information on the LCA of the production of EV batteries and related materials available
  ➔ Assumptions have been made based on from previous studies, available literature and material safety data sheets (MSDS) of Li-Ion battery cells (*e.g. Argonne National Laboratory, Center for Transportation Research; International Battery - Lithium Nickel Cobalt Manganese Oxide – Material Safety Data Sheet; KOKAM Material Safety Data Sheet – Superior Lithium Polymer Battery; Dewulf J, et al., Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings; Ishihara, K. et. al; Environmental burdens of Large Lithium-Ion Batteries Developed in a Japanese National Project, Central Research Institute of Electric Power Industry, Japan)*
- The power electronic components (e.g. inverters) are based on existing models of comparable components in the GaBi database

EVREST: Life cycle inventory analysis (LCI) LCA model "life cycle"



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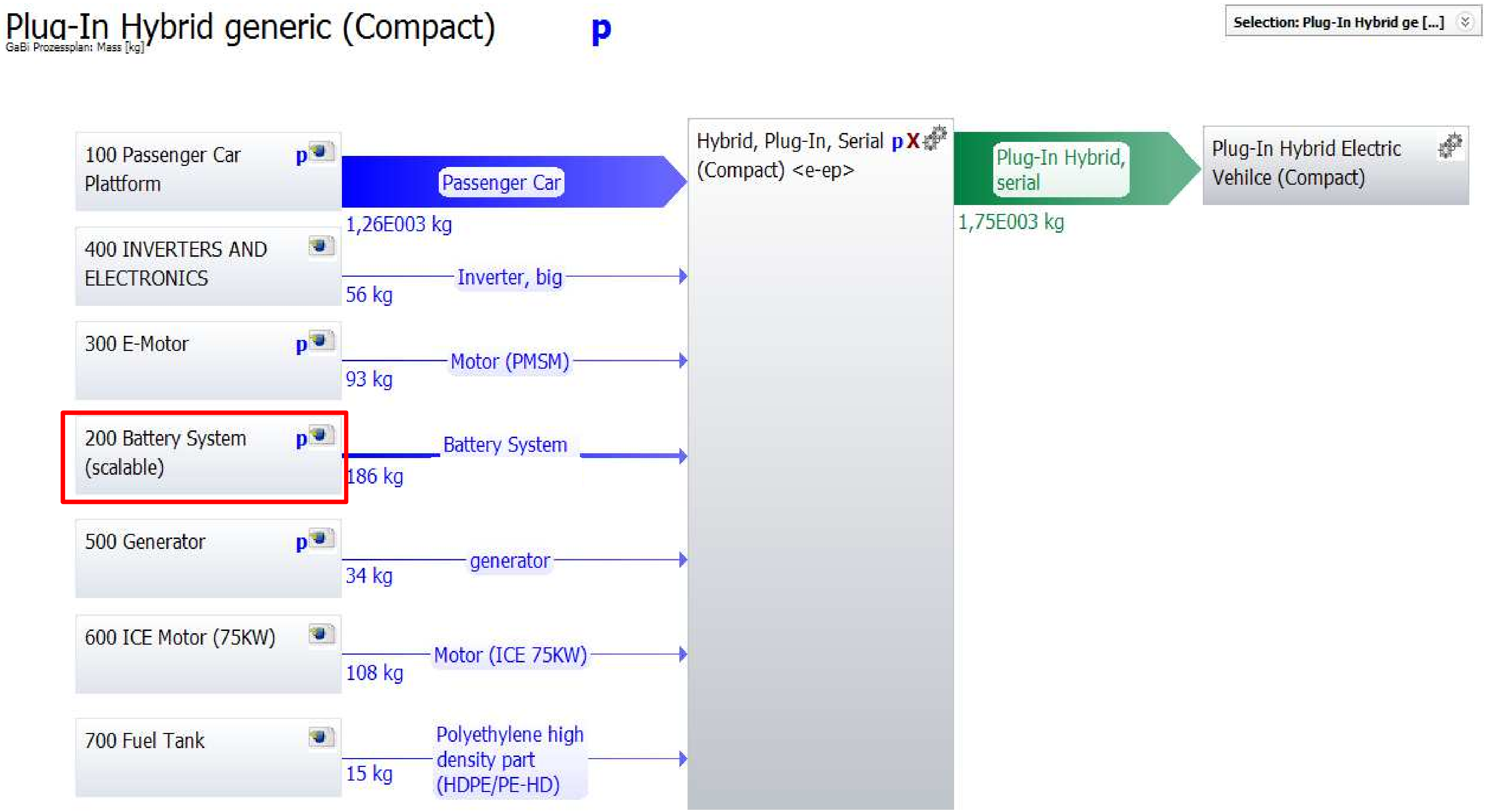
EVREST: Life cycle inventory analysis (LCI)
LCA model "vehicle production"

EVREST data sheet (by IFSTTAR-LTE):

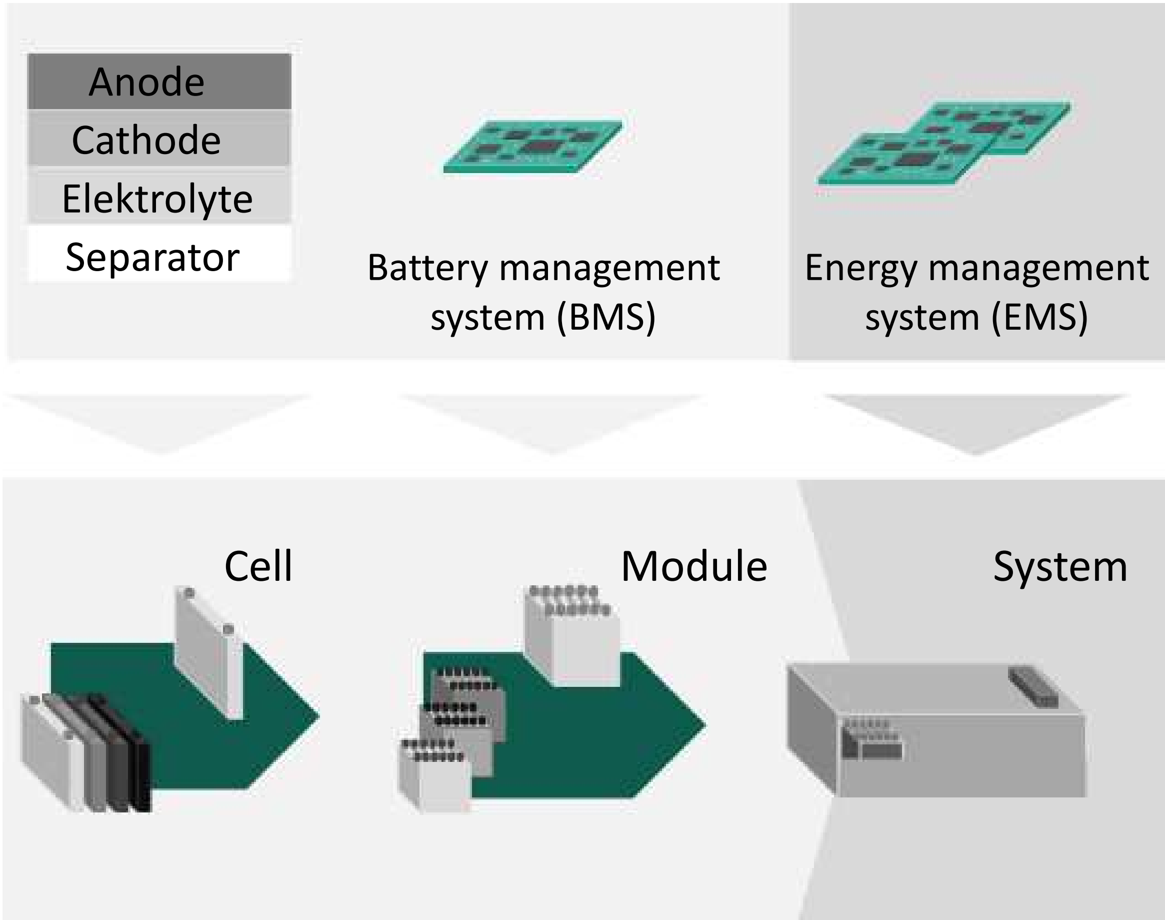
Production data

Medium Class	EREV	Battery (kWh)	19	RE (kW)	20	Total Weight (kg)	1751
ICE based RE						Prop. Mot./Eng. Weight (kg)	93
	Yearly Electricity Consumption (kWh)			2436.4		Battery Weight (kg)	186
	Yearly Gasoline Consumption (L)			68		RE's Gas. Engine Weight (kg)	108
	Yearly CO2 Emission (kg)			116.2		RE's Generator Weight (kg)	34
	Yearly CO Emission (kg)			18.6			
	Yearly HC Emission (kg)			5.1		Propulsion Engine / Motor maximum power (kW)	87
	Yearly NOx Emission (kg)			0.5			
	RE's Emission Standard			EURO3			
	Vehicle Lifetime Considered			12			
	Battery Cycling Lifetime > Vehicle Lifetime ?			YES			
Comments	EREV sized to offer an All Electric Range of 90km, a Full Power Range of 300km and a maximum speed of 110km/h while in degraded mode.						

EVREST: Life cycle inventory analysis (LCI)
LCA model "vehicle production"



EVREST: Life cycle inventory analysis (LCI)
LCA model "battery system production"



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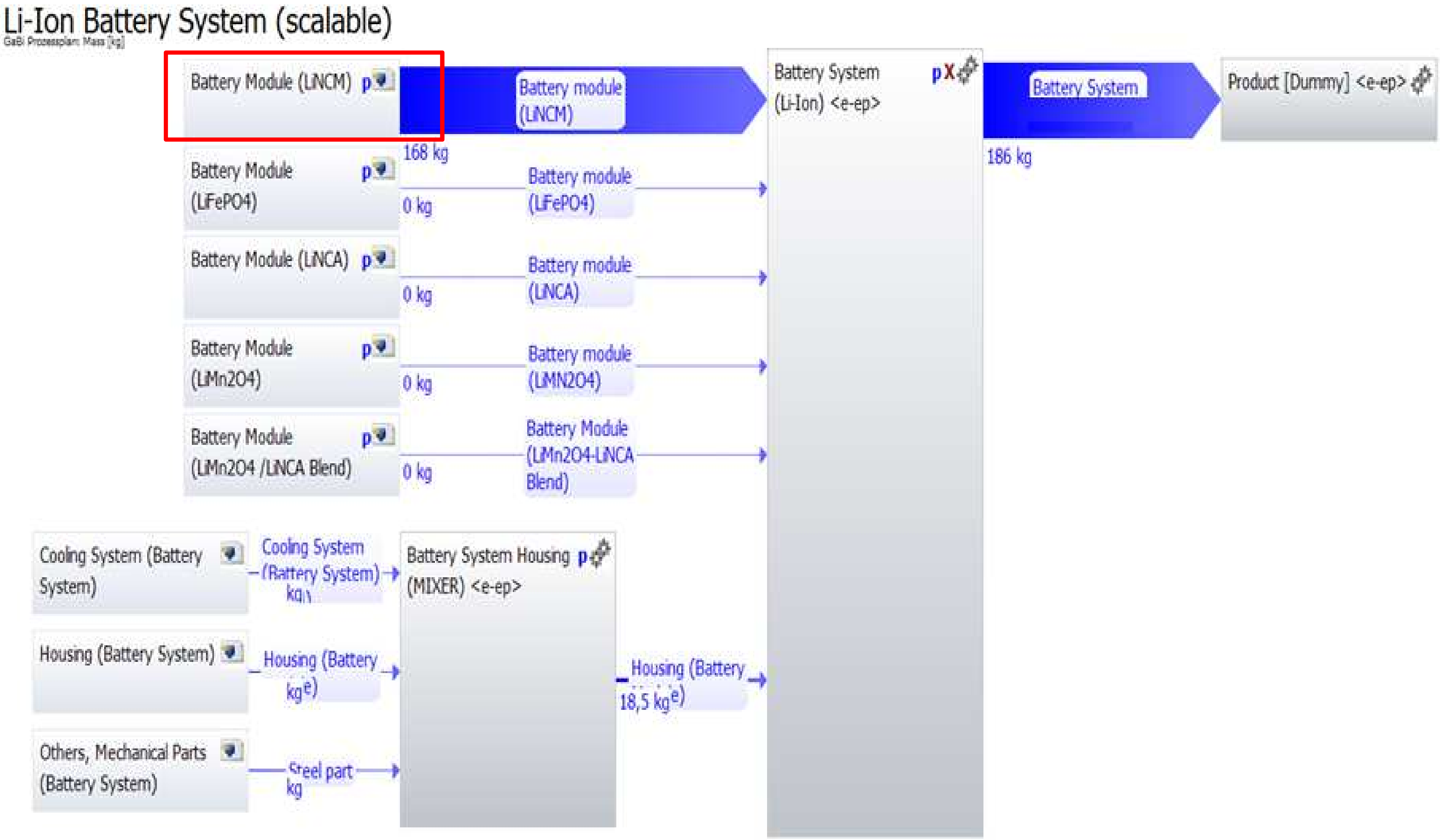
EVREST: Life cycle inventory analysis (LCI)
LCA model "battery system production"



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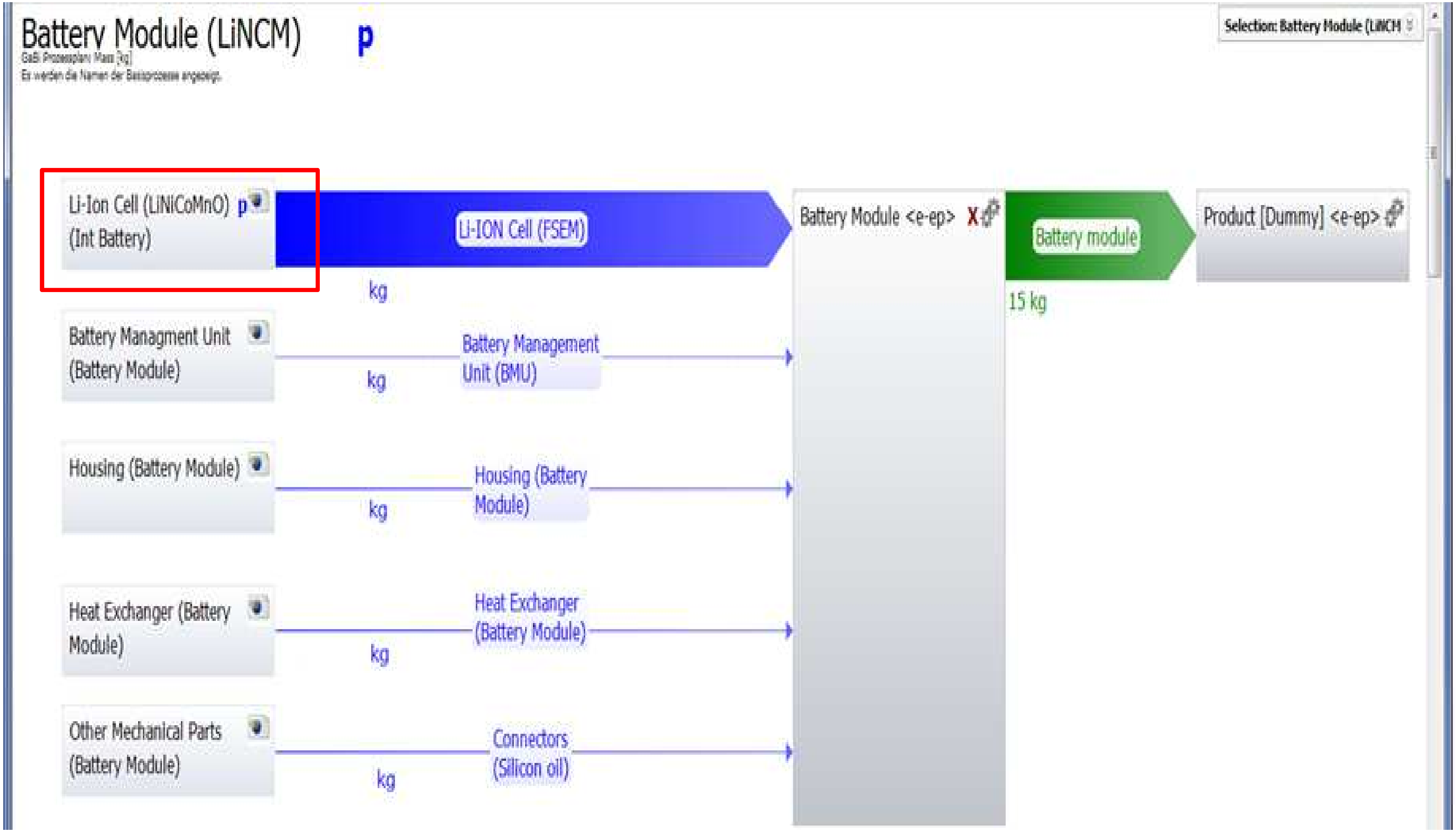
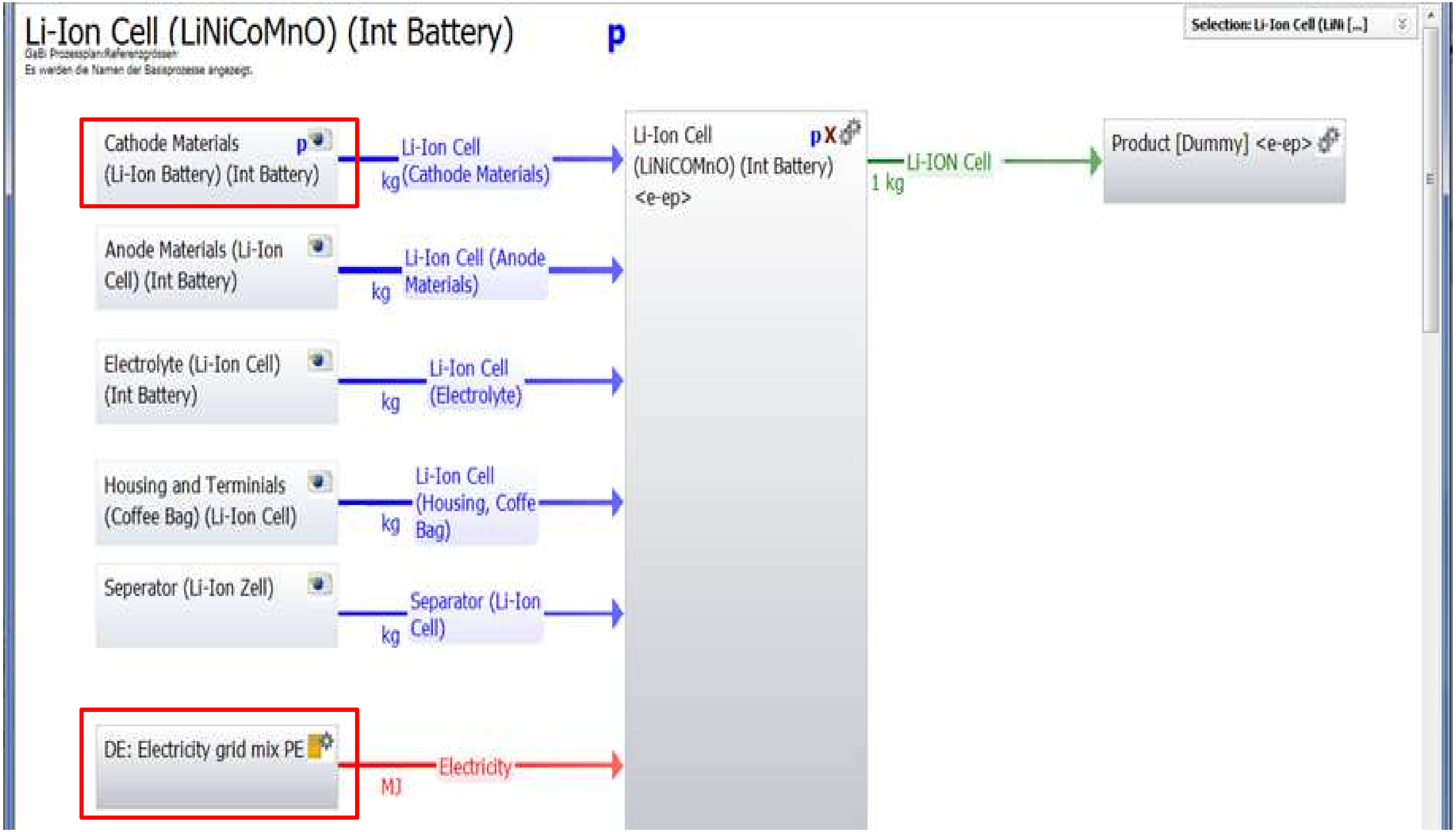
EVREST: Life cycle inventory analysis (LCI)
LCA model “battery module production”



EVREST: Life cycle inventory analysis (LCI)
LCA model "battery cell production"



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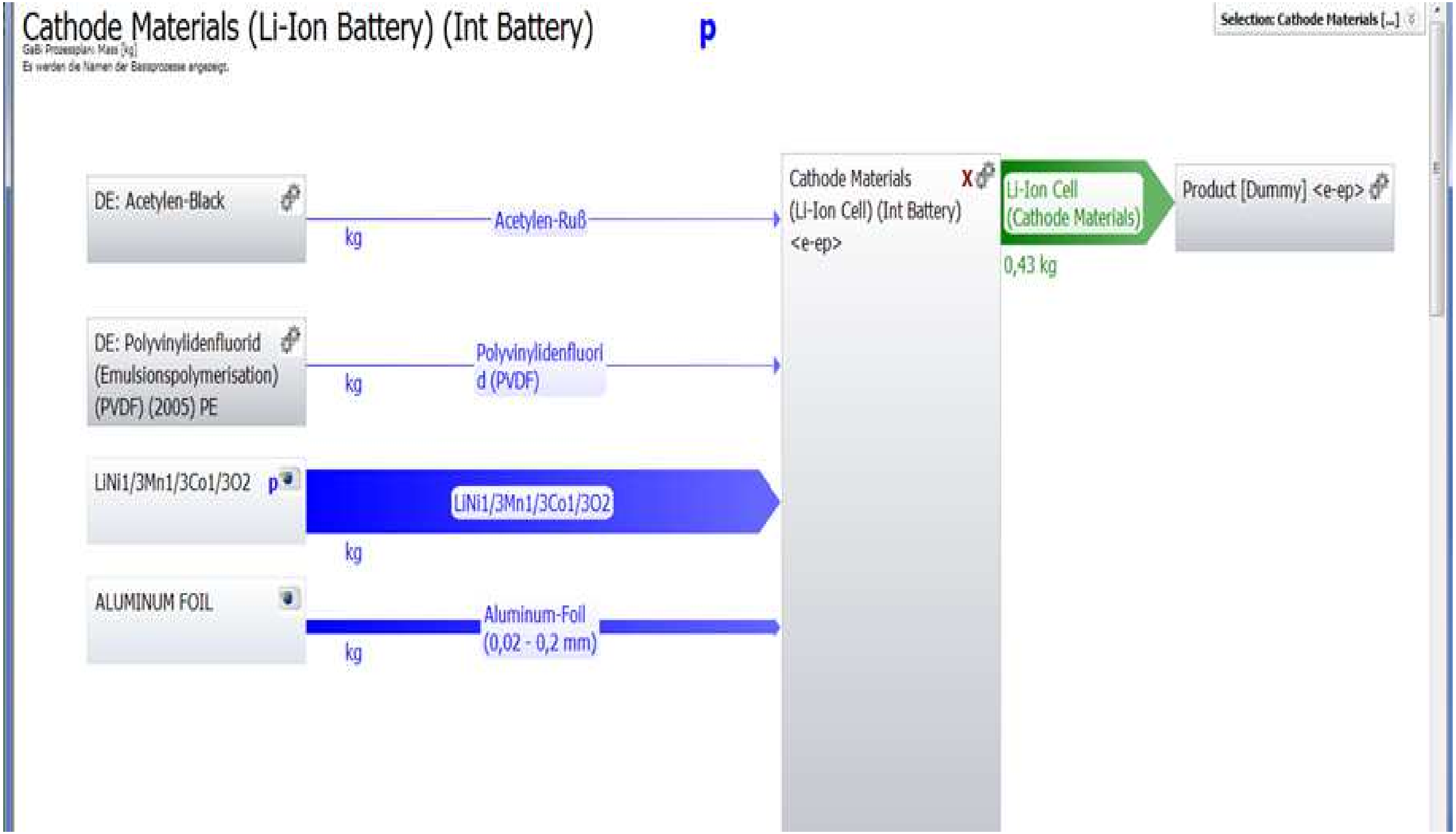
EVREST: Life cycle inventory analysis (LCI)
LCA model “cathode materials production”



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EVREST: Life cycle inventory analysis (LCI)
LCA model – process example

Name: DE | Electricity grid mix | agg - LCI Ergebnis

Parameter

LCA | **VF** | **LCC: 3,71 EUR** | **LCWE** | **Dokumentation**

Vollständigkeit: All relevant flows recorded

Excerpt of GaBi process "Electricity mix Germany"

Inputs

Fluss	Grösse	Menge	Einheit	We	Standar	Herkunft	Kommentar
Hard coal (in MJ) [Hard coal (resource)]	Energy (net calor	1,97	MJ		0 %	Literature	
Heavy spar (BaSO4) [Non renewable resources]	Mass	4,02E-009	kg		0 %	Literature	
Ilmenite (titanium ore) [Non renewable resources]	Mass	7,88E-008	kg		0 %	Measured	
Inert rock [Non renewable resources]	Mass	3,28	kg		0 %	(Literature)	
Iridium [Non renewable elements]	Mass	2,6E-013	kg		0 %	(Keine Angabe)	
Iron [Non renewable elements]	Mass	-0,000502	kg		0 %	Literature	
Kaolin ore [Non renewable resources]	Mass	6,43E-006	kg		0 %	Measured	
Land Occupation [Occupation]	Areatime	0,0095	m2*yr		0 %	Literature	
Land Transformation [Transformation]	Area	4,03E-005	sqm		0 %	Literature	
Lead [Non renewable elements]	Mass	2,24E-006	kg		0 %	(Calculated)	
Lignite (in MJ) [Lignite (resource)]	Energy (net calor	2,4	MJ		0 %	Literature	

Outputs

Fluss	Grösse	Menge	Einheit	We	Standar	Herkunft
Electricity [Electric power]	**Energy (net ca**	**3,6**	**MJ**	**X**	**0 %**	**Literature**
Sodium (+I) [Inorganic emissions to industrial soil]	Mass	6,06E-009	kg		0 %	Literature
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	Mass	3,34E-014	kg		0 %	Literature
Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water]	Mass	4,1E-007	kg		0 %	Literature
R 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	Mass	9,13E-015	kg		0 %	Literature
Sodium (+I) [Inorganic emissions to sea water]	Mass	5,96E-007	kg		0 %	Literature
R 124 (chlorotetrafluoroethane) [Halogenated organic emissions to air]	Mass	3,95E-016	kg		0 %	Estimated

Use stage

EVREST: Life cycle inventory analysis (LCI)
LCA model "use phase"

General requirements for the use phase LCA model

- Integration of specific user profiles respectively the energetic simulation of test driving cycles (e.g. NEDC, ARTEMIS etc.)
- Differentiation of the combustion engine concepts when assessing hybrids (gasoline, diesel, exhaust emission standard)
- Adaptation of conditions of use (vehicle lifetime, mileage, distribution of the mileage: e.g. 60% full electric mode, 40% range extended mode)
- Consideration of the maintenance of the drivetrain components (e.g. because of battery lifetime)
- Consideration of the energy supply:
  - Fuel supply (gasoline, diesel, hydrogen)
  - Implementation of electricity grid mix scenarios (e.g. country-specific)

EVREST: Life cycle inventory analysis (LCI)
LCA model "use phase"

EVREST framework conditions for the use phase LCA model (project partner: IFSTTAR-LTE)

- "Artemis Mix" driving cycle is used for the determination of energy and fuel consumption and emissions,
  "Artemis Mix" is based on:
  - 6 x "Artemis Urban" driving cycles
  - 2 x "Artemis Extra-Urban " driving cycles
  - 1 x "Artemis Motorway " driving cycle
- Background data for "Artemis Mix"
  - ARTEMIS European driving cycles (urban, extra-urban and motorway types)
  - ARTEMIS cycles are then combined to meet an European road share (assessed using the HBEFA 3.1 database)

EVREST: Life cycle inventory analysis (LCI)
LCA model "use phase"

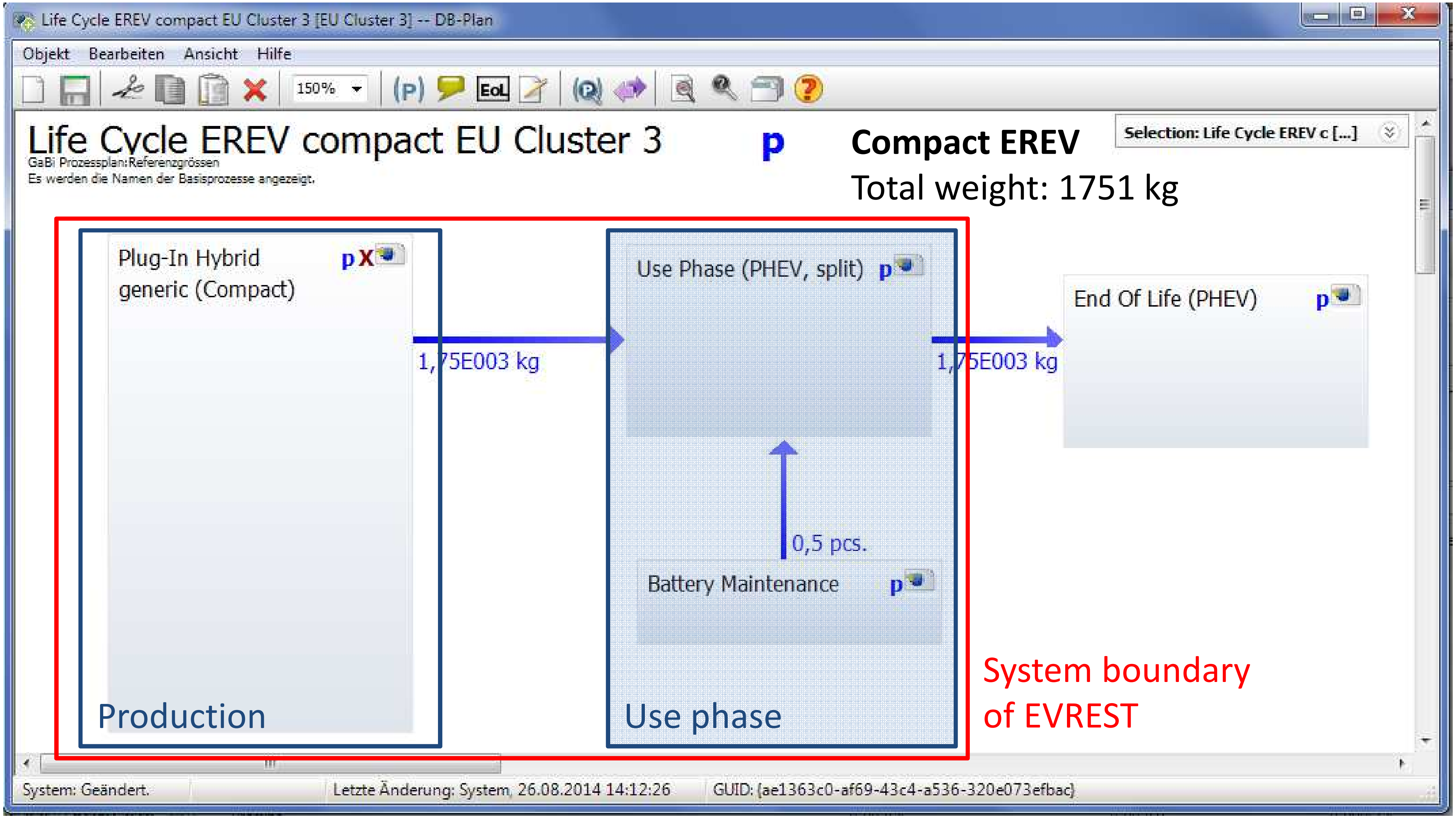
EVREST framework conditions for the use phase LCA model

- Conditions of use, see „Functional unit":
  - Total mileage for small vehicles: 58,524 km
  - Total mileage for compact vehicles: 144,012 km
  - Lifetime of the vehicles: 12 years
  - Share of propulsion modes is assessed by project partner IFSTTAR-LTE
- Maintenance of the battery system after 8 years operation

➔ Two battery systems have to be used during the lifetime

- Vehicles are assessed for European fuel supply and Austrian, French and German electricity grid mix

EVREST: Life cycle inventory analysis (LCI)
LCA model "life cycle"



EVREST: Life cycle inventory analysis (LCI)
LCA model “use phase”

EVREST data sheet (by IFSTTAR-LTE):

Medium Class	EREV	Battery (kWh)	19	RE (kW)	20	Total Weight (kg)	1751
ICE based RE			Use phase data			Prop. Mot./Eng. Weight (kg)	93
	Yearly Electricity Consumption (kWh)			2436.4		Battery Weight (kg)	186
	Yearly Gasoline Consumption (L)			68		RE's Gas. Engine Weight (kg)	108
	Yearly CO2 Emission (kg)			116.2		RE's Generator Weight (kg)	34
	Yearly CO Emission (kg)			18.6			
	Yearly HC Emission (kg)			5.1		Propulsion Engine / Motor maximum power (kW)	87
	Yearly NOx Emission (kg)			0.5			
	RE's Emission Standard			EURO3			
	Vehicle Lifetime Considered			12			
	Battery Cycling Lifetime > Vehicle Lifetime ?			YES			
Comments	EREV sized to offer an All Electric Range of 90km, a Full Power Range of 300km and a maximum speed of 110km/h while in degraded mode.						

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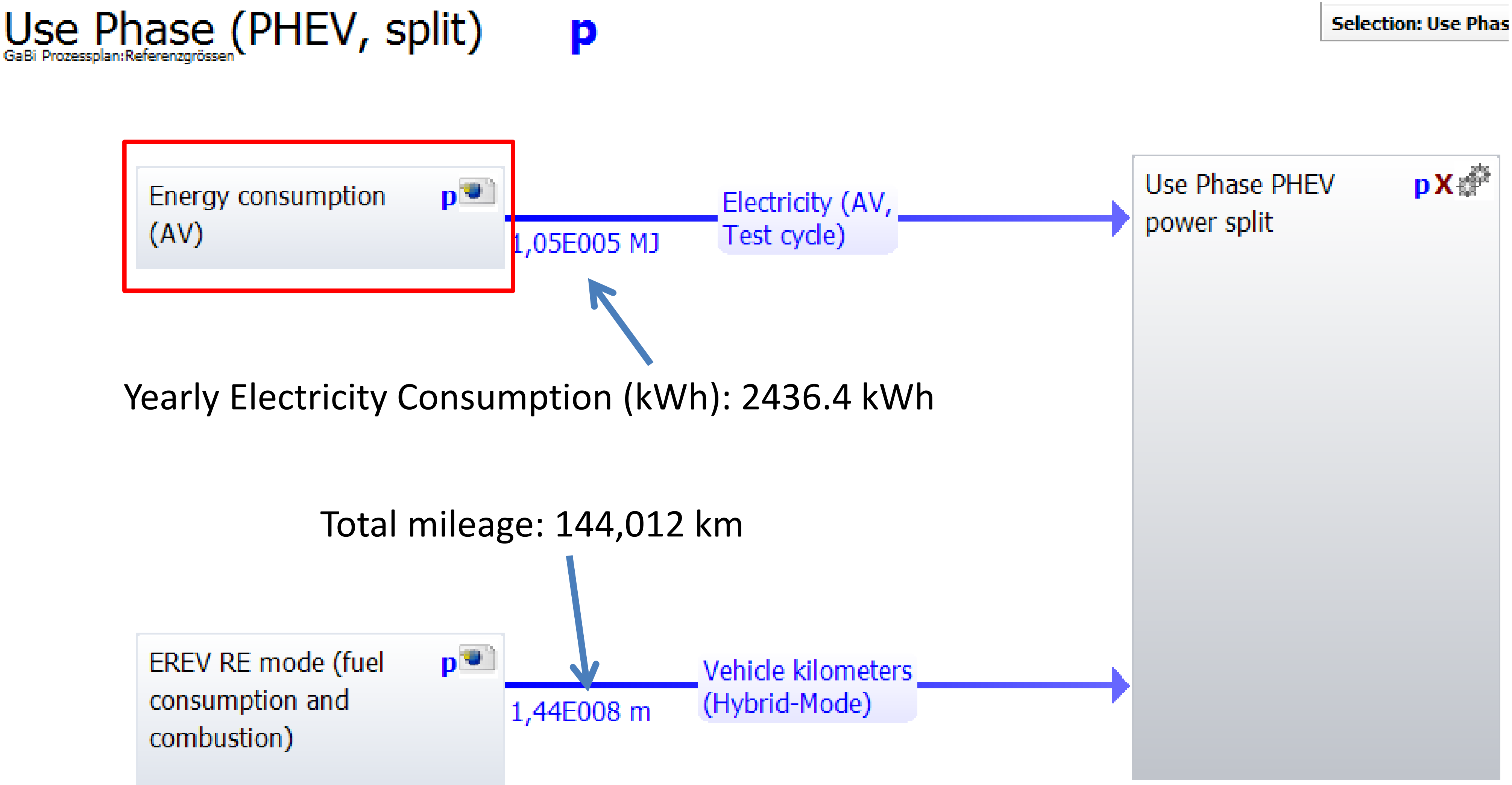
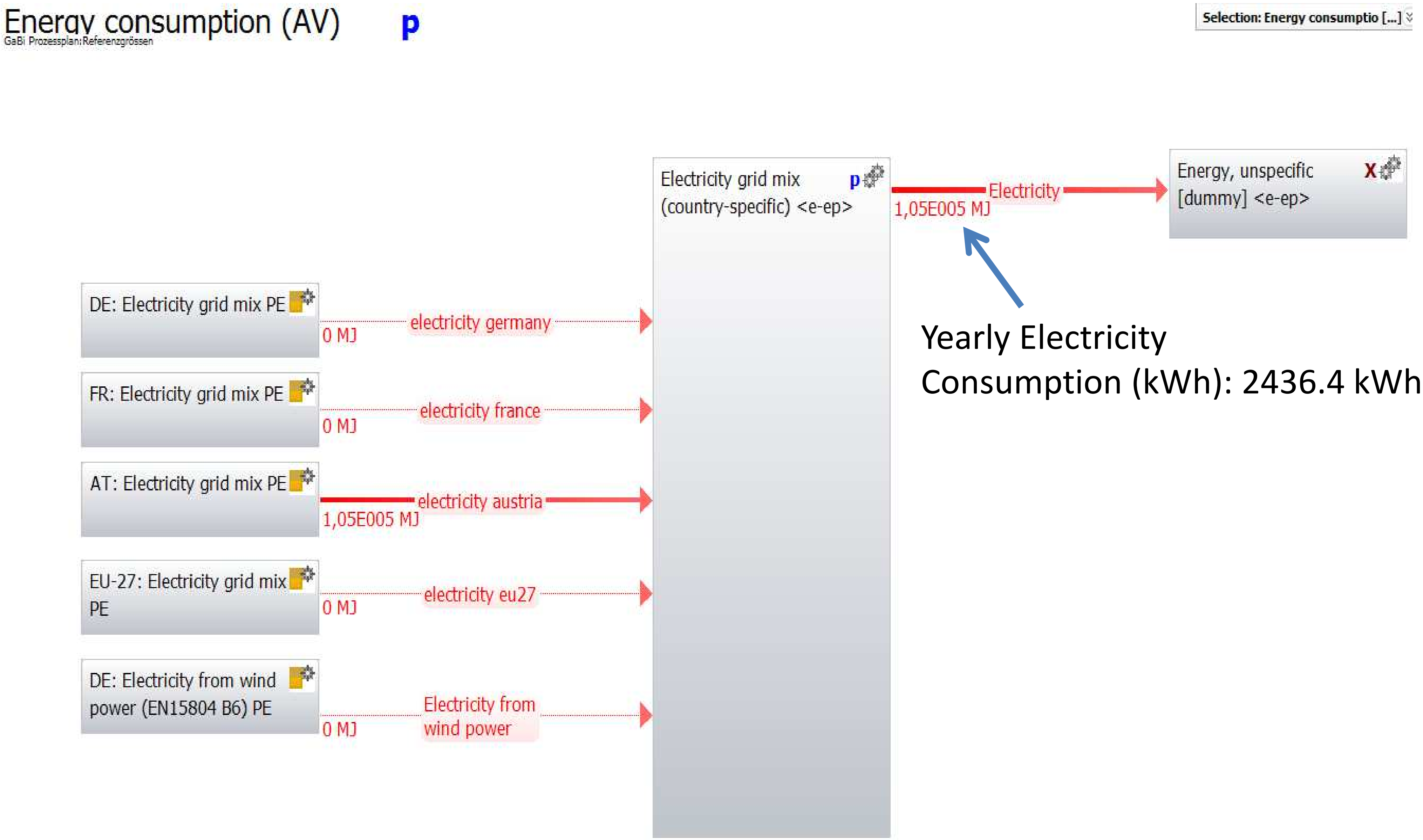
EVREST: Life cycle inventory analysis (LCI)
LCA model "use phase"



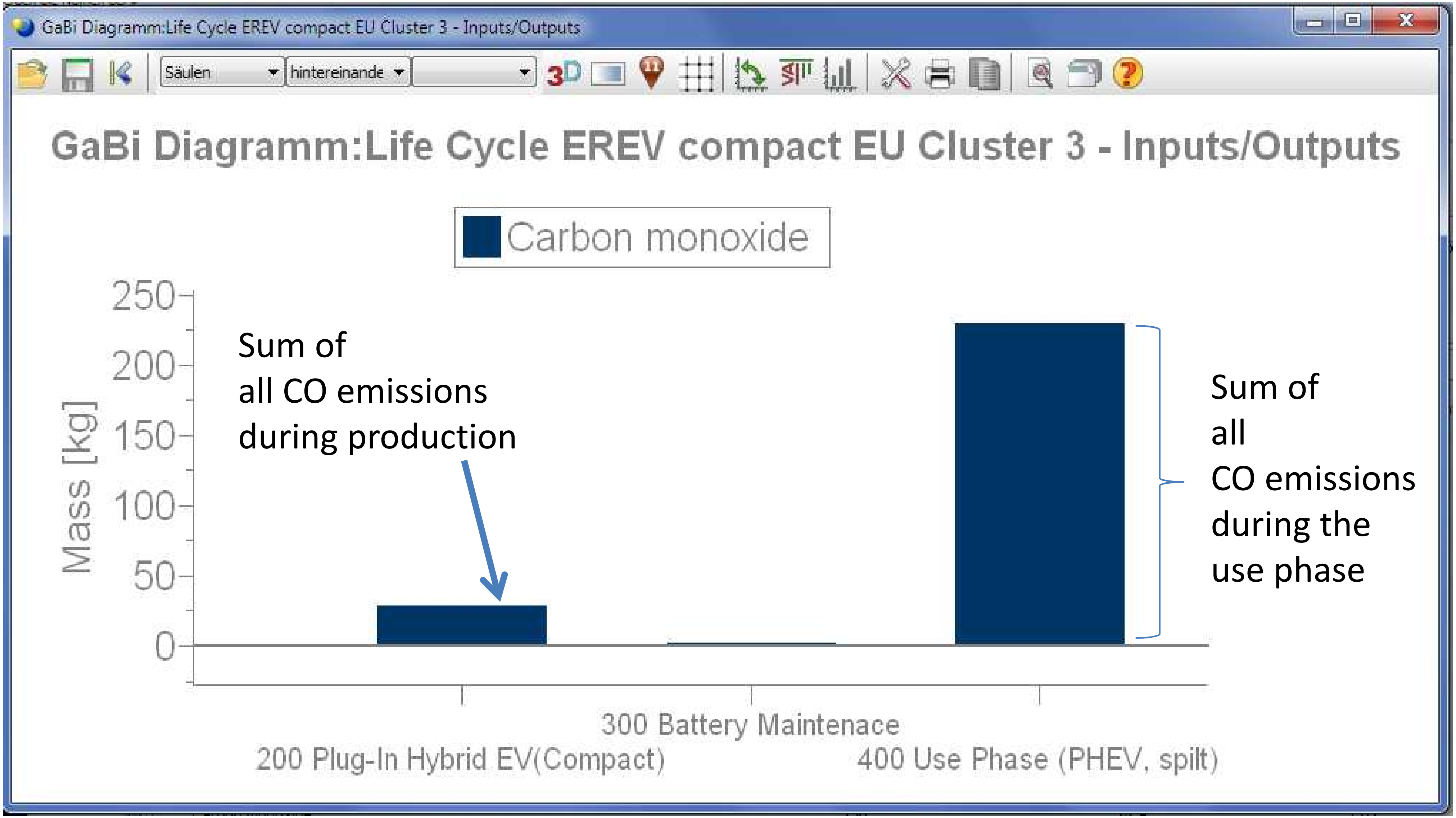
EVREST: Life cycle inventory analysis (LCI)
LCA model “use phase, electricity mix”



Yearly Electricity Consumption (kWh): 2436.4 kWh

Analysis of production and use stage

EVREST: Life cycle inventory analysis (LCI)
Quantification of inputs and outputs



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EVREST: Life cycle impact assessment (LCIA)

Classification and characterization

Life Cycle Inventory value	*	GWP Factor	=	Impact potential
24 kg CO_2	*	1	=	24 [kg CO_2-equivalent]
2 kg CH_4	*	25	=	50 [kg CO_2-equivalent]
...	*	...	=	...
		Total:		74 [kg CO_2-equivalent]

1 kg of CH_4 emission is equivalent to 25 kg of CO_2 emission

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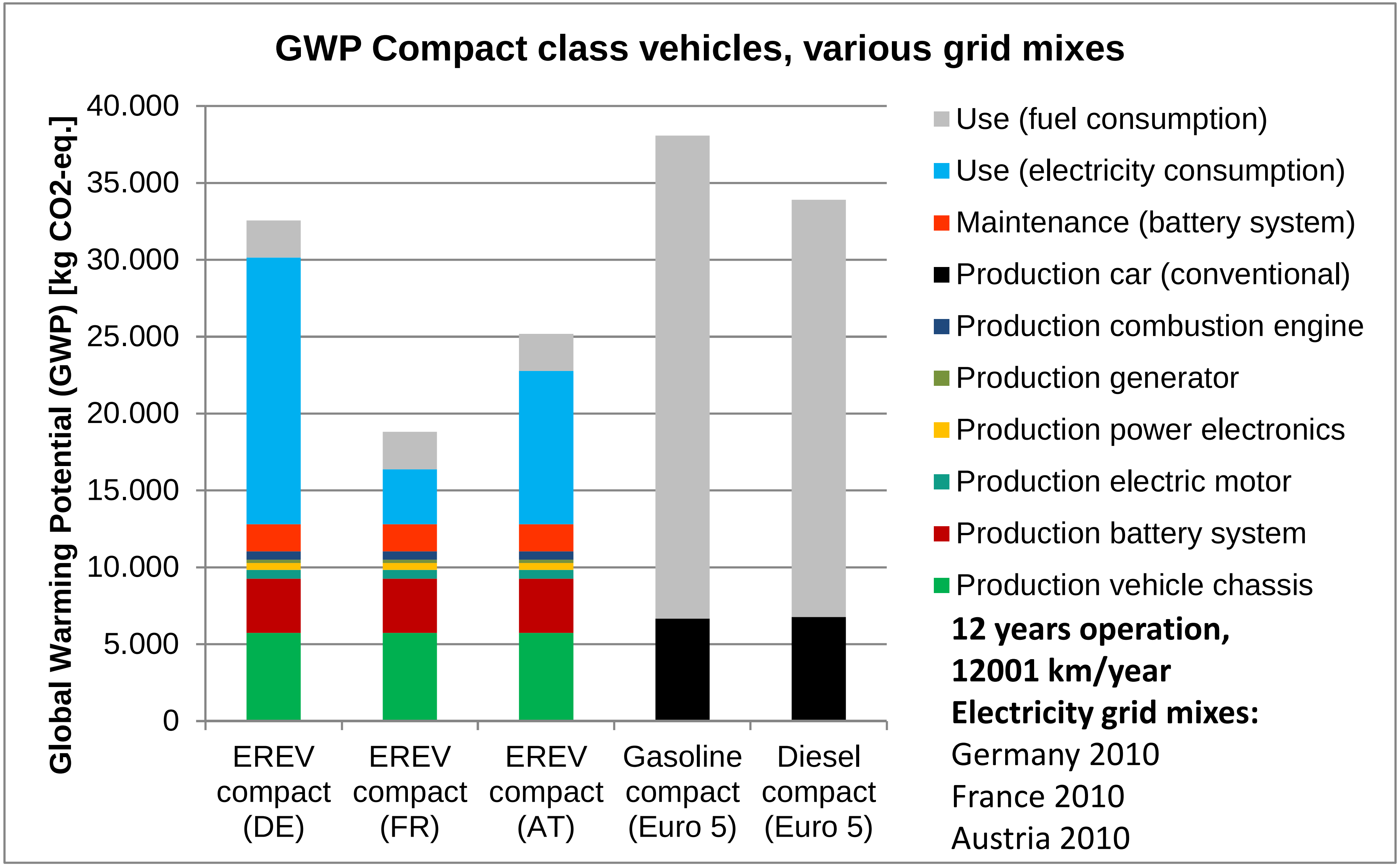
EVREST: Life cycle impact assessment (LCIA)

- Life cycle impact assessment is done automatically by the LCA software GaBi (the classification and characterization factors for all resources and emissions are stored in the LCA software system)
- Used impact assessment method at Dept. GaBi is **CML 2001 Method**
- Assessed impact categories in EVREST:
  - Global Warming Potential (GWP)
  - Acidification Potential (AP)
  - Eutrophication Potential (EP)
  - Photochemical Ozone Creation Potential (POCP)

EVREST: Life cycle impact assessment (LCIA)



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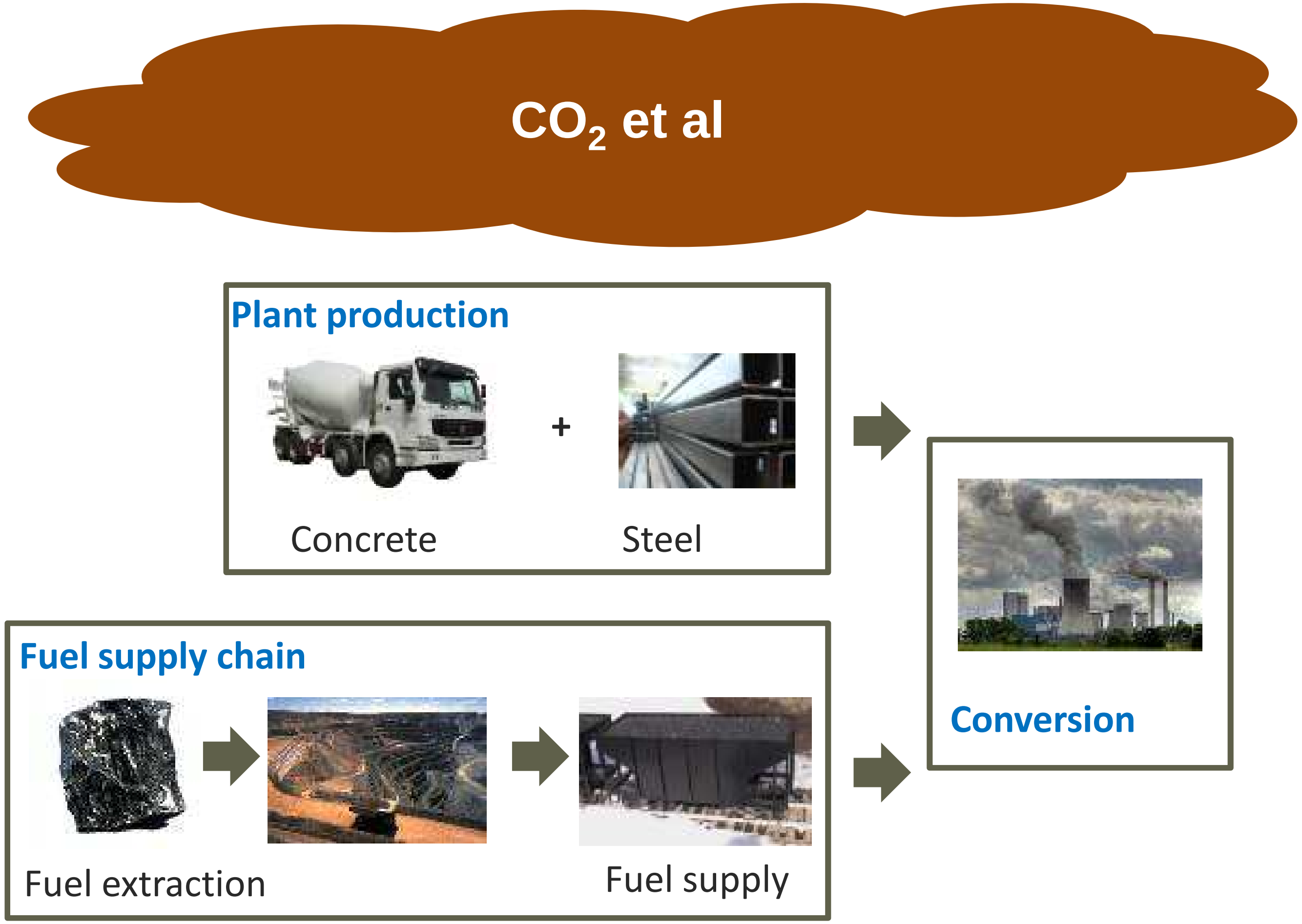
Hourly electricity production – carbon footprint



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Challenges and solutions

Average values

Outdated data

↓

Hourly electricity mix

All power plants in Belgium

Measured data

Life cycle approach

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The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment

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HIGHLIGHTS

- This paper brings a temporal resolution in LCA of electricity generation.
- Dynamic life cycle assessment of electricity production in Belgium for 2011.
- The overall average GWP per kW h is 0.184 kg CO_2eq/kW h.
- The carbon footprint of Belgian electricity ranges from 0.102 to 0.262 kg CO_2eq/kW h.

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ABSTRACT

In the booming research on the environmental footprint of, for example, electrical vehicles, heat pumps and other (smart) electricity consuming appliances, there is a clear need to know the hourly CO_2 content of one kW h of electricity. Since the CO_2 footprint of electricity can vary every hour; the footprint of for example an electric vehicle is influenced by the time when the vehicle is charged. With the availability of the hourly CO_2 content of one kW h, a decision support tool is provided to fully exploit the advantages of a future smart grid. In this paper, the GWP (Global Warming Potential) per kW h for each hour of the year is calculated for Belgium using a Life Cycle Assessment (LCA) approach. This enables evaluating the influence of the electricity demand on the greenhouse gas emissions. Because of the LCA approach, the CO_2 equivalent content does not only reflect activities related to the production of the electricity within a power plant, but includes carbon emissions related to the building of the infrastructure and the fuel supply chain. The considered feedstocks are nuclear combustible, oil, coal, natural gas, biowaste, blast furnace gas, and wood. Furthermore, renewable electricity production technologies like photovoltaic cells, hydro installations and wind turbines are covered by the research. The production of the wind turbines and solar panels is more carbon intensive (expressed per generated kW h of electricity) than the production of other conventional power plants, due to the lower electricity output. The overall average GWP per kW h is 0.184 kg CO_2eq/kW h. Throughout the 2011 this value ranges from a minimum of 0.102 kg CO_2eq/kW h to a maximum of 0.262 kg CO_2eq/kW h depending on the timing.

1. Introduction

A temporal resolution in LCA (Life Cycle Assessment) of electricity production is presented. This paper introduces an hourly carbon footprint of the electricity production in Belgium in 2011, taking the life cycle emissions into consideration. In the booming research on the environmental footprint of electricity consuming appliances, there is a clear need to know the hourly carbon footprint of the production of one kW h of electricity for further optimization. The footprint of for example a battery electric vehicles (BEV) is largely influenced by the electricity mix used to charge the battery [1]. As a consequence, the environmental performance of a BEV will change over time together with the changing electricity mix. In [1] the Global Warming Potential (GWP) of electric vehicles is compared to other vehicle technologies considering a life cycle assessment. A contribution analysis indicates that the consumption of electricity contributes to 85% of the global warming potential of the electric vehicle when considering an EU electricity mix.

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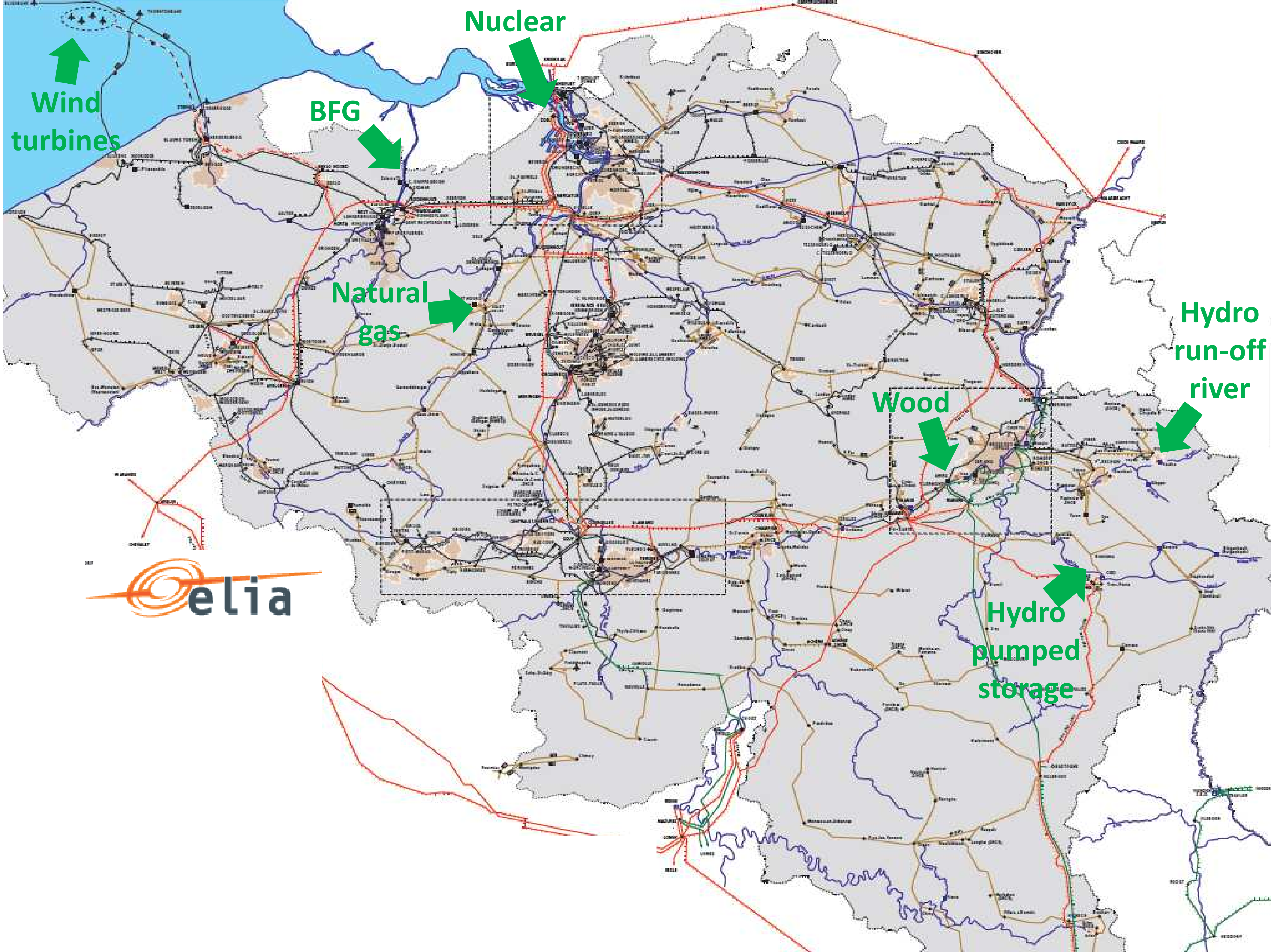
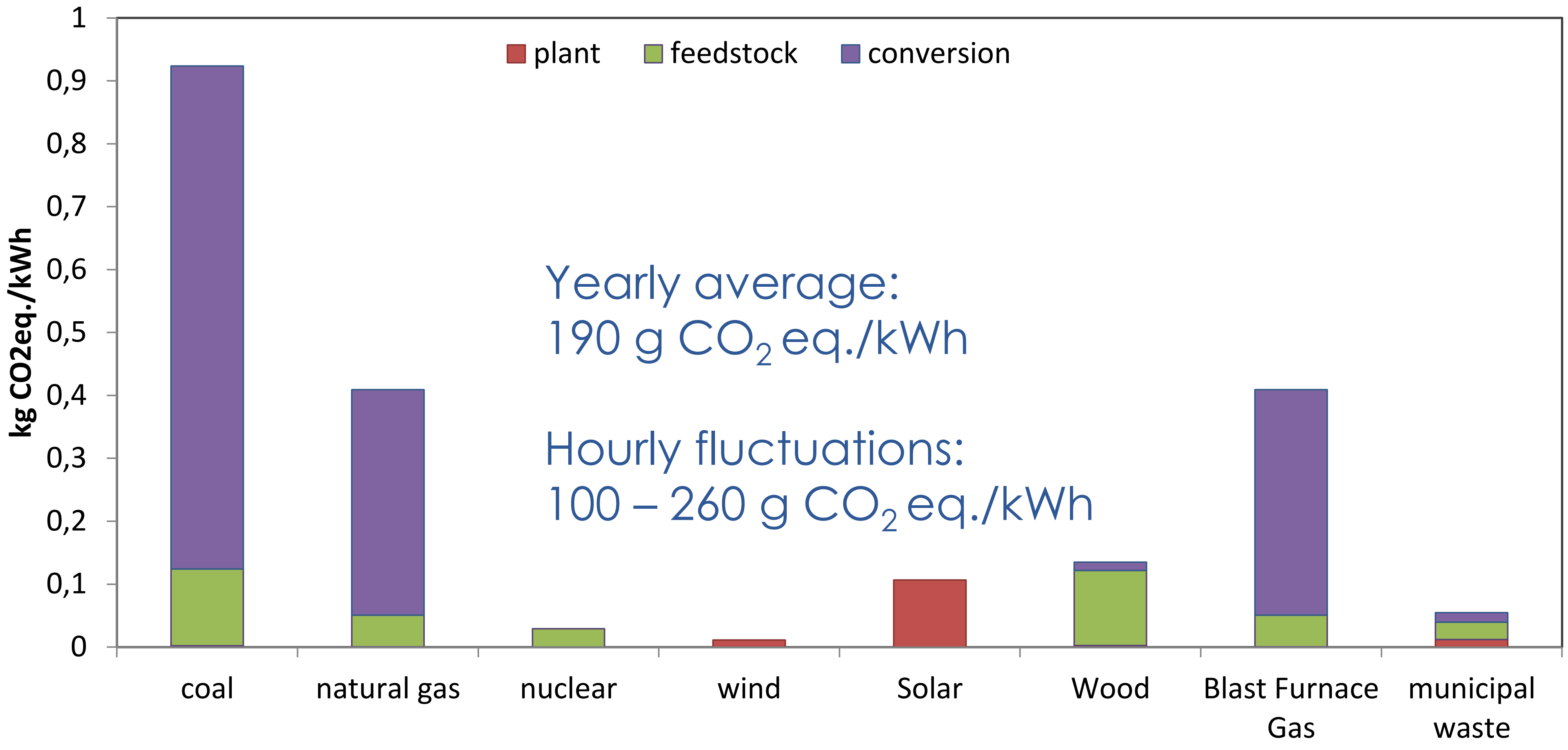


Nuclear
Wind
turbines
BFG
Natural
gas
Hydro
run-off
river
Wood
Hydro
pumped
storage
elia

Carbon footprint of individual power plants



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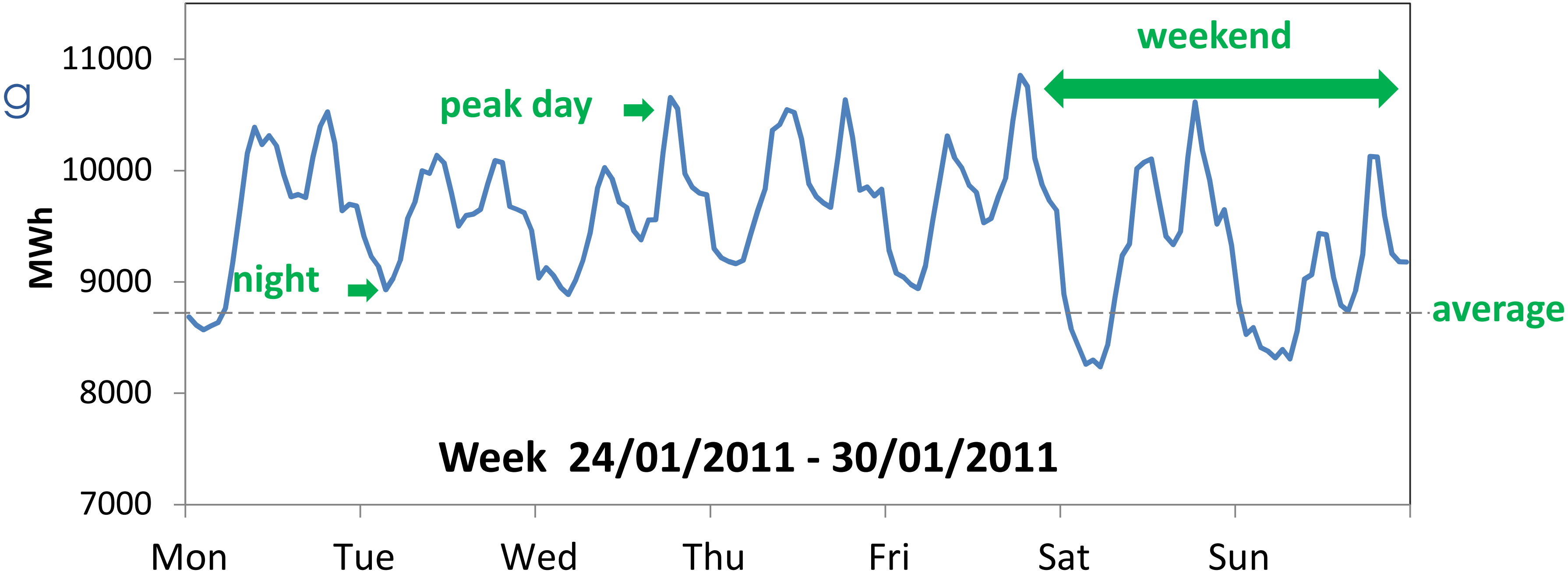
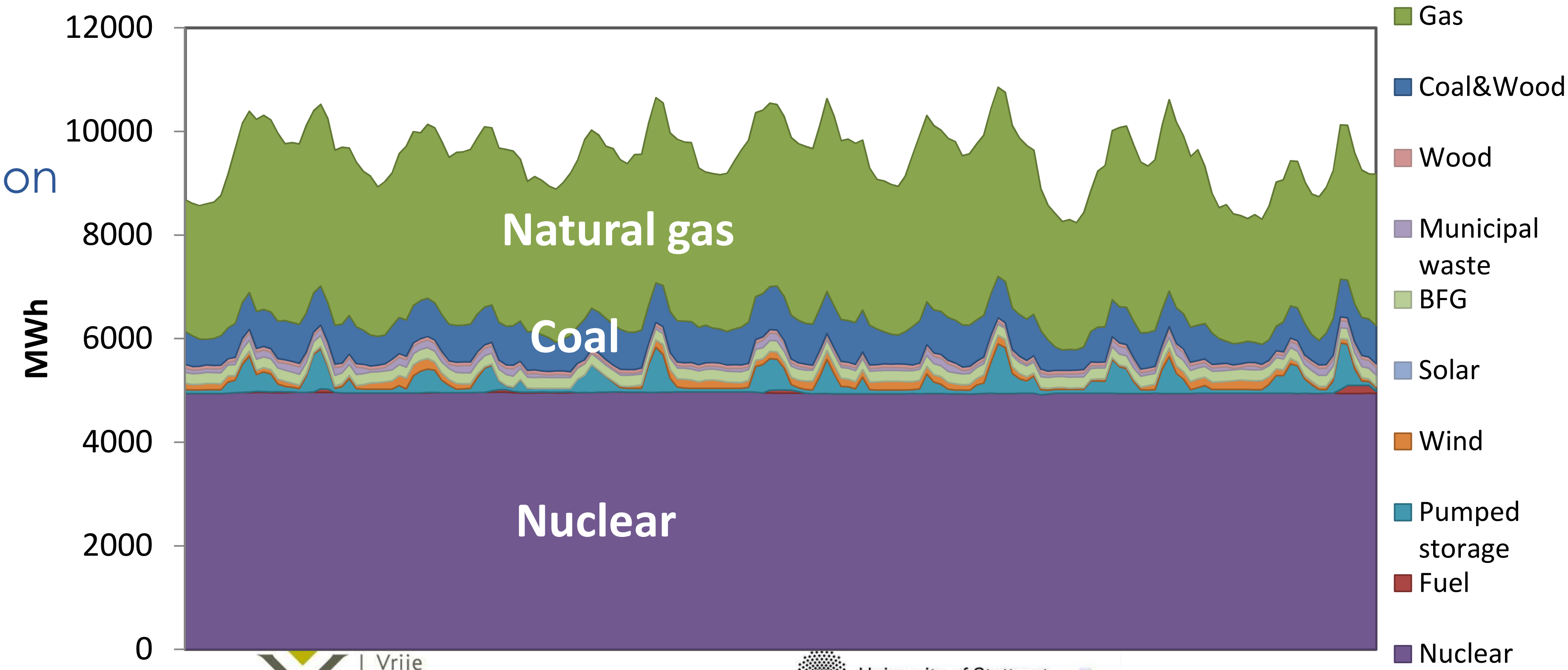
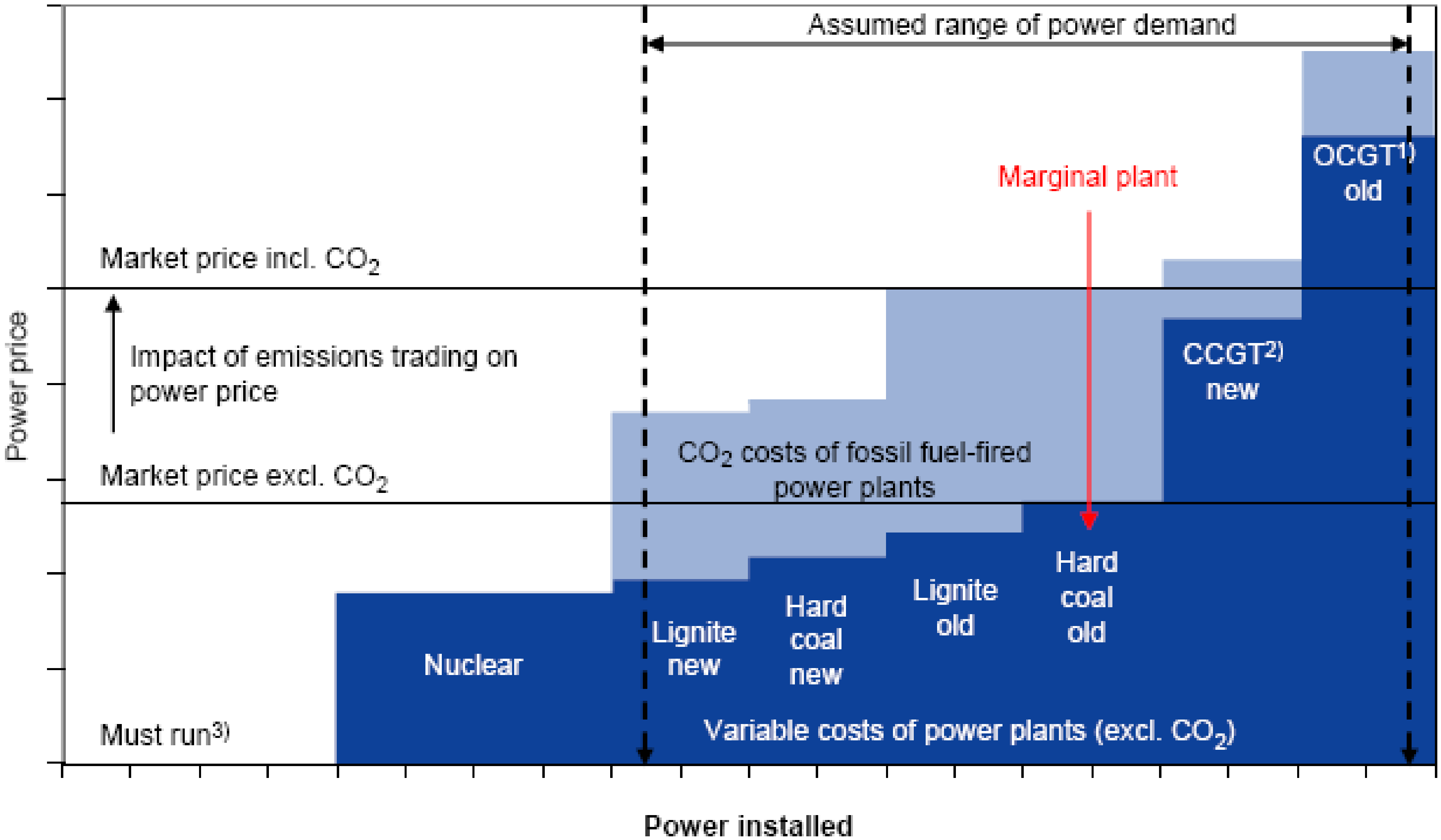
Fluctuating demand



Plant contribution



Why?
Changing demand and merrit order



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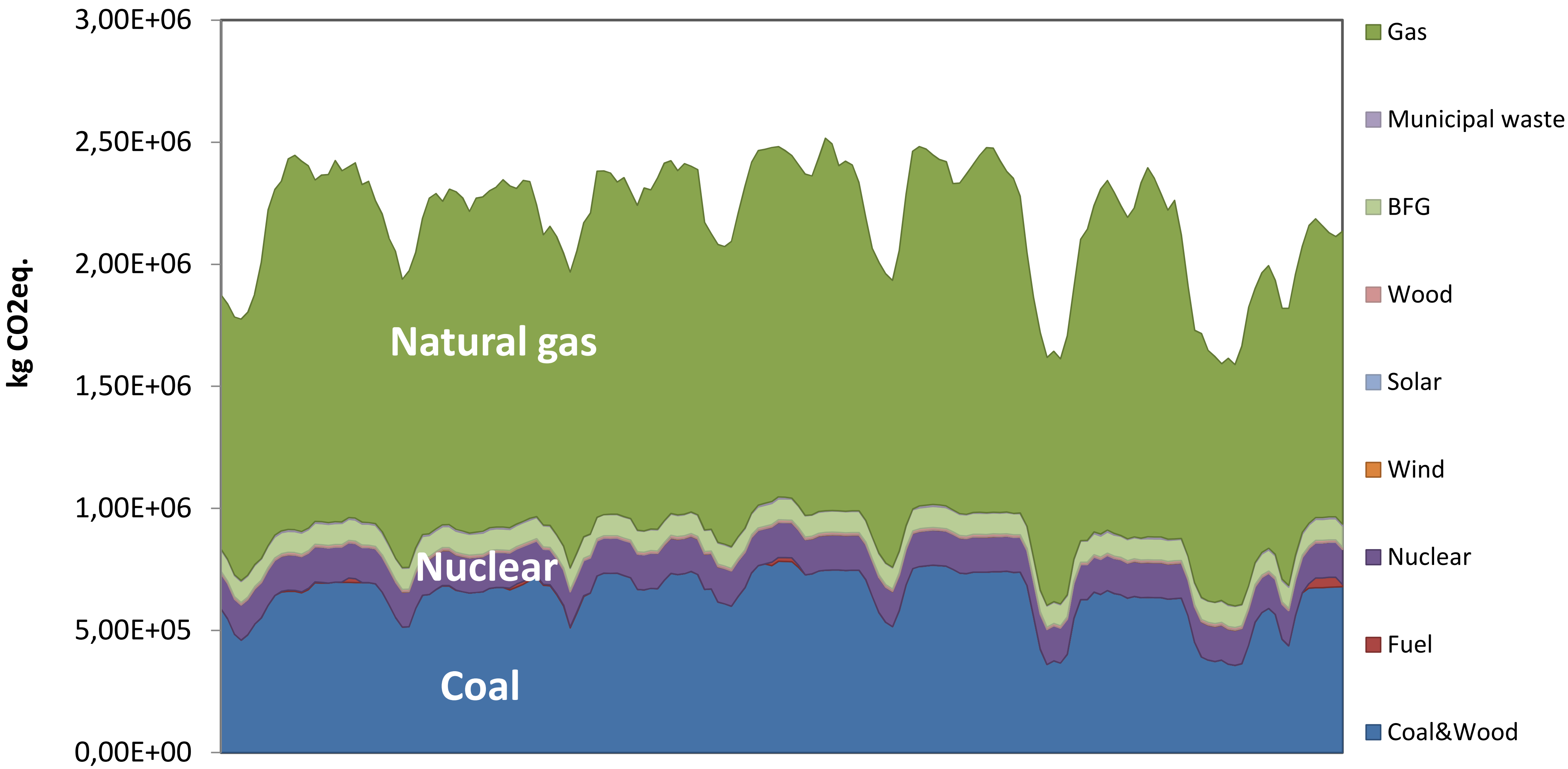
Hourly carbon footprint of electricity production



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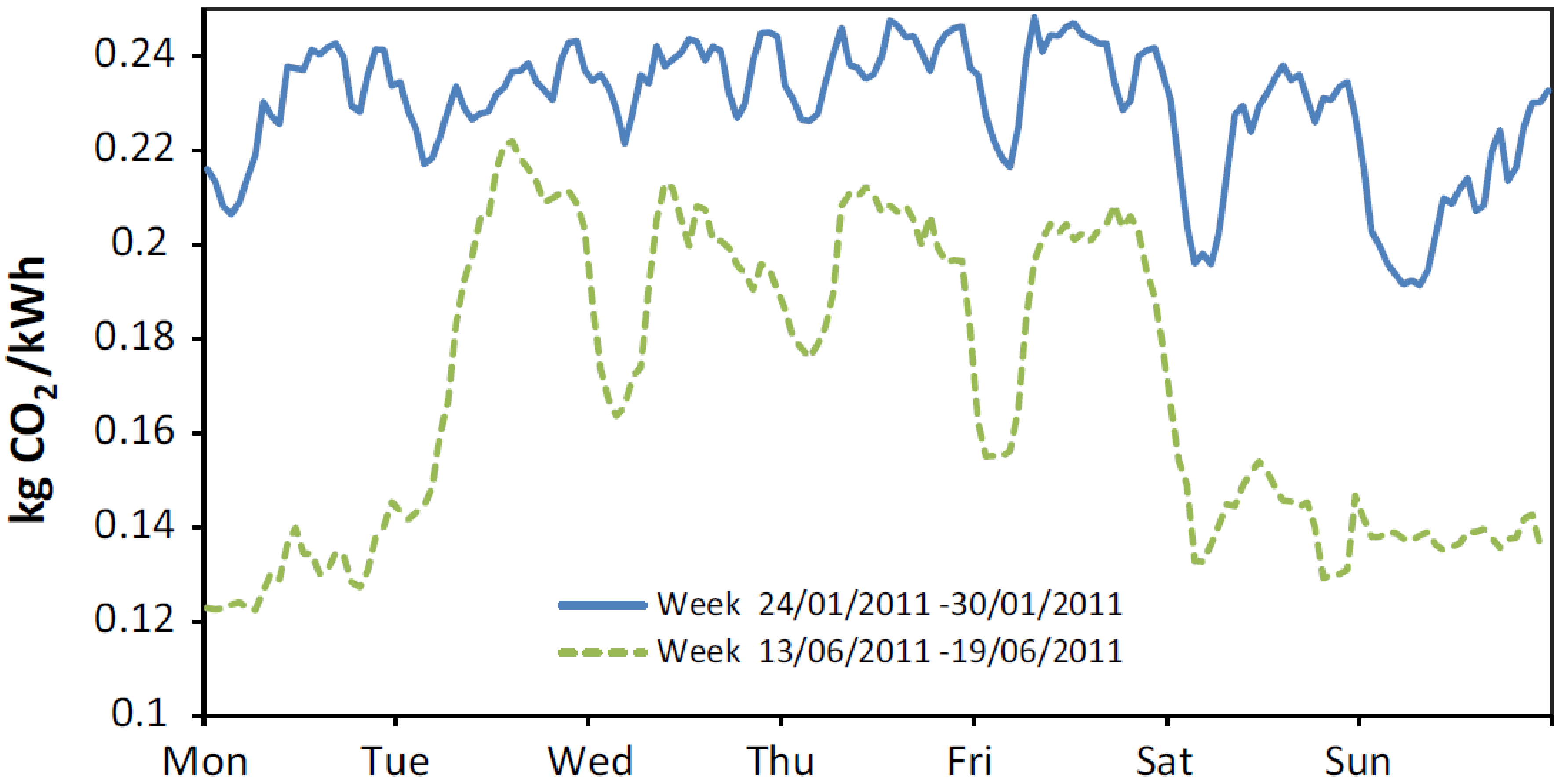
Hourly carbon footprint of electricity production in Belgium



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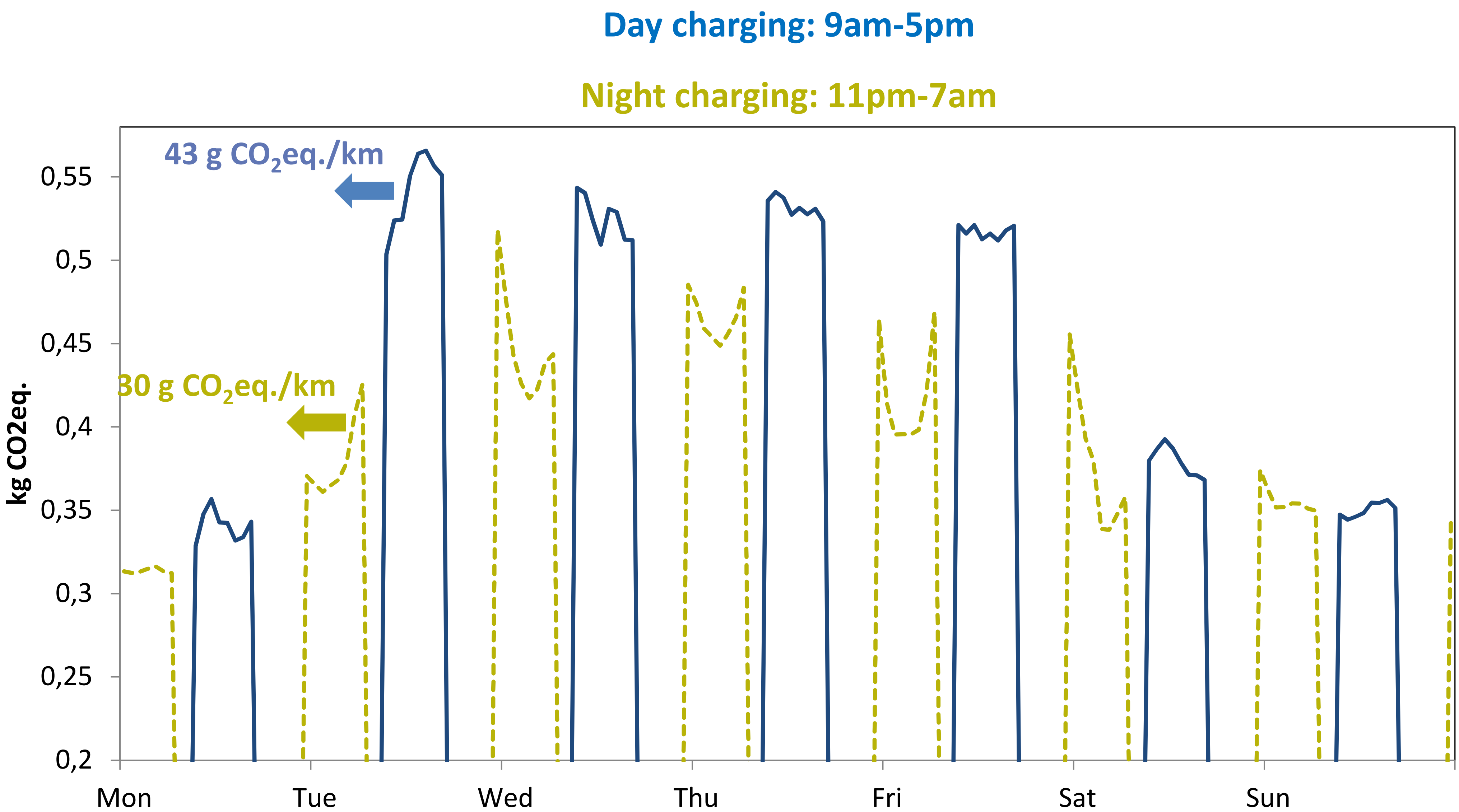
Day and night charging



Week 13/06/2011 - 19/06/2011

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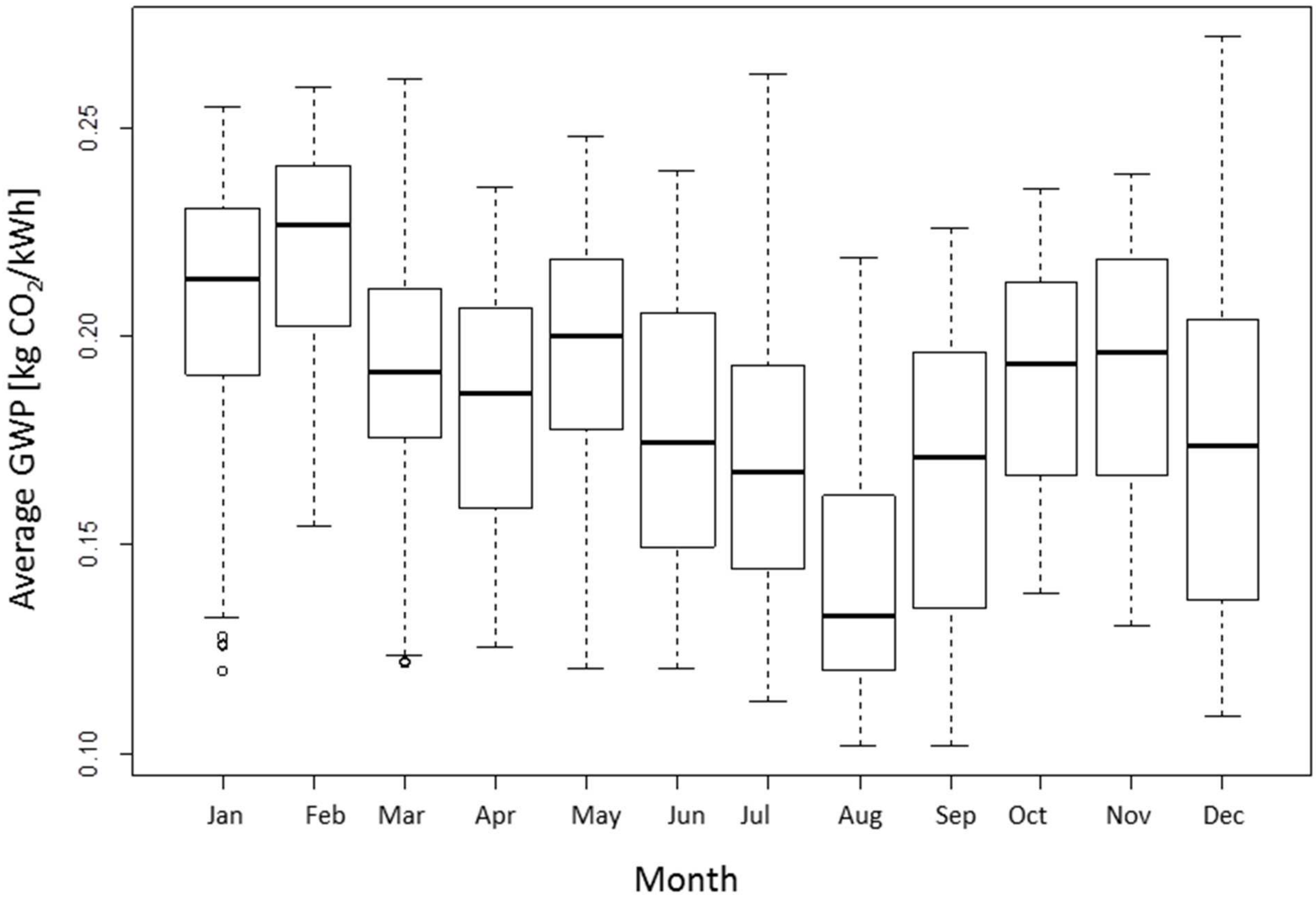
Monthly carbon footprint of electricity



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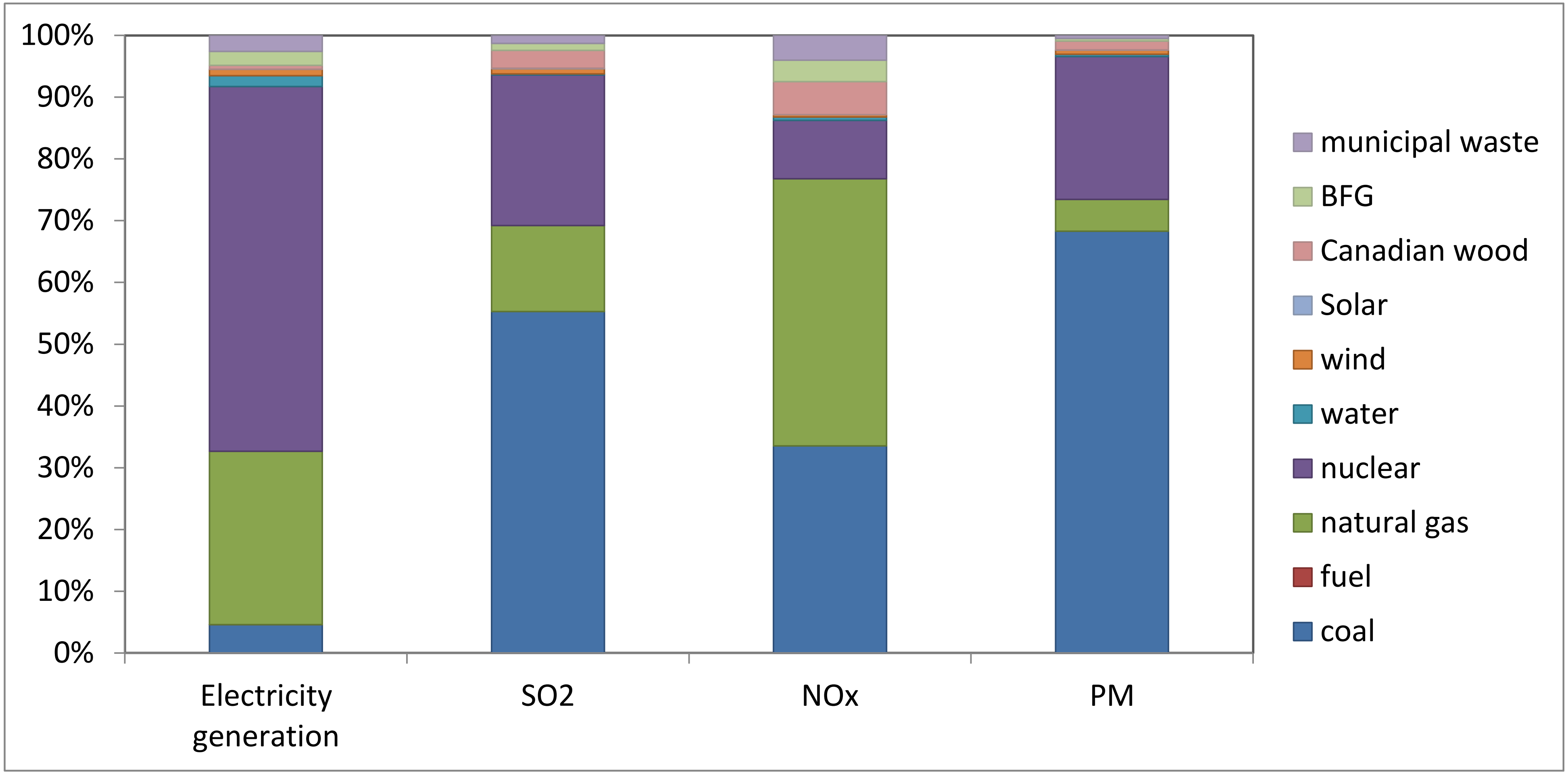
Hourly electricity production



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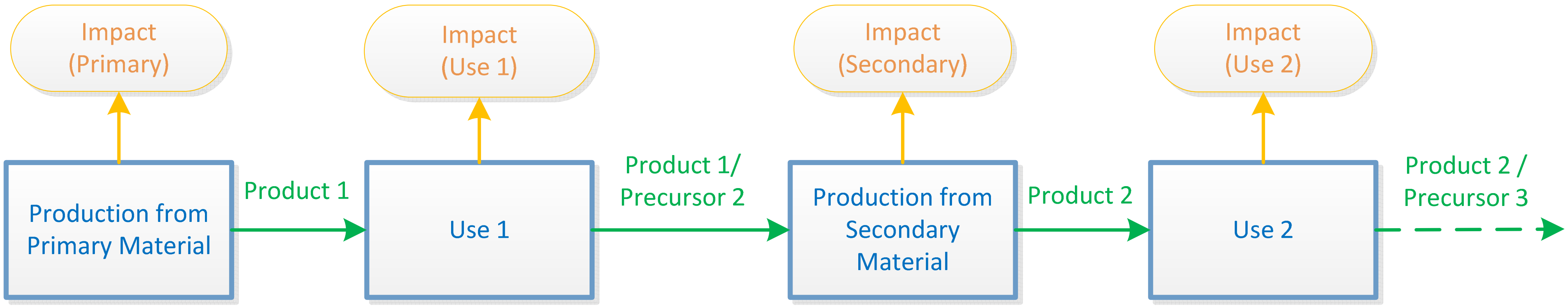
End of Life

End-of-Life Approaches

Sample Case: What actually happens

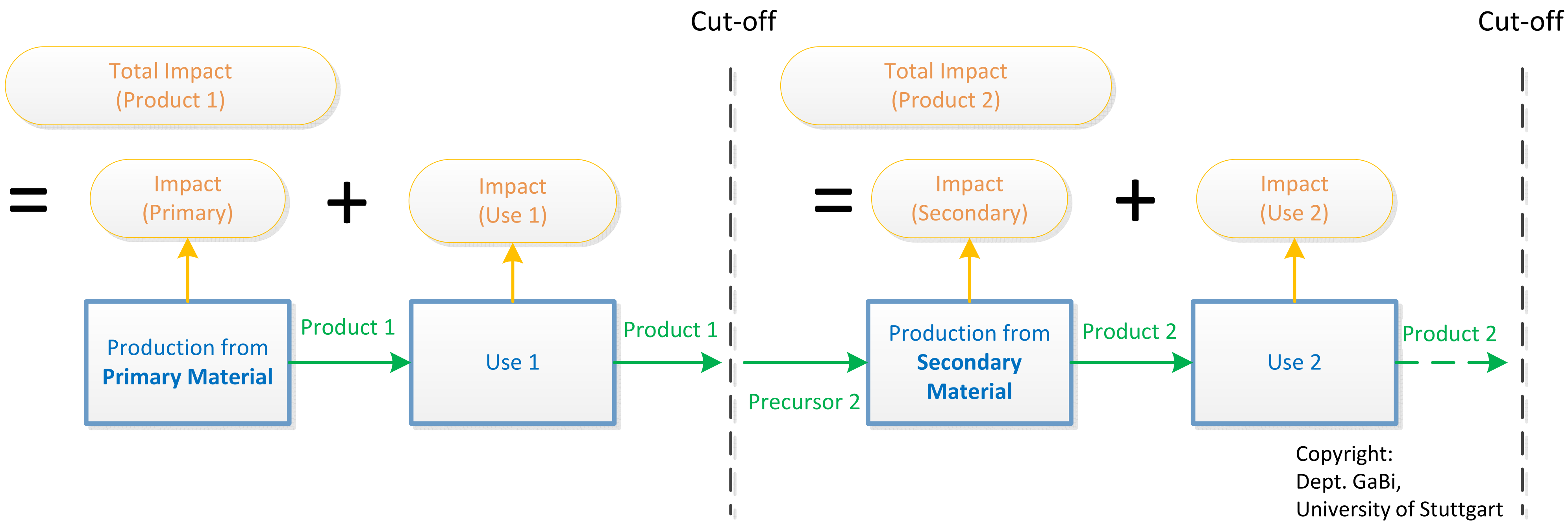


Three basic approaches:

- Cut-off approach (aka recycled content)
- Avoided burden approach (aka end-of-life approach)
- “burden sharing”

End-of-Life Approaches

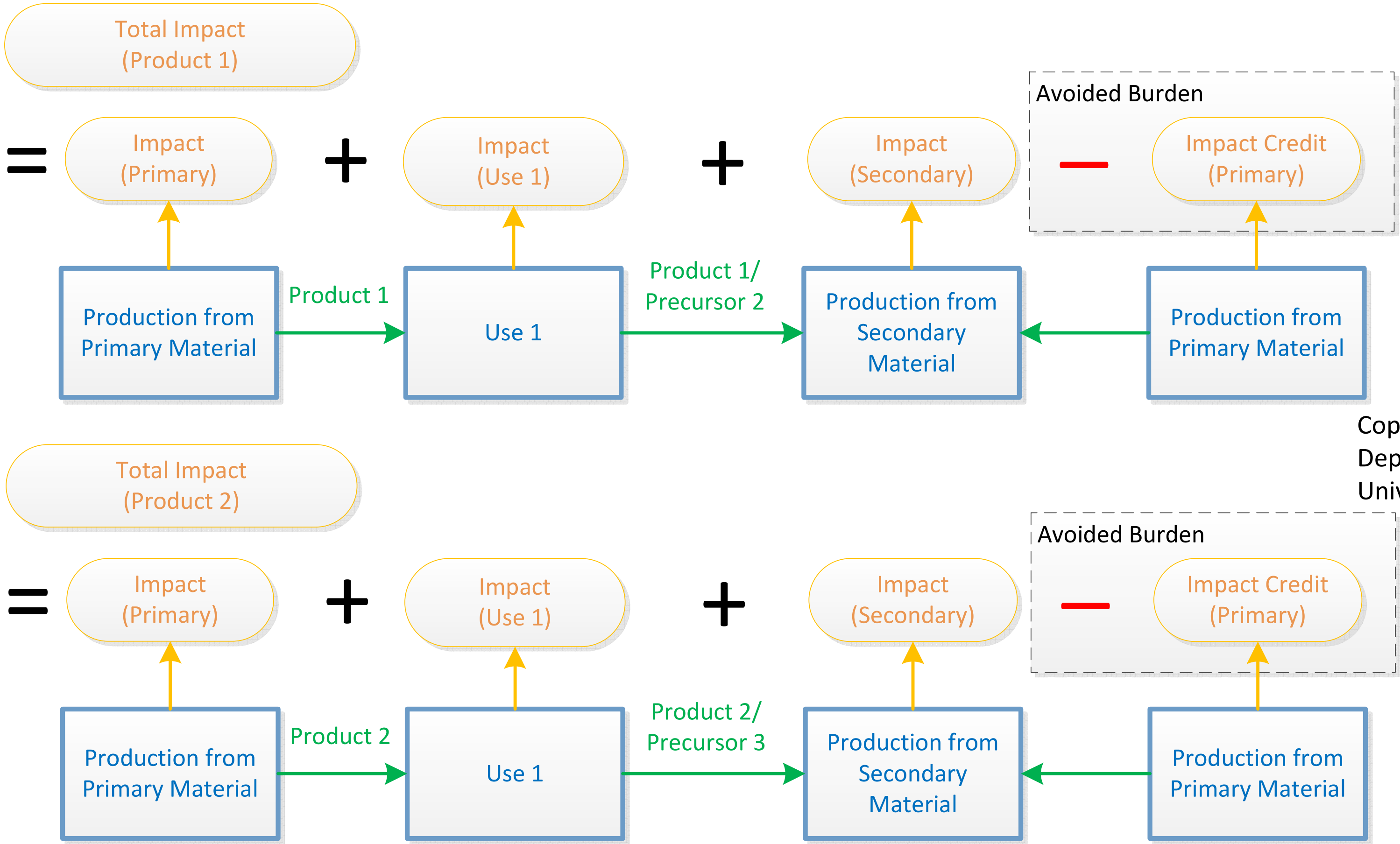
Sample Case: What „Cut-off“ calculates



- Burden free secondary material
- Source material focused (→ recycled content)

End-of-Life Approaches

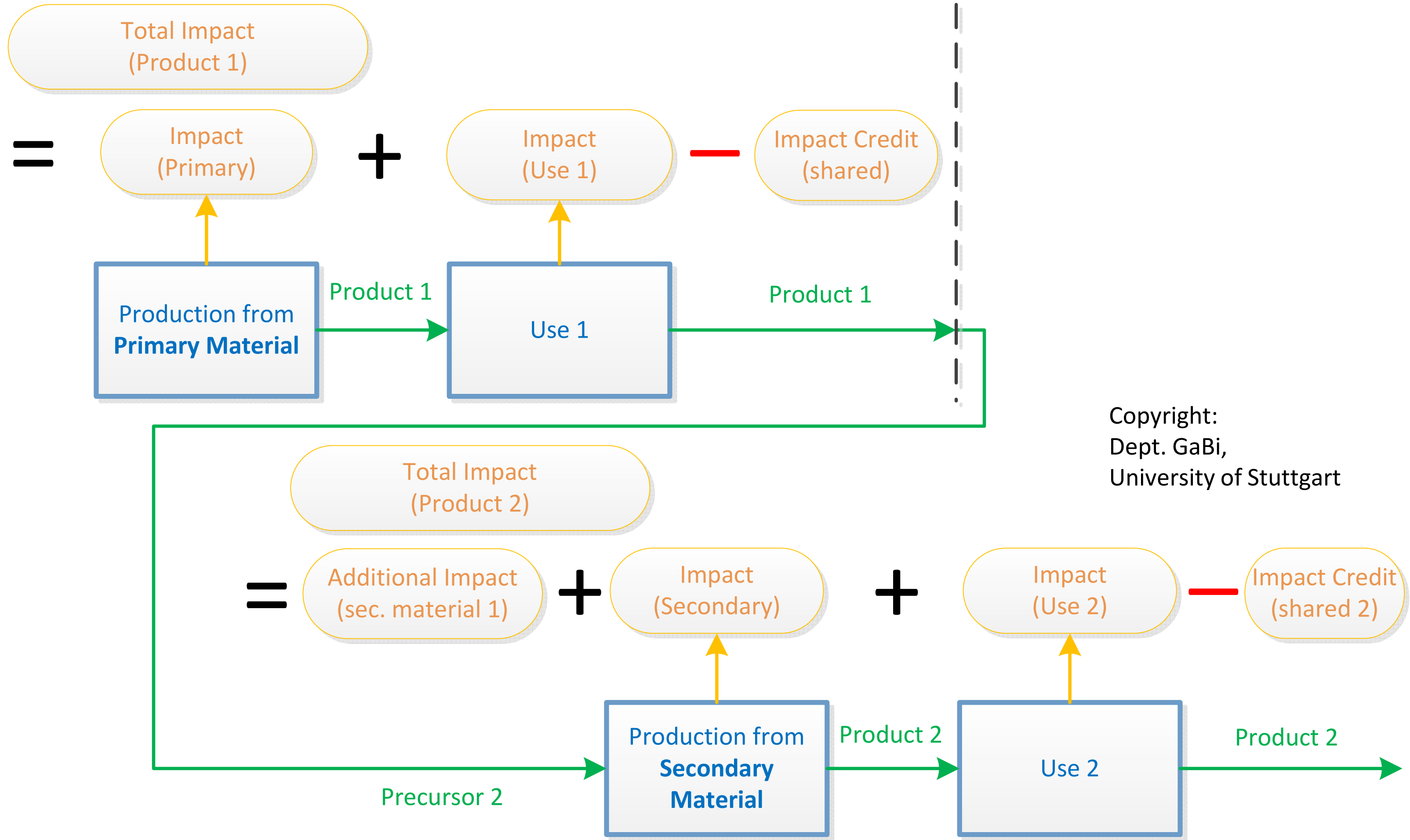
Sample Case: What „avoided burden“ calculates



- Assumption: all process inputs come primary sources
- End-of-life focused

End-of-Life Approaches

Sample Case: What „burden sharing“ calculates



- Burdened sec. material flows
- Product 1 and 2 share the credits for avoided primary production

End-of-Life Approaches

Conclusion

- None of the approaches is right or wrong in general
- Approaches can lead to different results for one particular case
- Reasonable selection depends on the goals of the analysis
- Particular implications of selection of a particular approach are complex and case-specific

Battery Recycling

- No information on large-scale recycling
- First results available from several studies
  - Libri (Li-Ion; UMICORE recycling process for active material recovery)
  - Lithorec (Li-Ion; recycling process for active material recovery)
  - Gaines (Li-Ion; UMICORE, Toxco, Eco-Bat recycling process for active material recovery)
  - DeWulf (Li-Ion; UMICORE recycling process for active material recovery)
  - SUBAT (various traction batteries, recycling potential of active materials)

→ First results can be used for estimations

Range-based vehicle-LCA
Uncertainty propagation in LCA

Why:
one single value ≠ robust

Inclusion of more data ranges:

- increases uncertainty
- decreases ignorance

Messagie, M., Boureima, F., Coosemans, T., Macharis, C., Van Mierlo, J. (2014) A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. ENERGIES Volume: 7 Issue: 3 Pages: 1467-1482

Uncertainty propagation in LCA

1. Sources of uncertainty and variability
2. Quantitative methods for uncertainty
3. An example of uncertainty propagation in vehicle LCA

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Sources of uncertainty

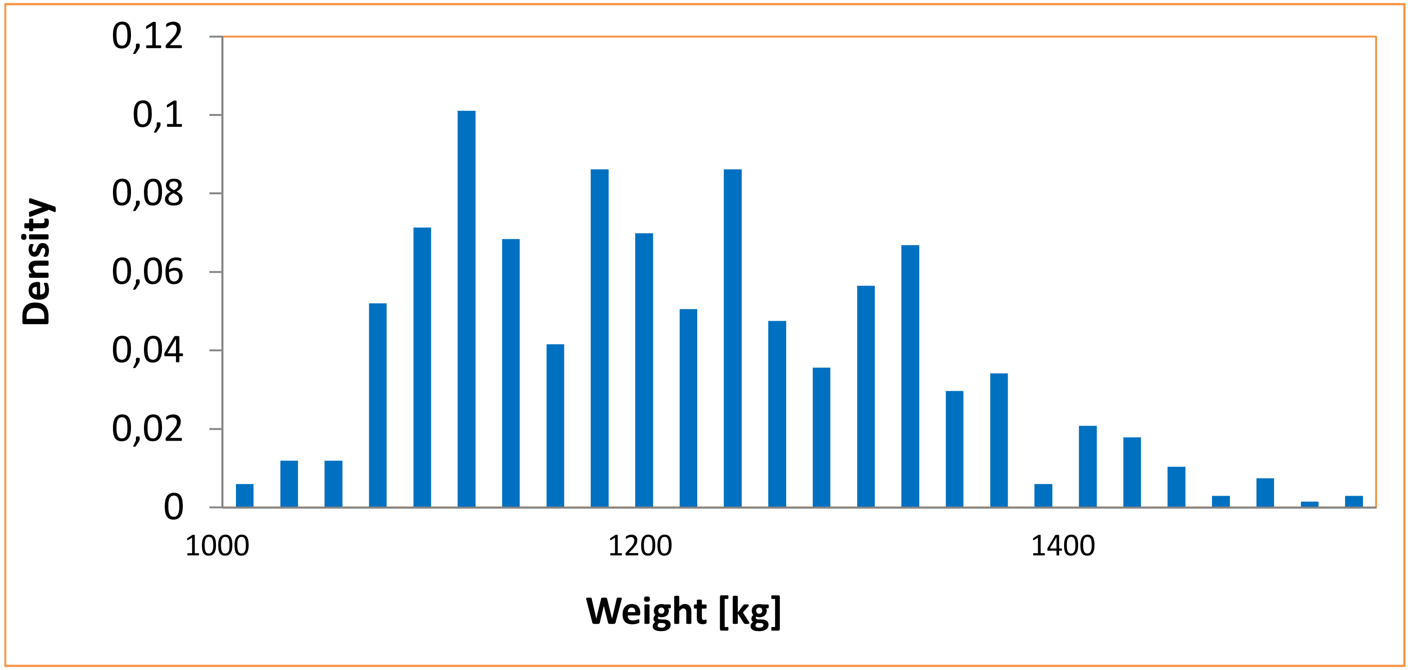
- **Parameter uncertainty:**
  insufficient knowledge of the true value of a parameter;
  (empirical inaccuracy, lack of data, market variability, …)

- **Modeling uncertainty:**
  uncertainty in life cycle impact assessment due to normalization, weighting and methodology;

- **Scenario uncertainty:**
  Choice based uncertainty: choice of functional unit, goal and scope definition, allocation procedures, future trends.

Sources of uncertainty

- Market variability (over 200.000 different vehicles)
- Differences between real life and NEDC
- Unrepresentative and inaccurate data
- Uncertainty in impact assessment



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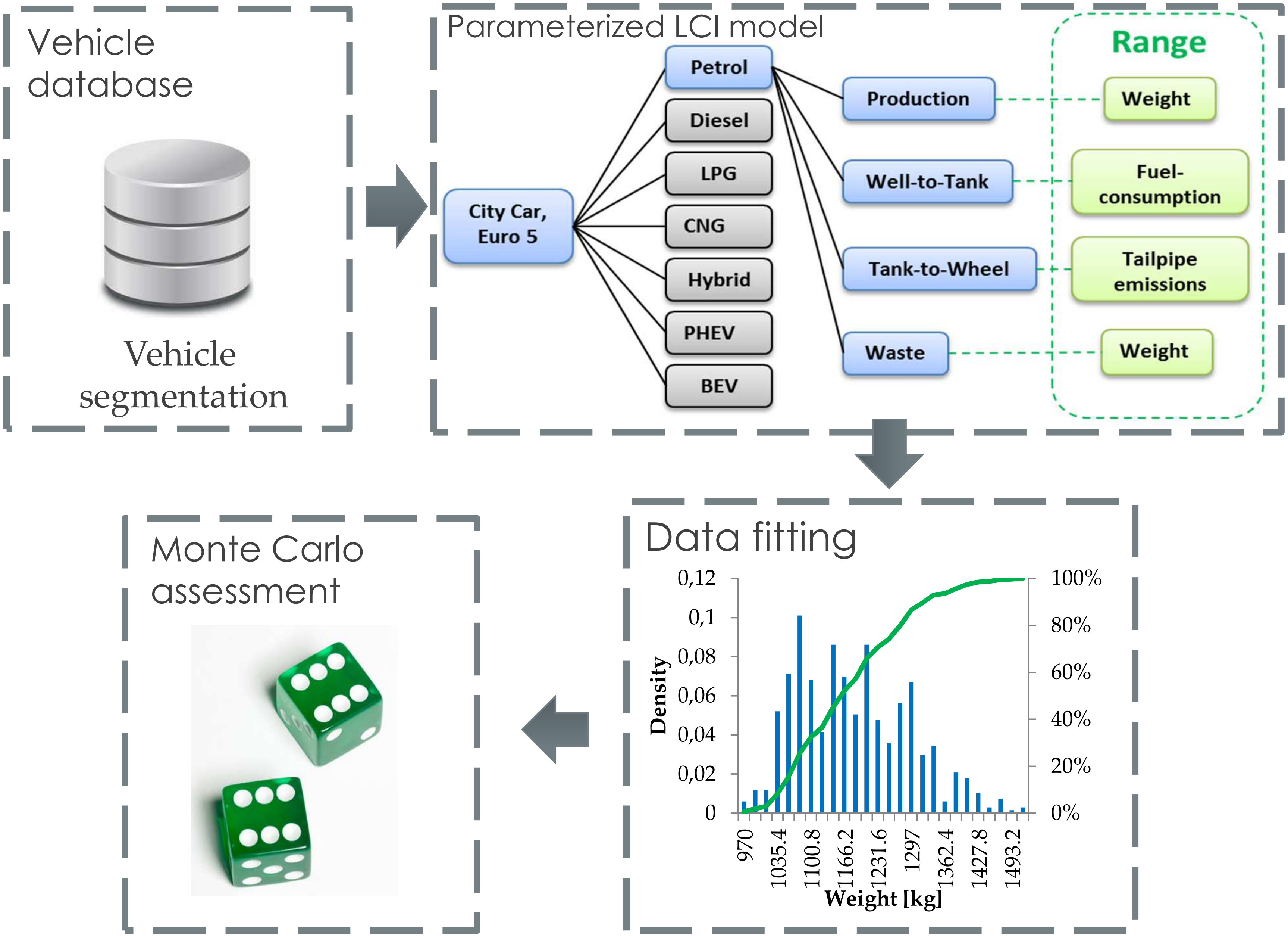
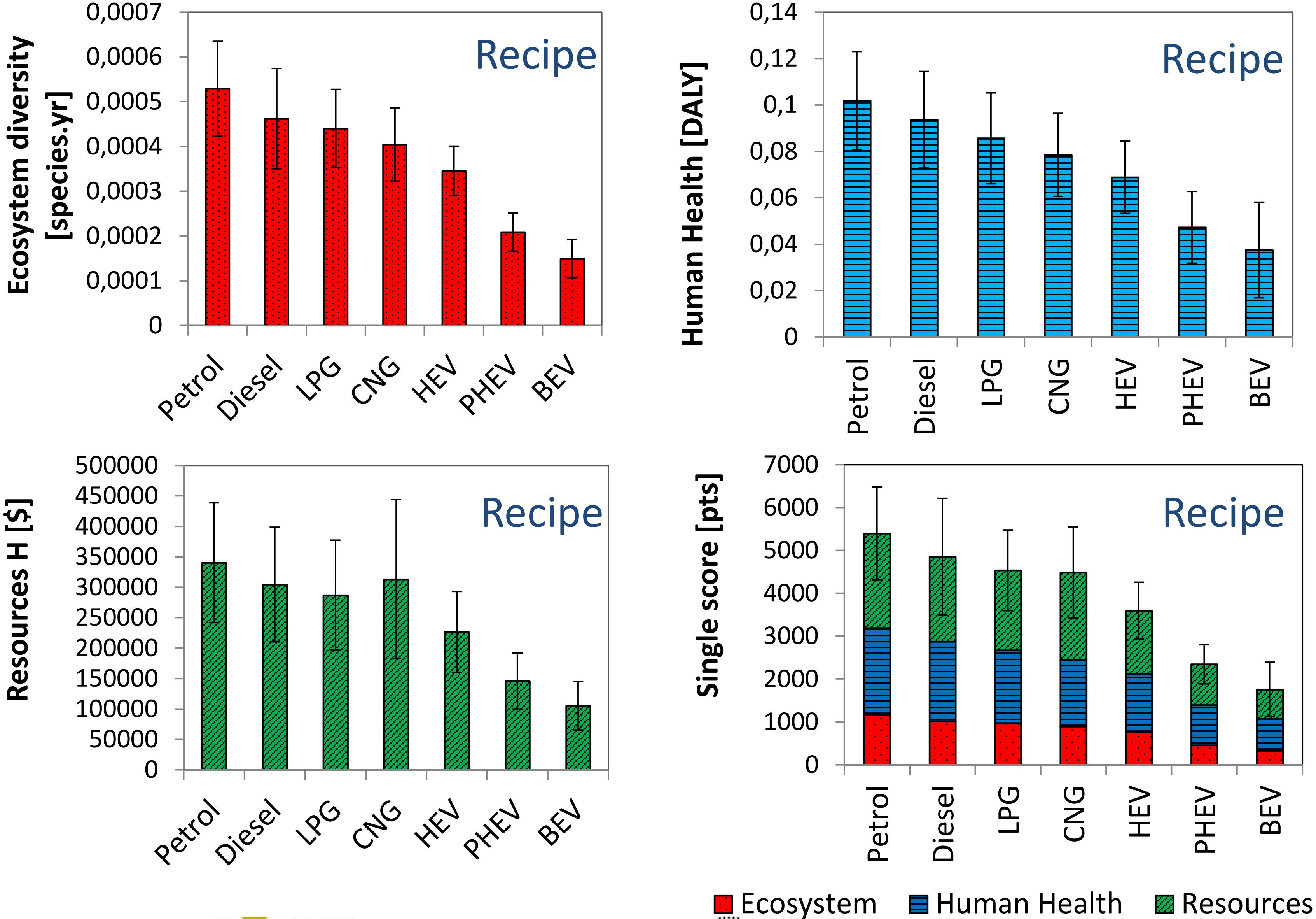
Quantitative methods for uncertainty



Uncertainty in vehicle LCA: an example

- Parameter uncertainty and variability
  - Market variability
  - Real life variability
  - Database unrepresentativity
- Modelling uncertainty
  - Impact methodology
  - Weighting factors (Multi-Criteria Analysis, MCA)
- Choice based uncertainty
  - Influence of electricity production
  - Influence of segmentation

Uncertainty in vehicle LCA: Impact category



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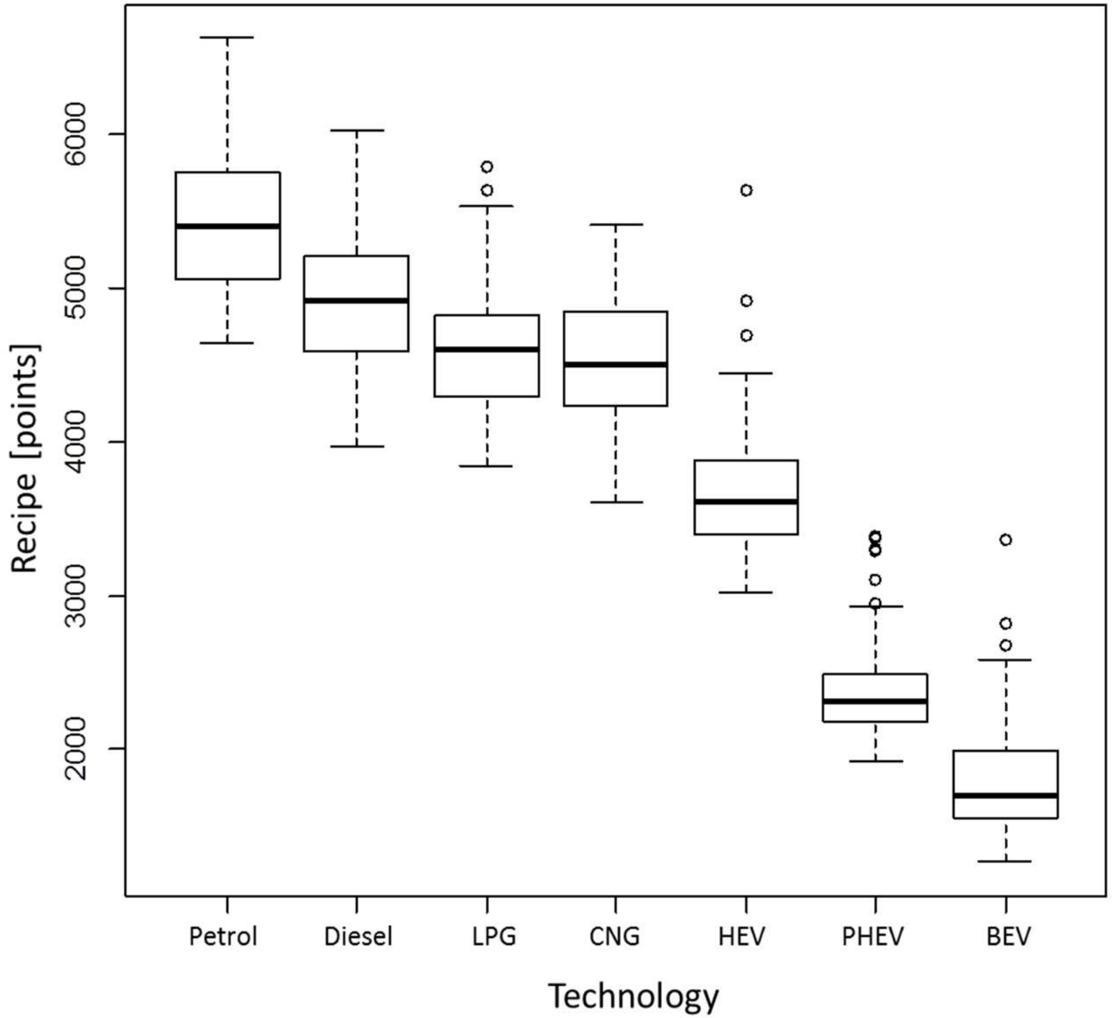
Uncertainty in vehicle LCA
200 000 km (14 years) passenger car



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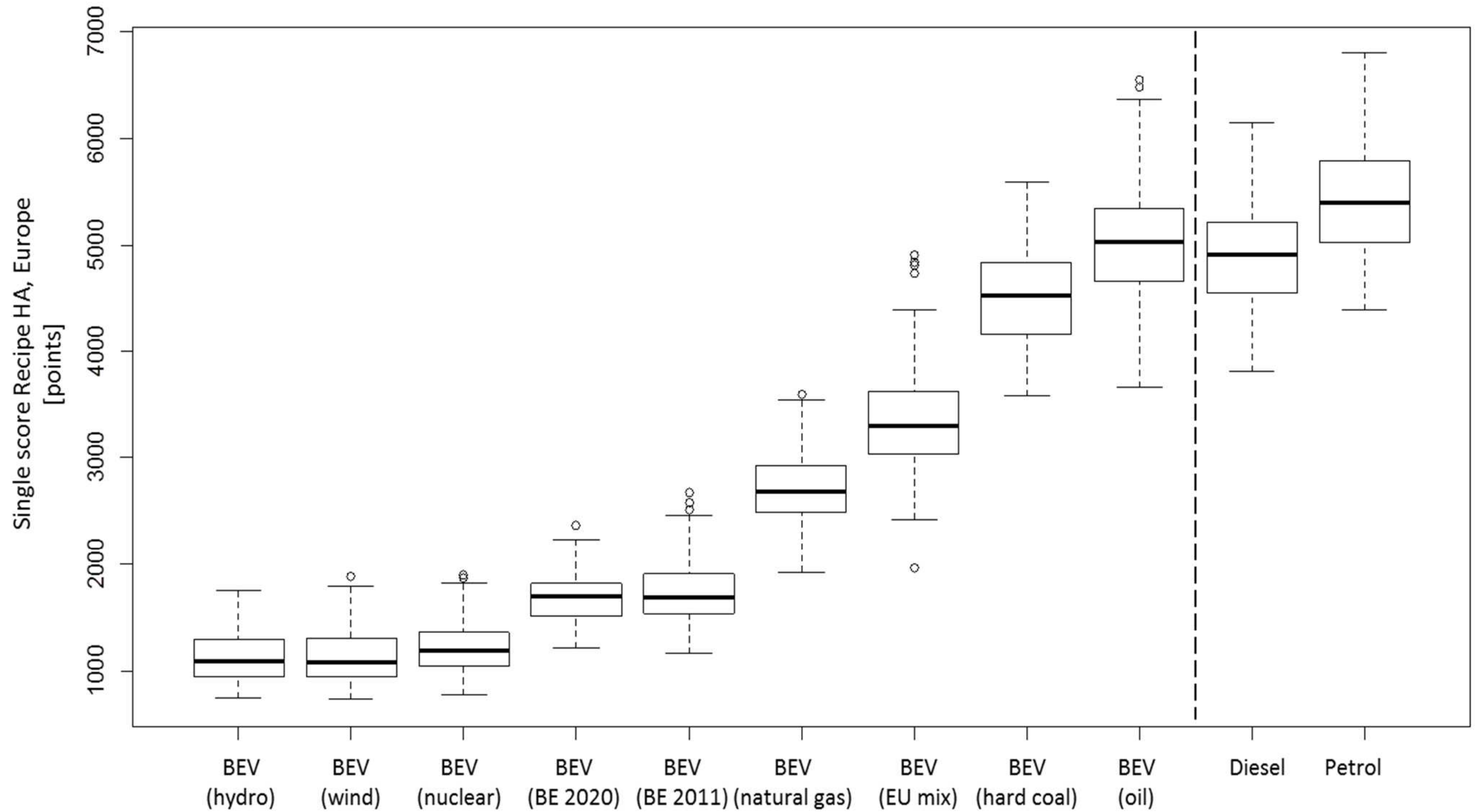
Uncertainty in vehicle LCA:
Influence of the electricity mix:



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Wrap up of tutorial and main conclusions

Conclusions

- Electric mobility
  - Climate change
  - Urban air quality
  - Fossil fuel depletion
- Trade-offs
  - Human toxicity (mining)
  - Mineral resource depletion (mining)
  - Radioactive waste (electricity production)
- Make your future

LCA => highlights opportunities

Conclusions: Relevant Indicators

- Power generation mix (share of renew. energies)
- Battery system: Technology, dimensioning and lifetime
- Production of required High-Tech materials (cobalt, graphite, rare earths, etc.)
- Vehicle and user specific driving profiles
- Total mileage

➢ Power train concepts are not directly comparable, as utilization profiles of vehicles might change

Discussion

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