Guide aLIFEca

Virtual open Course of Automotive Life Cycle Assessment

Co-funded by the European Union

1. GETTING STARTED

Transport accounts for one-third of all final energy consumption in the European Environment Agency member countries and for more than one-fifth of greenhouse gas (GHG) emission[1]. Transport is also responsible for a large portion of urban air pollution. It is the main cause of negative impact on human health and is associated with global warming. Important factor in reducing GHG emissions is the type of fuel used in transport[2]. The literature of the subject mentions individual methods used for assessment of environmental aspects, which can also be applied to the automotive industry. The LCA accounts for the environmental impacts throughout the vehicle life cycle, starting from the vehicle production phase (including manufacture of materials for vehicle production, vehicle assembly and fuel production), through the operation phase (including the fuel combustion phase and vehicle servicing), up to the life cycle end (waste management, including recycling and scrapping)[3],[4].

1.1 WHAT IS LIFE CYCLE ASSESSMENT?

LCA is the most mature technique considering the environmental dimension of products and technologies. It is in fact a methodology used to identify, characterise and assess environmental impacts across a product's entire life cycle from raw material extraction ('cradle') to final disposal ('grave'). LCA makes it possible to compare the environmental aspects of different products as well as technological solutions, and to choose products or solutions having the smallest environmental impact throughout their life cycle.

Governments all over the world are faced with the transition to sustainable mobility and renewable energy. The shift to green mobility causes the unprecedent transformation of the Automotive Industry and overall ecosystem restructuralization. New jobs are created to replace the ones lost in the fossil fuel industry. For these new jobs, qualified personnel will be needed. The analytics-related skills and environmental awareness will become a must to stand out as an employee or job candidate for all qualified positions in automotive and

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[1] Rievaj V, Synák F. Does electric car produce emissions? Scientific Journal of Silesian University of Technology. Series Transport. 2017; 94: 187-197

[2] Transport White Paper, 2011. Roadmap to a Single European Transport Area e towards a Competitive and Resource Efficient Transport System. European Commission Brussels, 28.3.2011, Brussels, Belgium. COM(2011) 144 final.

[3] Burchart-Korol D., Jursova S., Folęga P., Korol J., Pustejovska P., Blaut A. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic, Journal of Cleaner Production 2018, 202, p. 476-487

[4] Moro A., Helmens E., A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles, The International Journal of Life Cycle Assessment. 2017, vol. 22, issue 1, pp 4

all kinds of related industries and services. Life Cycle Assessment (LCA) as an accurate way to measure the environmental impacts of the automotive sector. Sustainability is one of the top priorities for the automotive supply chain.

1.2 WHO IS MOOC ALIFECA FOR?

The course is for everybody interested in the LCA, automotive and its transfer to green non-fossil technologies. It is particularly for tertiary or secondary students who present future green workers in automotive. Besides, MOOC aLIFEca would be useful for managers and engineers dealing with sustainability topics and future product development. Anyway, we cannot forget about entrepreneurs interested in environmentally sustainable innovations and last, but not least, lecturers, trainers, teachers who can use the course aLIFEca MOOC created within the project for their trainings, lectures and lessons.

MOOC aLIFEca reflects the needs of today’s fast growing automotive and also needs of the target group thanks to National MOOC Workshops arranged in each partner’s country. The pilot target group’s feedback has been implemented in the training. The moderation of the course during National MOOC workshop contributed to adapt the course to its students' understanding.

You can be sure that MOOC aLIFEca is tailored on your own needs according to the current trends of automotive labour market. The course is based on the study of todays’ automotive sector (see Project Result PR 1.1).

1.3 WHAT DO YOU NEED TO KNOW BEFORE YOU START MOOC ALIFECA?

You should have basic knowledge of the environment protection and basic terms of automotive. Neither general knowledge about combustion fuelled vehicles, electric vehicles or fuel cell electric vehicles is necessary because the theory about it is also included in MOOC aLIFEca and aLIFEca Guide. All the details relating to Life Cycle Assessment and its application on automotive sector is explained in the course.

The course is designed as Massive Online Open Course (MOOC) which is available free of charge with an online approach. MOOCs represent innovative teaching and learning in their own character, being run online, aimed at unlimited participation worldwide and open access via the web. MOOCs deliver in an online environment, free and open classes to anyone who registers regardless of their skin colour, religion, age, gender, medical condition or even previous education or qualification. The course MOOC aLIFEca is open to anyone, regardless of whether or not they have studied before. You can simply follow the course at their own pace, taking as much time as you need.

1.4 WHAT DO YOU LEARN AND WHAT DOES MOOC ALIFECA BRING TO YOU?

Graduated from the course, you will be aware of Life Cycle Assessment. You will find out what this analysis includes and how to apply it on automotive sector. You will learn about environmental impact of conventional and green mobility technologies. And what is the most significant, using LCA you will know how to compare the products, technologies and services in view of their impact on the environment. For your future career, you will gain a greater advantage in your job search.

The course is structured and tailored on your future career needs in green automotive. The course is prepared on base of requirements of automotive labour market shifting to green mobility and fully reflects the labour requirements of this industry for its workers. The course results from requirements of todays' automotive industry for sustainability job roles summarized in Project Result PR 1.1. On the background of this study, the whole course is prepared to be up-to date following the latest trends and cutting technologies in the automotive. The course MOOC aLIFEca is divided into 5 sections – chapter 1 Getting started, you are reading now, with general information about the course, prerequisites for the enrolment at it and 4 theoretical chapters. Each chapter is composed of theoretical background introducing the topic which is followed by additional materials such as case studies, videos, articles, etc.

CHAPTER 2: INTRODUCTION TO SUSTAINABILITY AND LCA

You will learn the main pillars of sustainability and LCA methodology. In the chapter a sound background on the topics from a theoretical perspective is explained. You will learn how to define system boundaries and what approaches are used for it. They will get familiar with terms such as environmental aspect, impact, LCA impact categories and environmental footprints. Four main stages of LCA will be presented and you will learn how to follow them. The theory will be supported by means of practical examples to help students framing concepts into a practical perspective. The chapter guarantees the acquisition of those technical skills that will help you in future professional careers related to LCA, and in particular within the automotive industry.

The chapter was prepared by SPIN 360, SRL – an Italian advanced and innovative consulting company whose overall mission is to support innovation and development strategies for enterprises and whole industrial sectors in the fields of employment, training, sustainability and Corporate Social Responsibility, EcoDesign of processes and products and supply chain management.

CHAPTER 3: LCA IN AUTOMOTIVE: CONVENTIONAL FUEL VEHICLES

You will be introduced to theoretical information about internal combustion engines through a description of their development and an explanation of the principles of their operation. The currently permitted emission limits are shown in view of the nowadays European emission regulations for passenger cars, light commercial vehicles, trucks and buses. Within the chapter various methods of fuel consumption measuring are presented based on driving cycles. The chapter includes a case study on Life Cycle Assessment of conventional fuel vehicles which presents a comparative study of ICEV – diesel and ICEV – petrol. Finally, the theoretical knowledge is supported by examples of the results of specific measurements of consumption and production of greenhouse gases of passenger car, bus and train in real operation. The chapter guarantees the acquisition of technical skills to better assess the advantages or disadvantages of using a particular means of transport (vehicle) on the basis of its technical characteristics and the type of fuel. The chapter develops skills and knowledge how to protect the environment in terms of energy consumption and greenhouse gas emissions.

The chapter was prepared by University of Zilina – one of the most significant educational institutions in Slovakia. It has a long tradition with focus on technical and transport studies. The university is divided into 7 faculties including the Faculty of Operation and Economics of Transport. The main goal of its activities is transport and all modes of transport operational technologies. The Faculty works intensively in engineering, technology, business and trade.

CHAPTER 4: LCA IN AUTOMOTIVE: ALTERNATIVE FUEL VEHICLES

The chapter deals with application of alternative fuels in automotive. At its beginning, it presents a theoretical background relating to electric vehicles, fuel cell electric vehicles and their LCA. It presents details on a computational model of environmental footprints. Besides, the chapter includes case studies on these vehicles LCA. The analysis LCA is presented within the chapter in the form of case studies with real operational data. There are presented results depending on various energy mix where the vehicles are operated.

The case studies are presented for several types of alternative fuel vehicles such as battery electric vehicles and fuel cell electric vehicles. The LCA of battery electric vehicles is presented on example of Poland and its energy mix. Then, the LCA of electric vehicle battery charging for every EU country is introduced. The fuel cell electric vehicles are analysed with hydrogen exploitation from coke oven gas, a secondary gas generated in metallurgy industry and rich in hydrogen. It is compared with hydrogen from different sources. The final case study sums up a comparative life cycle analysis of petrol, diesel and battery vehicles. You will acquire knowledge about application of life cycle assessment LCA in automotive, specially LCA of alternative ones.

The chapter was prepared by the Silesian University of Technology (SUT) which is the oldest technical university in Upper Silesia, one of the largest in Poland and only one in Silesia to be included in the prestigious group of 10 Polish universities. The SUT has 13 faculties and 2 institutes including the Faculty of Transport and Aviation Engineering aimed at research and development in the field of development of alternative fuels and environmental life cycle assessment methods and development sustainability transport models.

CHAPTER 5: TOOLS FOR LCA AND ENVIRONMENTAL IMPACT ASSESSMENT

You will acquire knowledge about different LCI databases and several LCA software tools which can be used for LCA analysis. It presents an overview of available software tools for LCA and then the chapter is specialised in the most common ones such as SimaPro, Gabi, Umberto and mentions also the most used free one. OpenLCA.

The chapter is prepared by Scoveco - an experienced small enterprise that helps to transfer the knowledge and know-how directly to the people in industry and build innovative solutions. After 10 years of experiences, the company has established processes, elaborated many successful projects and established strong network. SCOVECO's main focus in on consultation, training and coaching of Automotive companies and also support that work with development of IT solutions and own tools.

1.5 ASSESSMENT AND CERTIFICATION FRAMEWORK

After successful MOOC aLIFEca completion, a certificate or a digital badge is offered as a recognition of skills level achievement. The scheme below shows the global grading of MOOC aLIFEca. You can obtain a total of 100 points by doing the graded activities in the different chapters. Chapter 1 does not contain any graded activities, chapters 2 – 5 contain 80 points. You can earn the remaining 20% by completing all the chapters and fulfilling all their activities. Once successfully graduated, you will receive a certificate to prove the successful completion of MOOC aLIFEca. The passing grade for MOOC aLIFEca is 60%. The successful graduates can be offered by a certificate or a digital badge.

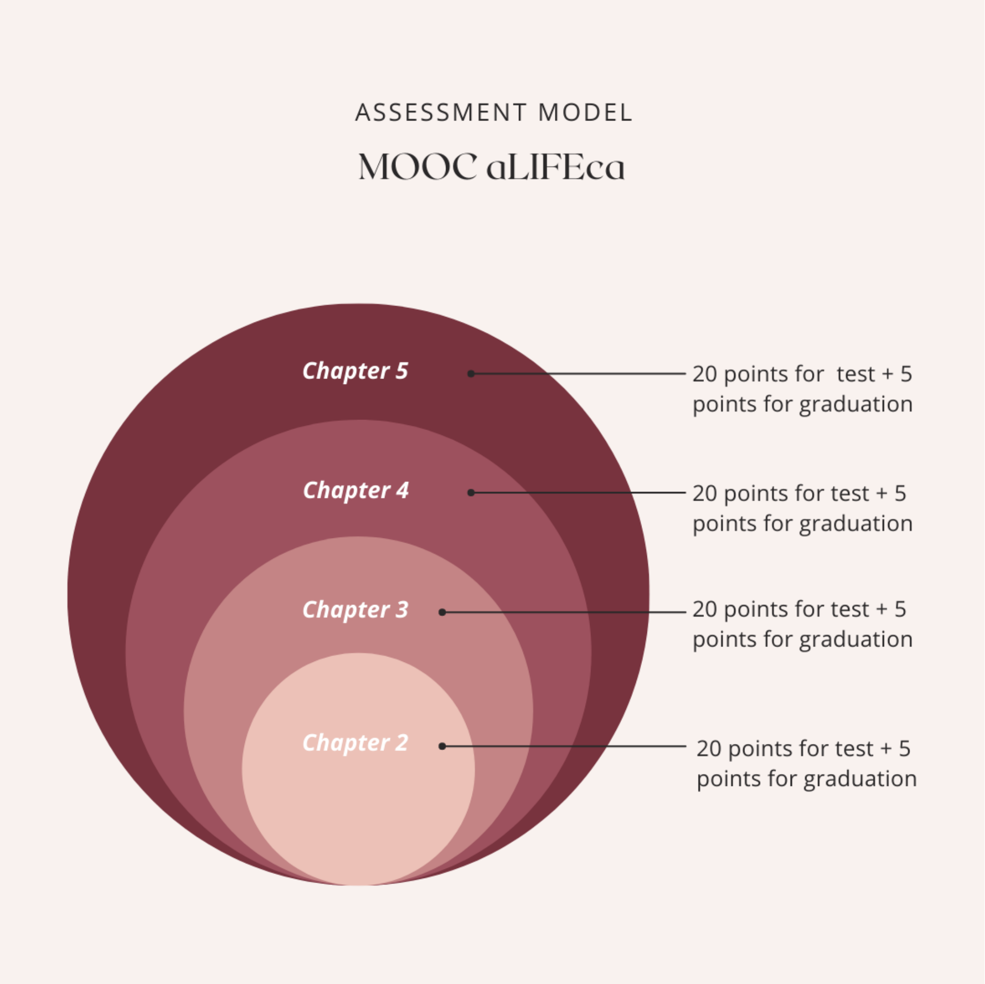

Figure 1: Assessment model of certification framework to gain a certificate or a digital badge

CERTIFICATE

You will gain a certificate after successful completion of MOOC aLIFEca if you pass the course at minimal 60% grade. The certificate will indicate that you have successfully completed the course, but will not include a specific grade. The certificate will be issued under name of project aLIFEca consortium, designating the institution from which the course originated.

DIGITAL BADGE

The digital badge will be issued after the course to all registered and verified participants who have achieved at least 60% of the total grade. This kind of certificate will include a grade which you achieved at the end of MOOC aLIFEca. The digital badge will be able to be downloaded from you Student Account. Check that, in your account, your name is correctly spelled, since it will appear on the final certificate. Again, it will be issued under name of project aLIFEca consortium.

2. INTRODUCTION TO SUSTAINABILITY AND LCA

Time to study 120 minutes

Objectives

WHAT KNOWLEDGE STUDENTS WILL ACQUIRE:

After these lessons, students will be able to:

- Acquire better knowledge on the topic of sustainability and sustainable development
- Better frame the different dimensions of sustainability and their implications
- Gain an understanding of what Life Cycle Assessment (LCA) is and how it is composed of, as well as the main LCA standards of reference.

HOW THE CHAPTER WILL HELP THEM TO UNDERSTAND THE TOPIC:

Students will learn the main pillars of sustainability and LCA methodology thanks to the provision of sound background on the topics from a theoretical perspective. At the same time, theory will be supported by means of practical examples to help students framing concepts into practical perspective.

WHAT SKILLS THE CHAPTER WILL DEVELOP

The chapter guarantees the acquisition of those technical skills that will help students in future professional careers related to LCA, and in particular within the automotive industry.

WHERE THE STUDENTS CAN USE THE KNOWLEDGE

Students can use the knowledge in their future work related to environmental protection and environmental impact assessment within the automotive industry.

Theory

2.1 FRAMING SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

The word “sustainability” is one of the most used words of our times. This concept has progressively gained huge global attention in the 21st century, but the discourse around sustainability brings us back to the late 20th century together with the definition of "sustainable development". On March 20, 1987, The Brundtland Report (also known as Our Common Future) was released by the World Commission on Environment and Development (WCED). The name was given by the coordinator Gro Harlem Brundtland, who in that year was the president of the WCED. Such document frames, for the first time, the concept of sustainable development as:

“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[5]

To such definition, we can also add the more general meaning of sustainability as “capable of being maintained in existence without interruption or diminution”. This is clearly broad in terms of fields of application: sustainable development is conceived as the commitment to meeting the basic needs of all, and extending to all the opportunity to satisfy their aspirations for a better life. There is not the sole environmental dimension, but rather to an ethical principle that *encompasses* also the environment. Therefore, within the concept of sustainability and sustainable development, several dimensions can be taken into consideration.

It is already evident through the above simple definition: sustainability is an **inherently complex phenomenon**. Understanding what sustainability is and how we can purse sustainability means integrating different spheres of action but at the same time being careful on how these spheres (or dimensions) are taken into account.

From 1987 to the present days, several commitments have been adopted by the international community to set environmental standards, guidelines and goals to pursue

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[5] United Nations, Report of the World Commission on Environment and Development: Our Common Future, 1987.

sustainability. One of the most recent and known is the 2030 Agenda for Sustainable Development and the 17 Sustainable Development Goals (SDGs) adopted by The United Nations General Assembly in 2015. With the vision leaving no one behind, the 2030 Agenda represents a global development strategy tackling action on people, planet, prosperity, peace and partnership. The 2030 Agenda stresses even strongly the need for an integration of the different spheres of sustainability. Traditionally, they are defined as environmental, social and economic but the interrelation among them creates even more sub-dimensions to be considered. However, "how" to integrate this multidimensionality is still not entirely clear; and it is this difficulty that often leads to inevitable trade-offs, where a dimension needs to be sacrificed for the benefit of the other.

Hence, if we want to better frame the concept of sustainability, the following statements need to be considered:

1. Sustainability is the most important issue that man shall address
2. Sustainability is complex
3. Sustainability is described by several different parameters and indicators
4. Sustainability is science-based
5. Sustainability can be measured
6. Sustainability has nothing to do with communication and marketing tools
7. Sustainability is not well understood by the majority of consumers
8. Sustainability shall be inherent to the system or activity, and cannot be added afterwards

2.2 ENVIRONMENT, ECONOMY AND SOCIETY: TOWARDS A HOLISTIC APPROACH

As previously evidenced, the 2030 Agenda commits the global community to "achieving sustainable development in its three dimensions—economic, social and environmental—in a balanced and integrated manner" [[6]]. But these concepts where already part of the international debate, as evidenced by the 2005 World Summit [[7]], thus

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[6] United Nations Department of Economic and Social Affairs (2015), Transforming our world: the 2030 Agenda for Sustainable Development https://sdgs.un.org/2030agenda , last accessed February 2022

[7] https://www.who.int/hiv/universalaccess2010/worldsummit.pdf

enabling the introduction of such dimensions in many subsequent national standards and certification schemes.

In fact, it is not possible to achieve a particular level environmental, social, or economic sustainability without considering at least a basic level of all three forms simultaneously, in other words, a holistic vision of sustainable development (Figure 2)

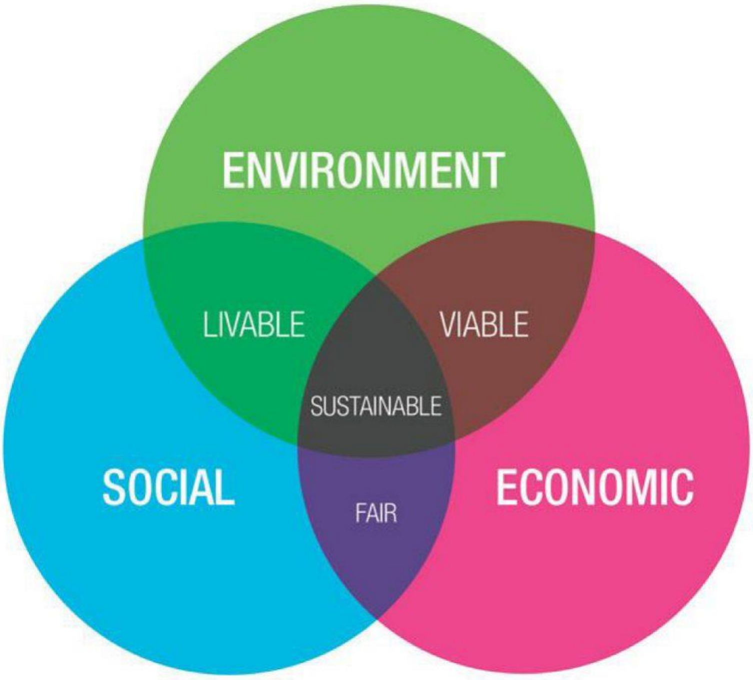

Figure 2: The three dimensions of sustainability

ECONOMY

The measure of the size and health of a country's economy is commonly determined by the Gross Domestic Product (GDP). GDP is the monetary value of the final goods and services produced within a country over a certain period of time (usually a year). It gives an economic snapshot of a country, used to estimate the size of an economy and growth rate. The GDP considers all transactions as positive, so that become part of it also damages caused by pollution, natural disasters etc. (for example: if you buy a car the GDP grows, if you have an accident, the GDP grows as well). In this way, the GDP does not make distinctions among the activities that include well-being and those that may hamper it.

Over the years, many indicators alternative to the GDP were introduced. An example is the Genuine Progress Indicator (GPI), a national-level measure of economic growth and prosperity. The GPI aims to measure the increase in the quality of life (which is sometimes in contrast with economic growth, which is instead measured by GDP) by distinguishing positive expenses (which increase welfare, such as those for goods and services) and negative ones (such as the costs of crime, pollution, road accidents). The GPI integrates therefore environmental aspects, from the perspective of green or social economics.

Similarly, the Green Gross Domestic Product (green GDP) is an index of economic growth that takes into account the environmental consequences of this growth. Green GDP monetizes biodiversity loss, and accounts for the costs caused by climate change.

The economic dimension of sustainability therefore takes into account the capability of developing a responsible economic system that guarantees, for example, optimal energy use, as well as providing incentives for businesses and other organisations to adhere to sustainability guidelines.

SOCIETY

The social dimension of sustainability takes into account the values that promote fairness and respect for individual rights, with a balance between the needs of the individuals and the needs of the group. In addition to the more traditional themes of social sustainability (such as poverty and employment) the community has also included new ones: social equity, diversity, social quality of life and integrated governance including corporate social responsibility (CSR) and hybrid business models [8]. Although CSR may be a more familiar term, the view that social responsibility is applicable to all organizations has recently emerged, as different types of entities recognized that they too had responsibilities for contributing to sustainable development and sustainability [9]. This involves of course welfare, quality of life and sustainable human development and includes human health and protection, environmental justice, access to education, equal opportunities.

A parameter that can be taken into consideration for a more holistic thinking of the three dimensions of sustainability is the ISO26000:2010 "Guidance on social responsibility". ISO 26000 aims at assisting organizations regardless size and location in contributing to sustainable development [9]. Although based on the concept of social responsibility, ISO 26000 is increasingly viewed as a way of assessing an organization's

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[8] Talan, A., Tyagi, R.D., Surampalli, Rao Y. (2020), "Social Dimensions of Sustainability", DOI: 10.1002/9781119434016.ch9

[9] https://iso26000.info/wp-content/uploads/2016/03/ISO_Sustainability_brochure.pdf

commitment to sustainability and its overall performance, since it entails core subjects and sub-requirements, as explained in Figure 3.

Figure 3: ISO 26000 core subjects

ENVIRONMENT

Environment is the third pillar but of course the primary concern of the future of humanity. Both the economy and society are constrained by the limits of the earth's ecosystems. As mentioned before, environmental issues have a preponderant role in the 2030 Agenda, and most of the SDGs targets include specific references to the link of the environment to other development priorities.

In more general terms, since 2000, the most urgent issues to be tackled within the environmental dimensions are of course climate change, loss of biodiversity, and pollution, especially plastic pollution; and human impacts on the atmosphere, land and water resources, working towards the ability to use natural resources without undermining the equilibrium and integrity of ecosystems.

Environment has therefore a direct impact on the economic and social aspects of sustainable development, and vice versa. Therefore, the need for a holistic thinking that underlines the interconnectedness between the three dimensions is even more crucial.

As underlined by UNESCAP (2015) [10], one approach could be that of thinking in terms of *multiple capitals*. In this model, five forms of capital are defined: manufactured, natural, financial, human and social capital. Balanced development through the recognition of the different forms of national wealth is at the heart of sustainability. In particular, the Daly Triangle refers to the different forms of capital and recognizes that each form contributes to human well-being in unique ways (Figure 4).

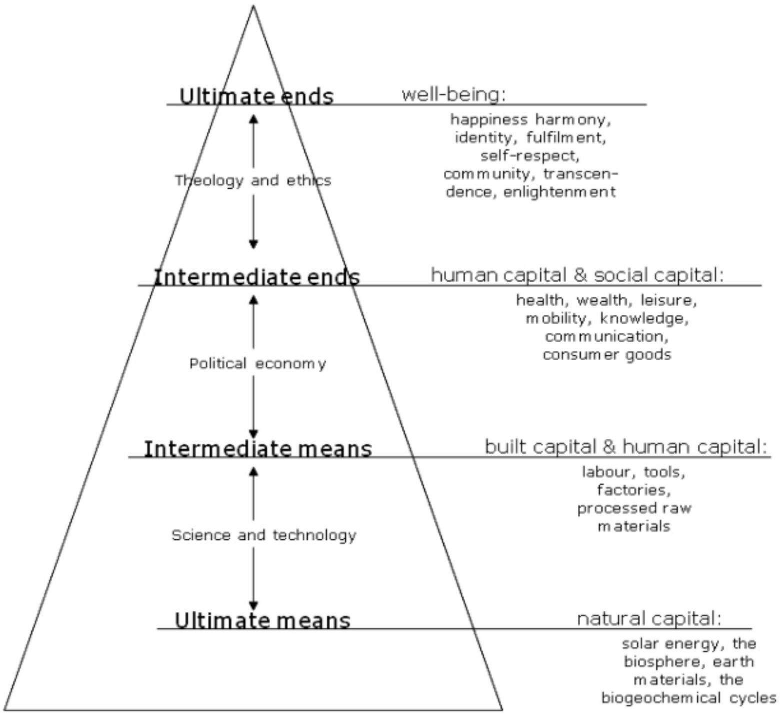

Figure 4: Daly Triangle, from 1973 in Meadows 1998

In this sense, natural capital forms the ultimate means of development. Without these resources and services there is nothing to build human societies and human well-being on. The Daly Triangle can therefore help in better explaining the integration and connections between environment, economy and society.

For the purpose of this study, the sustainability discourse is focused on the automotive sector, and in particular on explaining Life Cycle Assessment (LCA) as an accurate way to measure the *environmental* impacts of the automotive sector. Sustainability is one of the top priorities for the automotive supply chain. With the objectives of reducing the emissions of the sector, building on consistent innovation strategies and global

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[10] United Nations ESCAP (2015), “Integrating the three dimensions of sustainable development: a framework and tools”. https://www.unescap.org/sites/default/files/Integrating%20the%20three%20dimensions%20of%20sustainable%20development%20A%20framework.pdf

efficiency in the value chain, new developments are underway: few examples are new powertrain technologies, light-weighting, and the use of recycled and bio-based materials. [[11]].

However, the goal is of course that of having a more integrated approach to sustainability (i.e., being able to assess the environmental, social and economic aspects together). Therefore, if the environmental dimension is covered and well established by LCA, methods and tools to measure the economic and social dimensions need to be strengthened.

Several studies explore the concept of Life Cycle Sustainability Assessment (LCSA) [[12]], which stands for the combination of LCA, Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA), and which can be synthetized in the formula:

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA}$$

LCSA integrates the sustainability criteria: LCA for the environmental aspects, LCC for the economic aspects and SLCA for the social aspects. Only comprehensive assessment of these three components enables the realization of the principles of sustainable development.

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[11] CLEPA (2021), “Automotive suppliers work towards a carbon-neutral mobility, prioritising both human health and the environment”, https://clepa.eu/mediaroom/clepa-pr-materials-regulations-event-2021/ , last accessed February 2022

[12] Burchart-Korol, D., (2011) „Application of Life Cycle Sustainability Assessment and Socio-Eco-Efficiency Analysis in Comprehensive Evalutation of Sustainable Development“, Journal of Ecology and Health.

2.3 USAGE OF LCA AS A METHODOLOGY FOR ENVIRONMENTAL IMPACT ASSESSMENT

In the previous paragraph we have seen that the preservation of the natural environment is a prerequisite for a well-functioning economy and society.

Following the terminology of ISO 14001 [13], we can define:

- **Environment**: the surroundings in which the organization operates and includes air, water, land, natural resources, fauna, flora, humans and their interrelationships.
- **Environmental aspect**: an element of an organization's activities, products or services that may interact with the environment.
- **Environmental impact**: is an adverse or beneficial change to the environment resulting from the organization's environmental aspects.

An environmental impact is therefore a result of an environmental aspect. Examples of aspects and impacts are shown in Table 1:

Table 1: examples of environmental aspects and impacts

Aspect	**Impact**
Emissions of carbon dioxide	Climate change (via global warming)
Oil consumption (vehicles)	Depletion of natural resources
Discharges to water	Water contamination
Air emissions	Air contamination

According to ISO 14001, a systematic approach to determine aspects and impacts is required by any organization: Life Cycle Assessment (LCA) can support in achieving such objectives from an environmental perspective.

LCA is therefore the most mature technique and considers the environmental dimension. It is in fact a methodology used to identify, characterise and assess environmental impacts across a product's entire life cycle from raw material extraction

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[13] ISO 14000 identifies a series of technical standards relating to the environmental management of organizations, established by the International Organization for Standardization (ISO).

(‘cradle’) to final disposal (‘grave’). LCA makes it possible to compare the environmental aspects of different products as well as technological solutions, and to choose products or solutions having the smallest environmental impact throughout their life cycle.

In general terms, a product lifecycle consists of five main phases:

1. Raw material extraction (i.e., the resources used)
2. Manufacturing & processing (including assembly and storage)
3. Transportation
4. Usage & retail
5. End of life: reuse and recycle

Figure 5: LCA cycle

By taking a systems perspective, the main types of impacts are generally those associated with *inputs*, *outputs* and *processes*. Examples of inputs may include (but not limited to): raw materials, water, thermal energy, electric energy, chemicals, transports. Examples of outputs may include: finished products, co-products, wastewater emissions to water, recycled waste, disposed waste. Finally, examples of processes may include storage, cleaning, assembly, packaging.

In order to identify the environmental problems typical of numerous industries, including the transport sector, the LCA method is used to assess the potential environmental impact of technologies and products under different *categories* of damage, including greenhouse gas emissions and impact on human health. LCA is a technique which – among other functions – enables environmental impact assessment of different impact categories based on survey data, including of the emission of dust and gas pollutants. [14]

An impact category is a "class representing environmental issues of concern to which life cycle inventory analysis results may be assigned." Examples of impact categories include: greenhouse gas emissions, terrestrial acidification, water eutrophication, ecotoxicity, depletion of fossil fuels and minerals.

Many life cycle assessment methods are used to perform life cycle analyses, including:

- The ILCD Midpoint method recommended by the European Commission as representative of European conditions
- The IPCC method developed by the Intergovernmental Panel on Climate Change and used to assess the impact on GHG emissions,
- The Cumulative Energy Demand method which enables determination of cumulative energy demand,
- The IMPACT2002+ method making it possible to compile data inventories and assess them under more than a dozen intermediate categories assigned to the four primary damage categories,
- The ReCiPe 2008 method representing one of the most comprehensive assessment models [15].

LCA is the subject of international standards *ISO 14040:2006 and ISO 14044: 2006 /Amd 2: 2020*, which define four main steps of LCA, as Figure 6 and Figure 13 show:

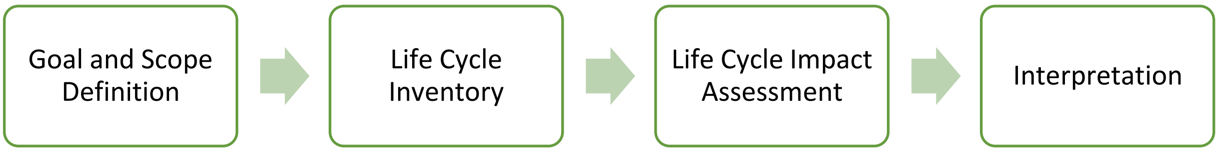

Figure 6: Phases of life cycle assessment

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[14] Burchart-Korol D., (2010): Ocena cyklu życia - nową techniką zarządzania środowiskowego, Wdrażanie nowoczesnych systemów i narzędzi zarządzania procesami technologicznymi. Praca zbiorowa. Pod red. Remigiusza Sosnowskiego, Gliwice: Wydaw. Politechniki Śląskiej, Monografia. nr 267, s. 231-242

[15] Burchart-Korol D., Korol J., Czaplicka-Kolarz K.(2016) "Life cycle assessment of heat production from underground coal gasification", International Journal for Life Cycle Assessment, Vol. 21, Iss. 10, p. 1391-1403.

There are many benefits in using LCA for the measurement of environmental impacts. LCA covers the entire product life cycle, starting from the raw material extraction and acquisition, through production of energy and materials, manufacturing, and operation, to end-of-life processing or disposal. LCA is used as a means to comprehensively evaluate processes, material choices and their effects on life cycle emissions of GHG as well as other impact and damage categories [[16]]. Benefits include, among others:

- Quantification of key environmental impacts
- Identification of opportunities to improve the environmental aspects of products across their entire lifecycle
- Foster decision-making within an organization – as you can only make decisions on things you have actually measured before
- Marketing (e.g., meeting consumer demand for green products and their possibility to learn how sustainable a product is)
- Having better knowledge on your suppliers

When considering LCA applied to the automotive industry, we see that it offers one of the most comprehensive tools to assess the transformation of the automotive industry and its transition from conventional fossil fuels such as diesel and petrol to alternative ones such CNG, LPG, electricity and hydrogen. It allows incorporating life cycle thinking into the decision-making, in order to achieve a sustainable, circular alternative.

2.4 ENVIRONMENTAL FOOTPRINTS

For purposes of environmental impact assessment, many industries refer to **environmental footprints.** Environmental footprints are derived from the LCA technique. An environmental footprint is an indicator based on multiple criteria, used to measure the environmental performance of products and services throughout their life cycles.

In 2013, the European Commission published recommendations on the use of common methods for measuring environmental performance over the life cycle of products and organisations, the consequence of which was that individual sectors prepared industry-specific guidelines for the methodology of measurement of

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[16] Burchart-Korol D., Jursova S., Folęga P., Pustejovska P., (2020) “Life cycle impact assessment of electric vehicle battery charging in European Union countries”, Journal of Cleaner Production, Vol. 257.

environmental performance of products and organisations, officially referred to as *Product Environmental Footprint Category Rules*, as well as *Organisation Environmental Footprint Sector Rules.* The European Commission is currently developing new rules for calculating the environmental footprint and labelling of products. *The European Commission Recommendation of 9 April 2013 on the use of common methods for measuring and communicating the environmental performance over the life cycle of products and organisations (2013/179/EU)* defines the European methodology proposed for measuring the environmental performance of products and businesses. The EC recommendations encourage the use of the method for measuring the environmental footprint in strategies and programmes envisaged for measuring the environmental performance over the life cycle of products or businesses. In accordance with the European Commission recommendation, the **product environmental footprint** (PEF) method is used to measure the potential environmental impact of a product over its life cycle, while the **organisation environmental footprint** (OEF) method is used to measure the potential environmental impact of a business over its life cycle.

The environmental footprint assessment consists of several steps: defining the purpose and scope of the analysis, identifying resources and emissions, assessing the environmental impact, interpreting the results, and preparing a report. The assessment of the environmental footprint of products and businesses should be performed in line with the principles of significance, completeness, coherence, accuracy, and transparency.

With regard to the framework of environmental footprints, the main objective of the European Union and its Member States is efficient use of the limited natural resources and elimination of products and technologies exerting a considerable negative environmental impact. The environmental footprint assessment methodology may become a part of mandatory environmental legislation, of environmental management systems, and of green public procurement schemes, as well as of many activities and initiatives contributing to the development of green economy, as it is commonly referred to, but it may also become an important element of the process in which decisions are made in the sphere of environmental protection.

The most important environmental footprints are:

- Carbon footprint (CF)
- Water footprint (WF)
- Ecological footprint (EF)

Carbon footprint is defined as the amount of emission of CO_2 equivalent caused directly and indirectly by greenhouse gas emissions, or as the total amount of GHG released throughout the entire life cycle of a process or product [[17]]. CF is expressed as the mass equivalent of carbon dioxide per a functional unit (FU) of a product or service (kg CO_2eq/FU). CF is also defined as the sum of greenhouse gas emissions produced over the life cycle of a product directly or indirectly by a person, business, product or service.

Water footprint (WF) is the volume of fresh water consumed in the manufacture of a product, measured throughout the entire manufacturing process. It is a multidimensional indicator demonstrating the amount of water consumed from the given source and the amount of contaminated water by the contamination type. WF is an indicator of clean water consumption, and it comprises not only direct water consumption but also indirect water consumption. One can distinguish between blue component (consumption of surface and groundwater), a green component (consumption of rainwater), and a grey component footprint (water required to assimilate pollution). The blue footprint corresponds to the volume of surface and ground water used. The term green footprint refers to the consumption of rainwater, unless it is drained, for instance, to the sewage disposal system. An increase in the amount of rainwater used for production or consumption reduces the blue footprint. When discharged into the sewage disposal system, rainwater can become contaminated by sewage, thus generating the grey footprint. Also the rainwater running off from arable land, contaminated with pesticides or fertilisers, can leave the grey footprint. The grey footprint determines the magnitude of the water pollution load, which can be expressed as the volume of water required to dilute the pollutants it contains to such a level that their concentration becomes environmentally acceptable. Clean water has become one of the rarest and most desired natural resources, and it is therefore necessary to begin by quantitatively assessing the consumption of water in order to be able to analyse processes or their individual stages where water consumption can be minimised.

Ecological footprint (EF) defines the human impact on the environment. This indicator demonstrates the magnitude of a bio-productive area (lands, seas and oceans) necessary to obtain resources and to produce goods consumed by its occupants. EF is a measure used to assess, both locally and globally, the regenerative potential of the biosphere, utilised

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[17] Burmistrz P., Chmielniak T., Czepirski L., Gazda-Grzywacz M.: Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification. Journal of Cleaner Production Vol. 139, 2016, p. 858-865.

directly or indirectly by people, with reference to the magnitude of the biological potential available. EF refers to direct and indirect utilisation of land as a resource.

2.5 SYSTEM BOUNDARIES

System delimitation in LCA is a part of the goal and scope phase described in *ISO 14040:2006.*

The system boundary defines which processes will be included in, or excluded from, the system and delimits which processes should be included in the analysis of a product system, including whether the system produces any co-products that must be accounted for by system expansion or allocation[18].

Defining system boundaries is partly based on a subjective choice, made during the scope phase when the boundaries are initially set.

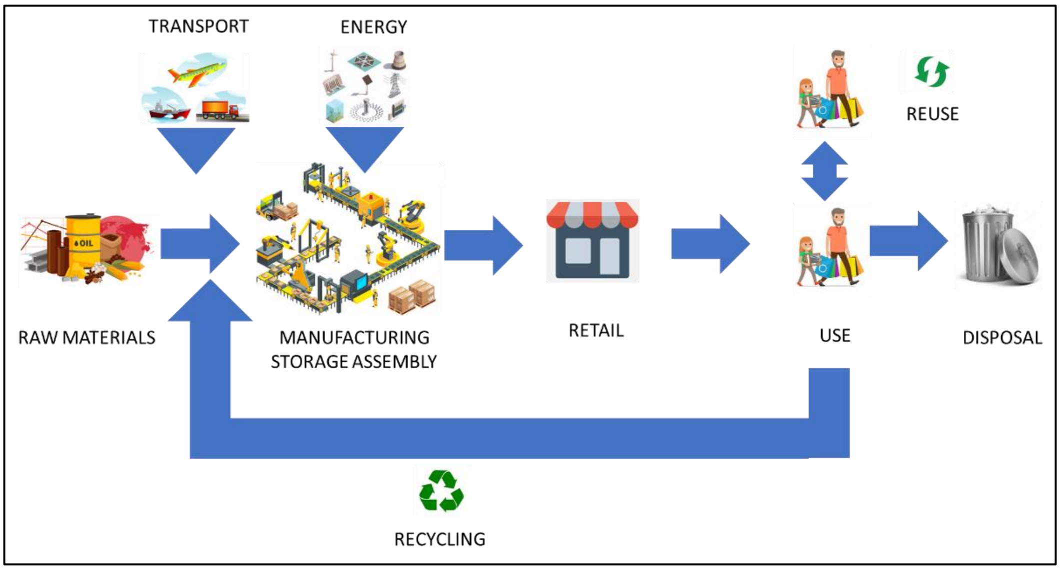

Figure 7 shows a schematic representation of a system boundary.

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[18] A detail of LCA phases is available into chapter 2.6 LCA PHASES

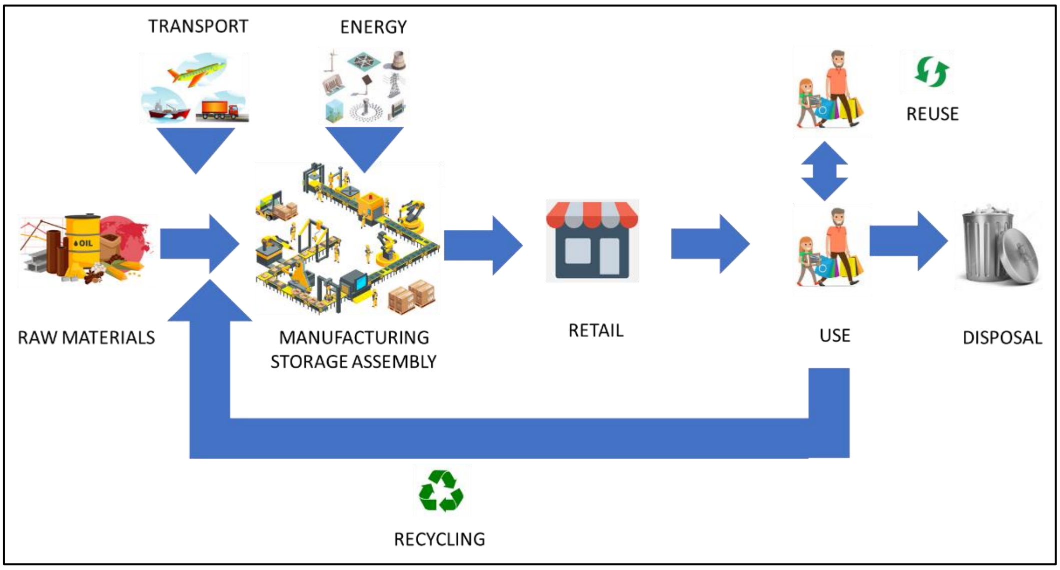

Figure 7: an LCA system boundary representation

The following boundaries can be considered [19]:

Boundaries between the technological system and nature. A life cycle usually begins at the extraction point of raw materials and energy carriers from nature. Final stages normally include waste generation and/or heat production

Geographical area. Geography plays a crucial role in most LCA studies, e.g., infrastructures, such as electricity production, waste management and transport systems, vary from one region to another. Moreover, ecosystems sensitivity to environmental impacts differs regionally too.

Time horizon. Boundaries must be set not only in space, but also in time. Basically, LCAs are carried out to evaluate present impacts and predict future scenarios. Limitations to time boundaries are given by technologies involved, pollutants lifespan, etc.

Boundaries between the current life cycle and related life cycles of other technical systems. Most activities are interrelated, and therefore must be isolated from each other for further study. For example, production of capital goods, economic feasibility of new and more environmentally friendly processes can be evaluated in comparison with currently used technology. Interrelation of product systems has the tendency to be interrelated in a very complex manner. Ideally, life cycles of products used to produce the materials and product under investigation are also required. That however would lead to an endless and complex list of inflows and outflows. Consequently, limits, boundaries have to be set for the exclusion of certain parts, which can however alter the final output of the

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[19] LCA as a Decision Support Tool for the Eco Production of Olive Oil, project web, available at http://www.ecoil.tuc.gr, last accessed February 2022.

study. The smaller the system, the sharper its boundary; large systems may have multiple boundaries as they interface with multiple systems.

A diagram of the system is very helpful for the identification of the boundaries, and so are some choices such as production and disposal of capital goods, and nature boundaries.

There are **four** main options to define the system boundaries used into a LCA study and a **specific** "cradle to grave" approach for automotive (Well to Wheel):

- Cradle to Grave
- Cradle to Gate
- Cradle to Cradle
- Gate to Gate
- Well to Wheel

CRADLE TO GRAVE

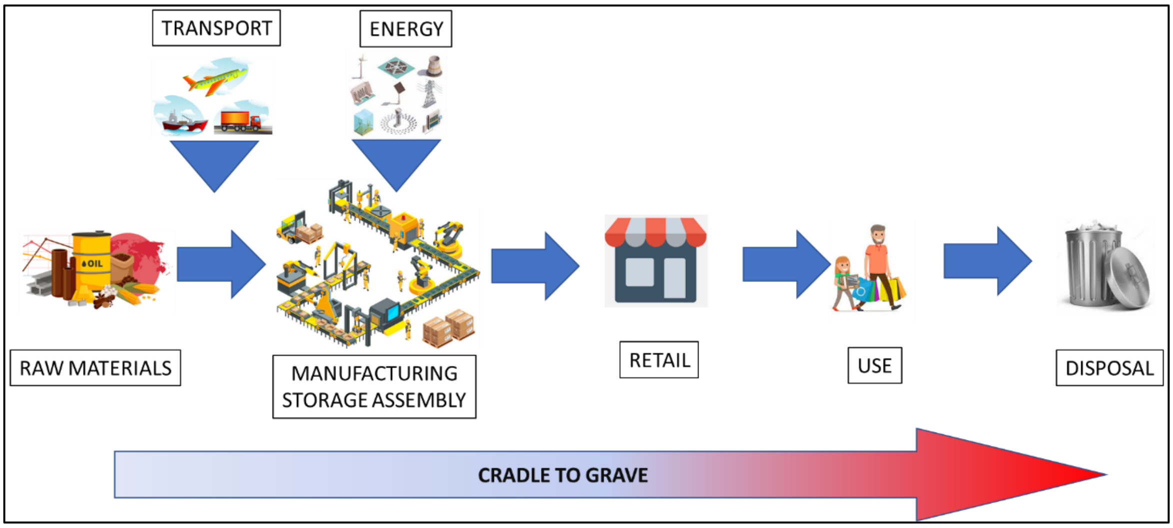

Figure 8: the Cradle to Grave diagram

This boundary includes the material and energy production chain and all processes from the raw material extraction through the production, transportation and use phase up to the product's end of life treatment.

The Cradle to Grave is the "conventional disposable approach", which is no longer sustainable in view of the development goals set by Europe for 2030 [20]. A large part of

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[20] Sustainable Development Goals, https://ec.europa.eu/international-partnerships/sustainable-development-goals_en, March 2022

greenhouse gas emissions, in fact, are due precisely to this production approach, based on fossil fuels. To comply with the Paris Agreement [21], therefore, a radical change in production models is necessary.

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[21] The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016.

CRADLE TO GATE

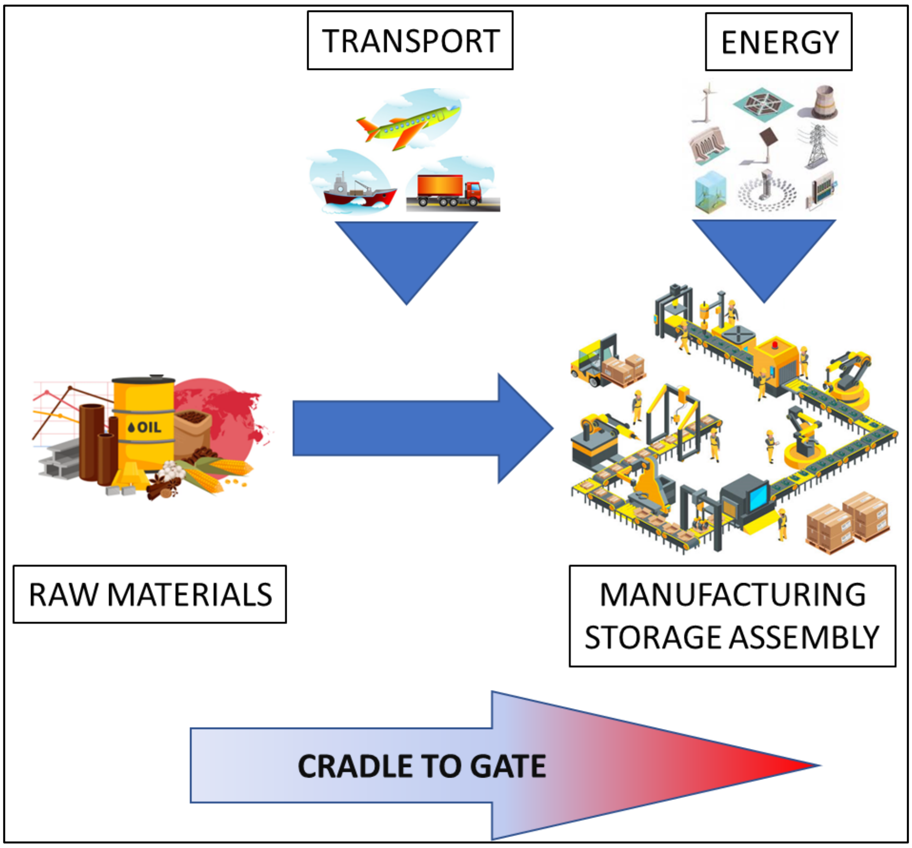

Figure 9: the Cradle to Gate diagram

This boundary includes all processes from the raw material extraction through the production phase (gate of the factory); used to determine the environmental impact of the production of a product, thus excluding the phase of use and disposal of the same. It is a partial analysis, useful in large system LCA process.

CRADLE TO CRADLE

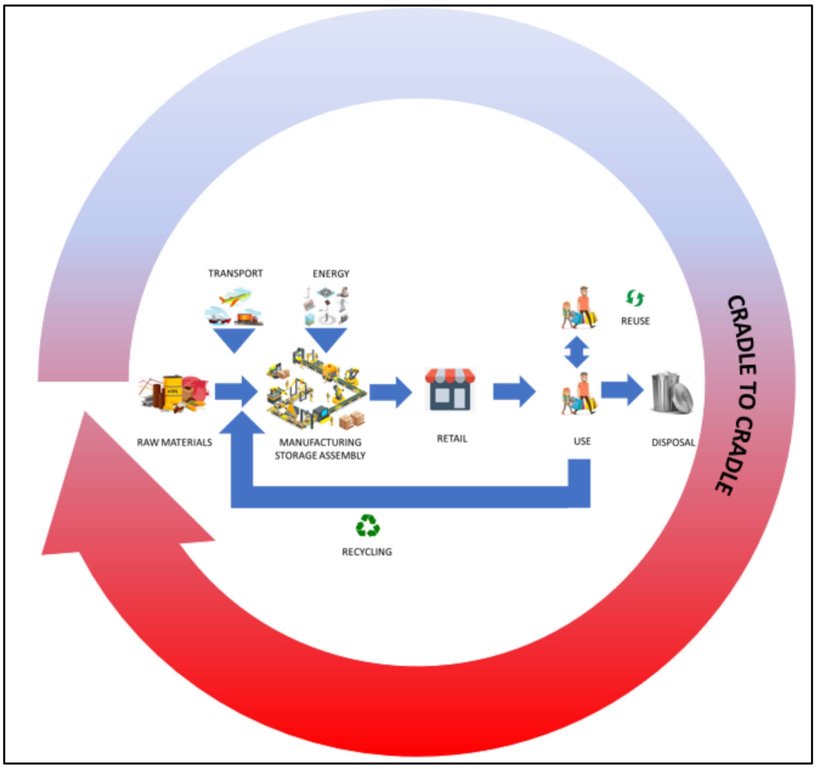

Figure 10: the Cradle to Cradle diagram

This is a specific case of the previous system boundary cradle to grave where the end of life treatment step is a recycling process; used to minimize the environmental impact of products by employing sustainable production, operation, and disposal practices and aims to incorporate social responsibility into product development.

The Cradle to Cradle approach is an essential tool of the circular economy, which allows to transform production processes by reducing waste to a minimum level and allows to create a positive footprint. The founders of the Cradle to Cradle approach are Michael Braungart and William McDonough [[22]], and they explore the process boundary through three fundamental elements:

- Everything is a resource for something else: in nature, waste from one system becomes food for another. Everything can be designed to be subsequently broken down and returned to the environment in the form of nutrients, or it can be reused as a raw material for the creation of new products.

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[22] "Cradle to Cradle: Remaking the Way We Make Things", Michael Braungart and William McDonough, 2002

- Use clean and renewable energy: living beings thrive thanks to the energy of the sun. Similarly, products can be made using various forms of renewable energy, for the protection of the environment and health.
- Celebrate diversity: all over the world, geology, hydrology, photosynthesis and the nutrient cycle, adapted to the place, produce a surprising diversity of natural and cultural life.

GATE TO GATE

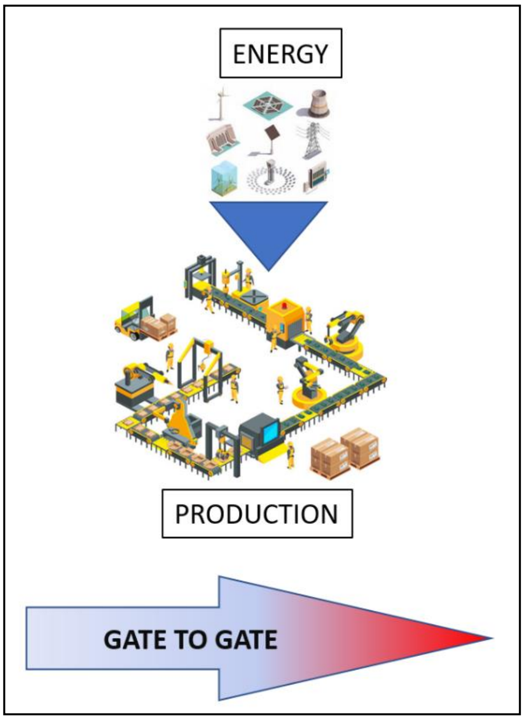

Figure 11: the Gate to Gate diagram

This boundary includes the processes from the production phase only; used to determine the environmental impacts of a single production step or process.

WELL TO WHEEL

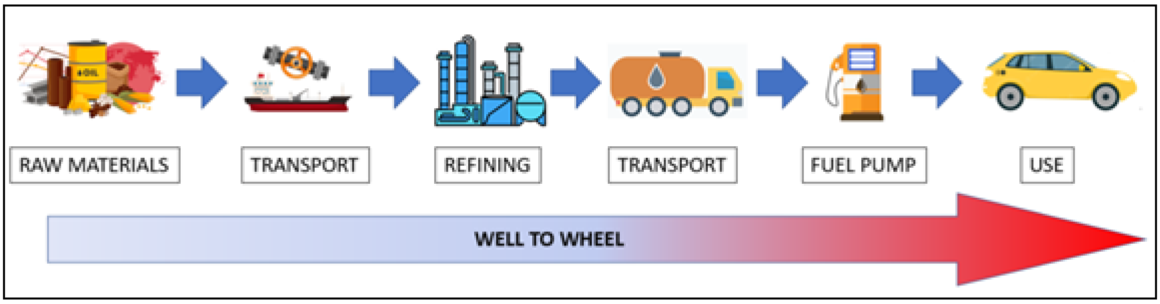

Figure 12: the Well to Wheel diagram

This is a specific system boundary used to assess the total energy consumption (or the energy conversion efficiency and emissions impact) of marine vessels, aircraft and motor vehicles, including their carbon footprint (see Figure 12), and the fuels used in each of these transport modes useful to evaluate the impacts of fuel use using a well-to-wheel evaluation while a traditional cradle-to-grave approach.

2.6 LCA PHASES

Life Cycle Assessment is a methodology that allows you to evaluate the environmental impact associated with a system (product, process, service), through the analysis of energy and consumed materials, waste, logistics and transport, as well as emissions released into the environment, all throughout the entire life cycle.

An LCA study must be structured according to four consequential phases [[23]] as indicated in Figure 13: Goal and Scope, Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA) and Interpretation.

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[23] In accordance with the provisions of ISO 14040

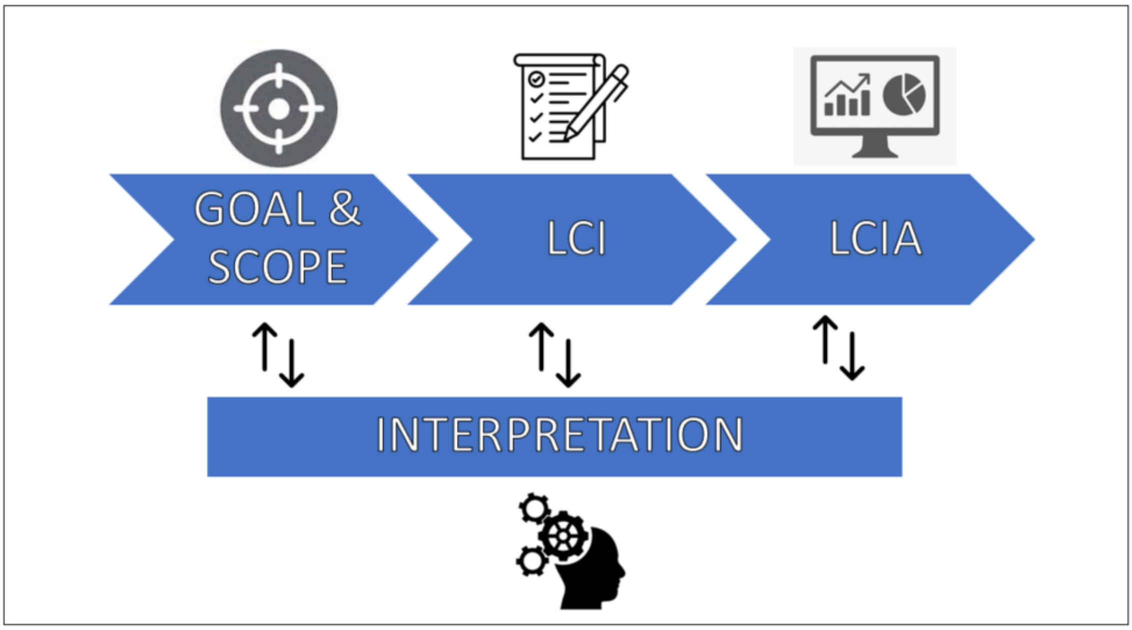

Figure 13: LCA 4 main stages

GOAL AND SCOPE

Definition of goals and scopes is fundamental because with this step it is possible to **design the framework** of the study, identifies the **reason why** it is performed and describes all its **characteristics**. In this phase it is mandatory to define:

- **the objective of the study:** the application for which it is intended and the reasons for carrying it out. The different approach is based on (i) comparing products/services with each other, (ii) comparing the object of the study with a reference standard, (iii) planning improvements for an existing product/service or (iv) designing a new product/service;
- **the functional unit**: which must be consistent with the objective and field of application. It is, the product, service or function on which to set the analysis and comparison with possible alternatives ([kg] of product, [t] of waste treated, [kWh] of energy supplied, ...). The functional unit indicates the reference object of the LCA study to which all input and output data will be normalized. According to ISO 14040, the main purpose of the functional unit is to provide a reference to which to link the outgoing and incoming flows and it is a necessary reference to allow the comparability of the LCA results.

- **the system boundaries [24]**, necessary to define which processes will be included in, or excluded from, the System and delimits which processes should be included in the analysis;
- **the categories of data** to be collected and analysed: which determines the possibility of collecting them in the field, measuring them, calculating them, estimating them, obtaining them from existing databases. Usually, it is possible to sort collected data by 3 categories: (i) *Primary data* (from direct surveys), (ii) *Secondary data* (taken from the literature) and (iii) *Tertiary data* (from estimates and average values);
- **the data quality** requirements: with a consistency in terms of temporal, geographical and technological coverage, a correct representative and reproducible and, of course with a reliable source.

LIFE CYCLE INVENTORY (LCI)

The inventory analysis is the most delicate and demanding phase of an LCA study. Here the input and output flows in the life cycle of the system are defined and quantified, through a model that represents it in the most reliable possible way.

To proceed with the LCI, it is useful to adopt a process flowchart [25] representation with which it is possible showing the components of a system that is composed of sequences of processes (boxes) connected by flows of materials (arrows).

The most representative scheme, valid for most industrial systems, aims to identify the major environmental processes and interventions and can be divided into seven sequences:

1. **Main production**: this sequence highlights the product's priority manufacturing process; in this phase are highlighted the main process steps and the major material flows.
2. **Secondary production or co-product**: this sequence relates to the manufacturing process of the product which is carried out during the production of the main product.

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[24] See chapter 2.5 SYSTEM BOUNDARIES

[25] A flowchart is a type of diagram that represents a workflow or process, https://en.wikipedia.org/wiki/Flowchart, March 2022.

3. **Production of auxiliary materials**: this phase aims to extend the process flowchart with the processes that appear before, during and after the manufacture of the product; this phase will allow to analyse the extraction, production and components of raw materials, on the other hand it will show the use of the product, consumption, recycling or reuse and the processes of waste management.
4. **Energy production**: this sequence concerns the possibility of recovering energy by heat or electricity.
5. **Energy consumption**: this sequence takes into account the energy consumption due to the various processes.
6. **Transportation**: this sequence concerns the transport used for moving product or co-product and it concerns the quantity of product transported per kilometre.
7. **Waste treatment**: it considers the treatments that are applied to processing waste and auxiliary materials.

When the process has been outlined, it is possible to proceed with the effective data collection activity. This will be of two types: those relating to the input flows [[26]] (**input**) and those corresponding to the outputs [[27]] (**outputs**). Collected data must be evaluated on the basis of parameters like data age, reference technology, process to which the data refers, calculation methods used to obtain average values.

Once collected, all the data must be categorized (raw materials, energy, transport, ...) and filed in an **inventory table**, the fundamental basis for the next phase of impact assessment (LCIA).

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

This phase allows to determine the potential effects of the analysed system on the environment by linking the inventory data to specific **impact categories** as indicated in Table 2.

---

[26] Materials, transport and energy

[27] Products and gases released into the air, water and soil

Table 2: major environmental impact categories

ECOSYSTEM IMPACTS	HUMAN IMPACTS	RESOURCE DEPLETION
Acid rain	Carcinogens	Fossil fuel
Climate change	Ozone Depletion	Forest
Eutrophication	Particulate matter	Freshwater
Land use change	Smog	Grassland
Solid waste	Toxicity	Minerals
Toxicity		Soil

These environmental impact categories are attributable to three major areas of environmental protection directed linked with three areas of protection (AoPs)

- Ecosystem Impacts (Natural Environment)
- Human Impacts (Human Health)
- Resource depletion (Depletion of non-renewable resources)

And consequently, it is possible to refer to the following environmental issues:

- Potential depletion of raw materials.
- Potential depletion of energy sources.
- Global warming potential (greenhouse effect). (GWP: Global Warming Potential).
- Potential depletion of the ozone layer. (ODP: Ozone Depletion Potential).
- Ecotoxicity of water and soil.
- Potential acidification. (AP: Acidification Potential).
- Toxicity for humans.
- Eutrophication. (NP: Nutrification Potential).

The impacts can persist on a local, regional or global scale and concern different environmental sectors rather than effects on human health by identifying the contribution of the system to the primary energy, to the greenhouse effect, to the reduction of the ozone layer, to the acidification, to the eutrophication, to the photochemical smog, to the solid waste:

PRIMARY ENERGY

This indicator considers the primary energy demand for the entire life cycle of the considered product, taking into account, for example, the transformation of combustible materials into electricity. Combustible materials therefore contribute to this indicator with their primary energy content. The characterization factor in this case is the calorific value of the material considered.

GREENHOUSE EFFECT

The greenhouse effect indicator is calculated considering, among the substances emitted into the air, those that contribute to the global warming potential of the planet earth.

The mass quantity of each substance, calculated over the entire life cycle of the product, is multiplied by a weight coefficient, called the Global Warming Potential (GWP). Then, by adding the contributions of the various substances, the aggregate value of the indicator is obtained. The substances that contribute to the greenhouse effect are mainly: CO_2, CH_4, N_2O, CFCs, HCFCs and HFCs. CO_2 is the reference substance for this indicator, i.e., its weight coefficient is equal to 1 and the indicator values are expressed in kg of CO_2 equivalent [kg CO_2].

REDUCTION OF THE OZONE LAYER

The reduction of the stratospheric ozone layer is calculated as the previous indicator, but referring to different substances (CFC, HCFC) and with a different weight coefficient, called the ozone depletion potential (ODP, Ozone Depletion Potential). The substance taken as a reference is in this case a chlorine - fluorine - carbide [CFC – 11].

ACIDIFICATION

The acidification indicator is linked to the emissions into the air of particular acidifying substances, such as nitrogen oxides [NO_x] and sulphur oxides [SO_x]. The reference substance is SO_2 and the weight coefficient is called the acidification potential [AP, Acidification potential].

EUTROPHICATION

This indicator evaluates the eutrophication effect [28]. The substances that contribute to the phenomenon of eutrophication are compounds based on phosphorus [P] and nitrogen [N]. The reference substance is phosphate (PO_4) and the weight coefficient is called Nutrification Potential [NP].

PHOTOCHEMICAL SMOG

All those volatile organic substances that lead to the photochemical formation (in the presence of solar radiation) of tropospheric ozone are grouped under the name of *summer smog [*29*]*. The characterization factor is called the Photochemical Ozone Creation Potential (POCP) and the reference substance is ethylene [C_2H_4].

SOLID WASTE

The indicator in question groups all solid waste that are generated in any activity in the life cycle of a product, such as during the generation of electricity necessary for a given process, or during the production of steel sheets. There are no characterization factors for this indicator and each substance is added to the others simply by taking into account the quantity emitted in mass.

INTERPRETATION

With the interpretation phase it is possible to understand the result of the study, contextualize it and be able to indicate an **improvement** of the system by identifying the components to which changes can be made in order to reduce the environmental impact. of the whole system;

It is important to underline that even if the interpretation phase is linked with the (final) result of the study, as indicated in Figure 13, the interpretation of the data is necessary at every phase of a the LCA methodology.

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[28] i.e. the increase in the concentration of nutrients in aquatic environments

[29] Smog is often categorized as being either summer smog or winter smog. Summer smog is primarily associated with the photochemical formation of ozone. During the winter months when the temperatures are colder, and atmospheric inversions are common, there is an increase in coal and other fossil fuel usage to heat homes and buildings. https://en.wikipedia.org/wiki/Smog, March 2022

During the LCIA activity it is necessary to combine the technical-environmental results provided by the LCA with all the other information regarding the product under study; economic-financial and political-social information on the product and information on the receptivity-satisfaction of consumers and on the consensus of public opinion, in order to find an eco-compatible product or, in other words, in order to make a correct decision about the company product policy and the environmental programs that the company intends to develop in the future.

It is important to emphasize that the LCA, like all methodologies based on comparison, does not propose an absolute solution, but identifies a set of alternatives among which the decision makers will choose the best in their opinion.

The objectives of this phase are as follows:

- Translation and interpretation of the results.
- Verification of the achievement of the study objectives (iteration), data quality and system limits (sensitivity analysis)
- Compare the possible options.

The results must be interpreted and represented in such a way as to have a perception of the results that is easily usable, also trying to represent scenarios other than the one considered.

2.7 CHAPTER REFERENCES

Summarization

At the end of this chapter, students will understand following terms:

- Sustainability and sustainable development
- Life cycle assessment (LCA)
- Environmental aspect
- Environmental impact
- Inputs, outputs and processes
- LCA impact categories
- Environmental footprints
- System boundaries: cradle to grave, cradle to gate, cradle to cradle, gate to gate, well to wheel
- LCA phases: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), interpretation

Questions

- What does sustainability and sustainable development mean?
- What are the different dimensions of sustainability and how they can be described?
- Following the terminology of ISO 14001, what is the meaning of “environment”; “environmental aspect” and “environmental impact”?
- How would you define an “impact category”?
- What are the main general benefits of using LCA?
- System boundaries: please shortly describe each of them
- LCA phases: please shortly describe each of them

Abbreviations

AP - Acidification Potential

CF- Carbon footprint

CSR - Corporate Social Responsibility

EF - Ecological footprint

FU - Functional Unit

GDP - Gross Domestic Product

GHG emissions – Greenhouse Gas emissions

GPI - Genuine Progress Indicator

GWP - Global Warming Potential

LCA – Life Cycle Assessment

LCC - Life Cycle Costing

LCI – Life Cycle Inventory

LCIA - Life Cycle Impact Assessment

LCSA - Life Cycle Sustainability Assessment

NP - Nutrification Potential

ODP - Ozone Depletion Potential

OEF - Organisation Environmental Footprint

PEF- Product Environmental Footprint

SDGs - Sustainable Development Goals

SLCA - Social Life Cycle Assessment

WCED - World Commission on Environment and Development

WF -Water footprint

POCP - Photochemical Ozone Creation Potential

3. LCA IN AUTOMOTIVE: CONVENTIONAL FUEL VEICHELS

Time to study 120 minutes

Objectives

WHAT KNOWLEDGE STUDENTS WILL ACQUIRE:

After these lessons, students will be able to:

- Acquire better knowledge on the topic of development of combustion engines and Life Cycle Assessment of conventional fuel vehicles
- Better frame the different principles of operation of petrol, diesel and alternative internal combustion engines, methods of measuring fuel consumption, determinants of different footprints assessment of internal combustion engine vehicles and as well as results of real measurements of energy consumption and greenhouse gases production of individual and public passenger transport
- Gain an understanding of European emission standards for road vehicles

HOW THE CHAPTER WILL HELP THEM TO UNDERSTAND THE TOPIC:

Firstly, students will be introduced to theoretical information about internal combustion engines through a description of their development and an explanation of the principles of their operation. The currently permitted emission limits, which indicate the negative effects of the operation of internal combustion engines, are shown in the currently applicable European emission regulations for passenger cars, light commercial vehicles, trucks and buses. Students will also gain knowledge about various methods of fuel consumption measuring thanks to a theoretical description of each method supplemented by a graphical representation of driving cycles. General information about Life Cycle Assessment is then applied to the issue of conventional fuelled vehicles, which will give students knowledge about the practical use of Life Cycle Assessment. Finally, the theoretical knowledge is supported by examples of the results of specific measurements of consumption and production of greenhouse gases of passenger car, bus and train in real operation.

WHAT SKILLS THE CHAPTER WILL DEVELOP

The chapter guarantees the acquisition of technical skills to better assess the advantages or disadvantages of using a particular means of transport (vehicle) on the basis of its technical characteristics and the type of fuel. The chapter develops skills and knowledge how to protect the environment in terms of energy consumption and greenhouse gas emissions.

WHERE THE STUDENTS CAN USE THE KNOWLEDGE

Students can use the knowledge in decision-making processes when assessing the choice of the appropriate mode of transport and fuel, taking into account the protection of the environment and maintaining sustainable mobility.

Theory

3.1 COMBUSTION ENGINES

According to the European Automobile Manufacturers' Association, more than a half of all European passenger cars (55.6%) run on petrol [30]. Figure 14 provides a breakdown of passenger cars used in the European Union into fuel types. Passenger cars with small petrol engines are more common than medium-sized and large engines in the majority of Member States.

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[30] The European Automobile Manufacturers' Association (ACEA). Available at https://www.acea.be. Last accessed February 2022.

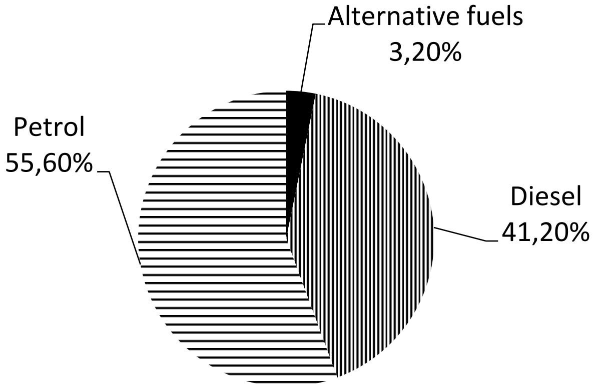

Figure 14:Passenger cars used in the European Union by fuel type [30].

An internal combustion engine is an engine that works on the principle of burning fuel, so an internal combustion engine is also called the heat engine. When fuel is burned, chemical energy is converted into mechanical work. The chemical reaction occurs during the combustion of the engine, which generates thermal energy, which, by using the suitable gas medium, converts the said chemical energy into mechanical work. The gaseous medium uses energy in two ways – 1st. potential energy of reciprocating internal combustion engines (pressure), 2nd. kinetic energy of combustion turbines (current speed of flow) [31].

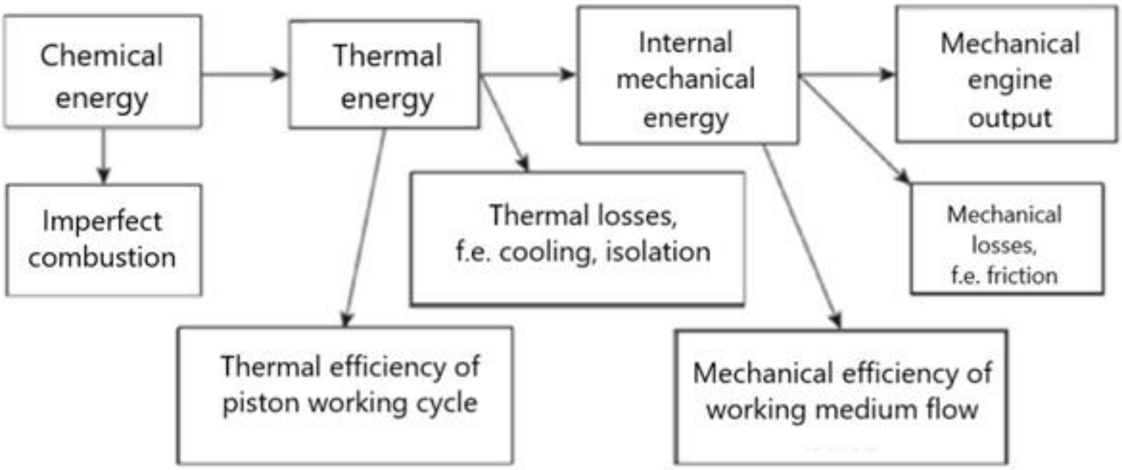

Figure 15:Diagram of an internal combustion engine and conversion of generated energy

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[31] Hromádko J., Höning V., Miler P. Spalovací motory, Praha, Grada, 2011, 296 pp.

Figure 15 shows the diagram of the successively generated energies of internal combustion engines that are part of the fuel. Chemical energy is converted into mechanical work by the internal combustion engine.

DEVELOPMENT OF COMBUSTION ENGINES

Internal combustion engines began to develop after the discovery of the first means of transportation, when humanity realized that these vehicles made life and work easier for them. The development of internal combustion engines is also associated with negative effects on nature, such as the use of minerals, environmental pollution, the greenhouse effect, acid rain and ozone depletion.

PETROL ENGINE

In 1786, French inventor Phillipe Lebon applied for the patent for the gas-powered engine. To this day, it isn´t known to build such an engine. In 1807, the inventor Issac de Rival obtained the patent for the vehicle powered by the gas combustion engine, which works on the principle of mixing an explosive gas mixture with air ignited under the piston by an electric spark. Later, the creator J.J. Etienne Lenoir patented the first usable gas engine, when in 1860 he created the two-stroke engine starting with an electric spark. Also, in 1860 - 1863, this inventor was the first to create an engine powered by liquid fuel - gasoline. K. Benz also received the patent for the two-stroke gas internal combustion engine in 1879, which created vehicles with the gas engine of its own design [[32]].

Figure 16 shows the three-wheeled vehicle powered by the four-stroke petrol engine, which operates similarly to the four-stroke diesel engine, the main difference being the intake of clean air into the cylinders and, after heating and compressing the air, diesel is injected into the cylinders.

The principle of operation of the four-stroke engine [[33]]:

1. INTAKE - The piston moves downwards, increasing the space above the piston and opening the suction valves. As the result, the atmospheric pressure is higher than the pressure above the piston, which in addition to air also supplies fuel to the cylinders. Fuel + air = flammable mixture

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[32] Rauscher J. Zoznam použitých pojmov zo spaľovacích motorov. Bratislava 2005 <http://www.iae.fme.vutbr.cz/userfiles/ramik/files/Spalovaci%20motory%202005.pdf>.

[33] https://autoride.sk/zazihovy-motor-jeho-funkcia-v-skratke

2. COMPRESSION - The piston moves upwards and compresses the mixture, which is heated and the result is the rise in pressure. High pressure and temperature promote the evaporation of fuel with mixed air, making the mixture more explosive.
3. EXPANSION - In this phase, the combustion process takes place, whereby the spark on the spark plug jumps and it then ignites the compressed mixture. Following ignition, the mixture expands and the piston moves downwards.
4. EXHAUST - Exhaust valves open to help get the exhaust gases out of the cylinder.

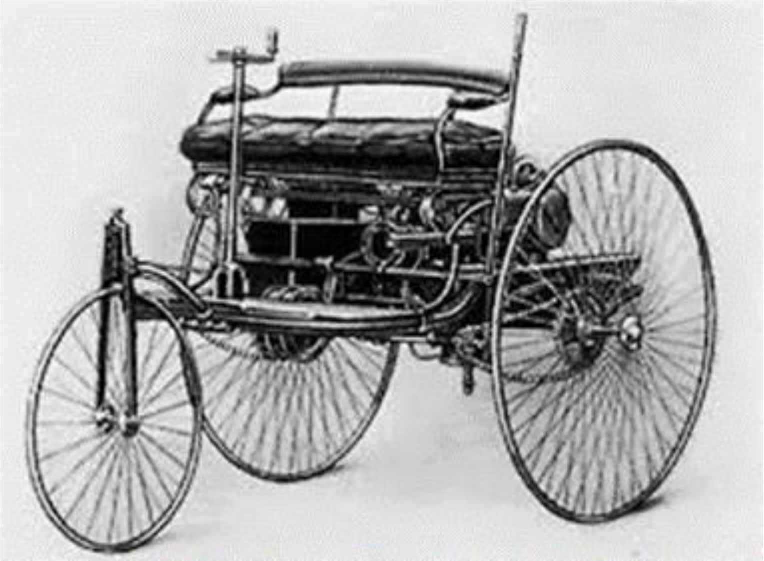

Figure 16 K. Benz - the first three-wheeled vehicle powered by the four-stroke engine [34]

Advantages of petrol engines:

1. simpler and less expensive construction,
2. petrol engines are more powerful,
3. more suitable for shorter routes because the time to obtain the operating temperature is much lower.

DIESEL ENGINE

In 1892, Rudolf Diesel obtained the patent for the diesel engine. He created the prototype of the four-stroke engine using MAN powered by sprayed kerosene fuel into the

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[34] https://www.superstock.com/asset/transport-transportation-car-vehicle-variants-benz-first-three-wheeled-motor/4430-4122

cylinder using compressed air. It was the compression-ignition engine. Diesel engines were considered economical engines in the past. Today, these engines are economical and powerful [32].

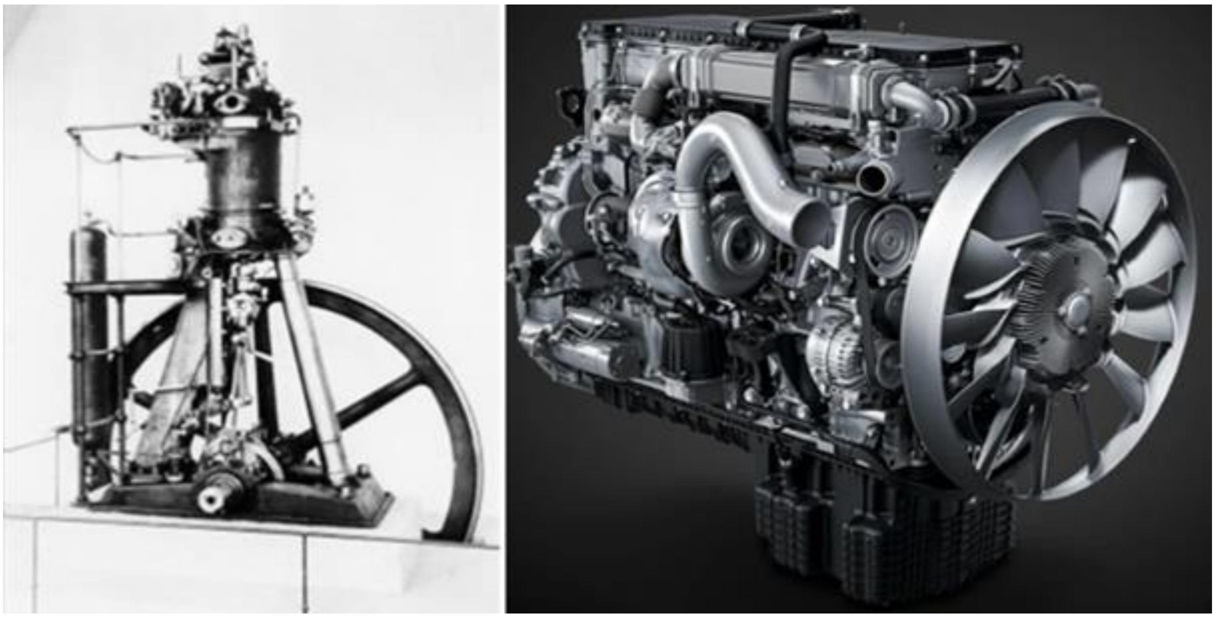

Figure 17:The historical and current diesel engines [35]

Operating principle [36]:

1. INTAKE - the crankshaft rotates from 0° to 180°, is the phase when air enters the cylinder through an open valve.
2. COMPRESSION - the crankshaft rotates from 180° to 360°, is the phase in which the piston causes the air in the chamber to be compressed 16 - 25 times and reaches the temperature of 700 - 900 °C.
3. COMBUSTION - the crankshaft is rotated from 360° to 540° and injects fuel, which is then ignited. Combustion results in substances that allow the piston to move downwards.
4. EXHAUST - the crankshaft is rotated 540° to 720° from the intake position. The piston moves upwards, the burned gases are discharged into the exhaust.

Advantages of diesel engines [36]:

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[35] https://www.reddit.com/r/MechanicalEngineering/comments/ojnpcp/rudolf_diesel_who_invented_the_diesel_engine/

[36] https://www.autodoc.sk/info/dieselovy-motor-zaklady

1. the service life of the diesel engine is twice that of the petrol engine,
2. they burn on average 30 % less fuel compared to the petrol engine,
3. diesel engine burns fuel immediately after commissioning, thus guaranteeing high torque at lower speeds.

ALTERNATIVE INTERNAL COMBUSTION ENGINES

Despite the proven conventional reciprocating internal combustion engines, alternative internal combustion engines were also created, which, however, didn´t prove to be ecological and economical engines in the future, thus ending their development [32].

Rotary piston engines

The rotary piston engine, also called the Wankel engine, was the only one to go into series production with one type of engine. This engine was first used in the NSU Prinz car and later used in the production of the Mazda RX-8 sports car [32].

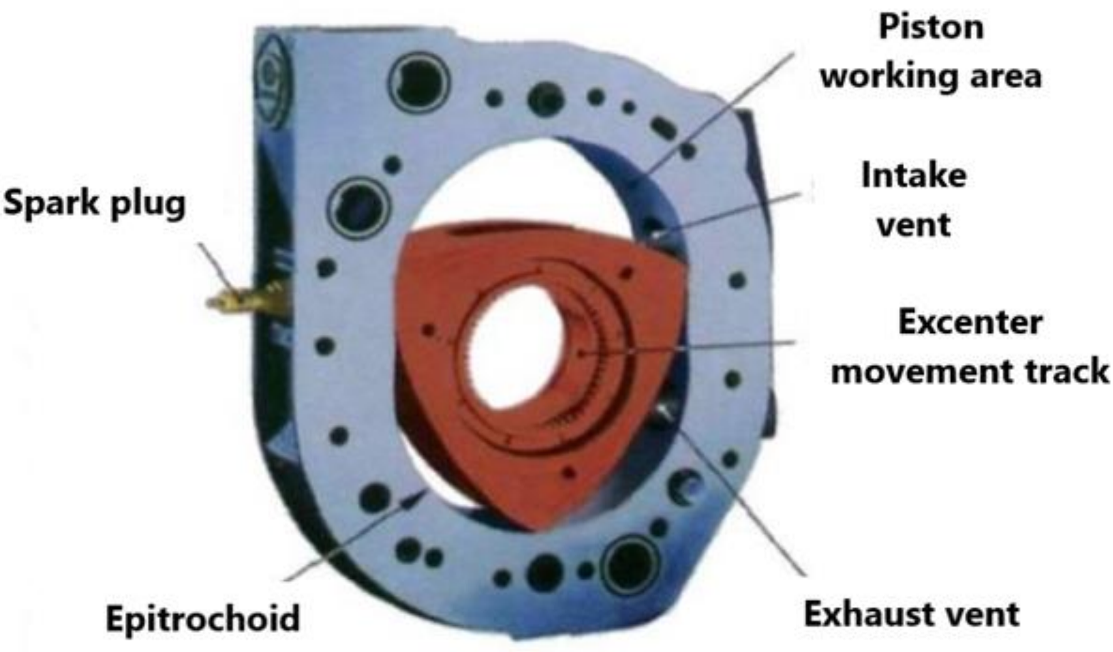

Figure 18:Wankel engine [37]

Figure 18 lists the individual parts of the Wankel engine. The engine consists of the spark plug, which is used to ignite with the spark. It also consists of the cabinet work surface, suction channel, eccentric orbit, exhaust channel and epitrochoid.

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[37] http://www.autorubik.sk/clanky/wankelov-motor/

Stirling´s engine

Robert Stirling created the reciprocating heat engine in 1816, in which he obtains energy for the duty cycle from an external source. Stirling engines weren´t among the most advantageous in terms of price and design, however, their advantages over other engines included low noise and low emissions in the exhaust. It is an external combustion engine [31].

Combustion turbine

The combustion turbine has found application mainly in military and transport aircraft, but also in helicopters, locomotives or maritime transport. All the present mention means are driven by the combustion turbine. The combustion turbine didn´t have much use in road transport. The only passenger car brand that uses the combustion turbine was ROVER. At present, automotive companies are trying to study the reduction of fuel consumption by increasing the temperature of the exhaust gases in front of the turbine. The temperature should rise up to 1 500 °C, which is only possible when using ceramic materials, e.g., on the turbine rotor blades [31].

The advantage of internal combustion engines is quick commissioning, the possibility of designing them to burn different fuels in different sizes and for different purposes, liquid fuel engines achieve low fuel consumption and reciprocating internal combustion engines have the high energy conversion. The disadvantages of internal combustion engines include, in particular, adverse effects on the environment, human health and other organisms, they need the foreign source to start and these engines also have the limited service life. Internal combustion engines are also the serious source of noise emissions [34].

3.2 EUROPEAN EMISSION STANDARDS FOR ROAD VEHICLES

The European Union has created EC/EEC directives that apply to all European Member States. Later, the directives were changed to EU regulations.

They are divided into two basic groups:

1. Emission regulations for passenger cars and light commercial vehicles (EURO 1, EURO 2, EURO 3, EURO 4, EURO 5, EURO 6),

2. Emission regulations for heavy trucks and buses (EURO I, EURO II, EURO III, EURO IV, EURO V, EURO VI).

Vehicles are divided by weight, if the weight is up to 2 610 kg, this is the first group. Weighing more than 2 610 kg, this is the second group of vehicles. European emission limits are set for diesel engines (diesel), but also for petrol engines (LPG, petrol, natural gas, etc.). CO diesel emission standards are stricter; NO_x values are higher. Spark ignition engines don´t have to undergo particulate measurement in the EURO 4 phase. In the EURO 5, 6 phases, the mass of particulate emissions is introduced. Emission regulations regulate the maximum amount of pollutants in the exhaust gases discharged from engines.

Regulated emissions include:

1. Particulate matter (PM) - formed only on diesel engines, it is carbon, ash, soot, residues of unburned oil or fuel,
2. Nitrogen oxides (NO_x) - is formed by oxidation of nitrogen added to the combustion chamber together with oxygen intended for oxidation of fuel or oxygen contained from fuels,
3. Hydrocarbons (HC) - are formed from fuel under poor oxidation conditions, also measured as THC or NMHC,
4. Carbon monoxide (CO) - is formed by imperfect combustion when there is the lack of oxygen in the combustion mixture.

EMISSION REGULATIONS FOR PASSENGER CARS AND LIGHT COMMERCIAL VEHICLES

Table 3: The emission limits Euro 5

		Reference weight (RW) (kg)	**Limit values**					
			Mass of carbon monoxide (CO)		**Mass of all hydrocarbons (THC)**		**Mass of non - methane hydrocarbons (NMHC)**	
			L1 ($\text{mg}\cdot\text{km}^{-1}$)		**L2 ($\text{mg}\cdot\text{km}^{-1}$)**		**L3 ($\text{mg}\cdot\text{km}^{-1}$)**	
Category	**Class**		PI	CI	PI	CI	PI	CI
M	**-**	All	1000	500	100	-	68	-
N1	**I**	RM≤1305	1000	500	100	-	68	-
	II	1305<RM≤1760	1810	630	130	-	90	-
	III	1760<RM	2270	740	160	-	108	-
N2			2270	740	160	-	108	-
		Reference weight (RW) (kg)	**Mass of nitrogen oxide (NO_x)**		**The sum of all weights ($THC+NO_x$)**		**Particulate mass (PM)**	
			L4 ($\text{mg}\cdot\text{km}^{-1}$)		**L2+L4 ($\text{mg}\cdot\text{km}^{-1}$)**		**L5 ($\text{mg}\cdot\text{km}^{-1}$)**	
Category	**Class**		**PI**	**CI**	**PI**	**CI**	**PI (2)**	**CI**

M	-	All	60	180	-	230	5	5
N1	**I**	RM≤1305	60	180	-	230	5	5
	II	1305<RM≤1760	75	235	-	295	5	5
	III	1760<RM	82	280	-	350	5	5
N2			82	280	-	350	5	5

Source [38] *(2) Particulate mass standards for positive ignition engines apply only to vehicles equipped with direct injection engines.*

PI = spark ignition, CI = diesel ignition

Emission limits were first regulated by Directive 70/220/EEC of 2004, later replaced by EC Regulation 715/2007 of 2007. Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 applies to new passenger cars and new commercial vehicles, new emission standards and thus replaces Regulations (EC) No. 443/2009 and (EU) No. 510/2011 (EUROPEAN PARLIAMENT AND COUNCIL OF THE EUROPEAN UNION, 2019).

Regulation (EU) 2019/631 seeks to comply with the Paris Agreement for 2021 - 2030, ensuring greener road transport, reducing high emissions and thus reducing greenhouse gas emissions. The Paris Agreement sets CO_2 emission limits for new passenger cars and new light commercial vehicles. The Paris Agreement aims to reduce greenhouse gas emissions by 30 % by 2030 compared to 2005 [38].

- EURO 1 (1993) - introduced by Directive 91/441/EEC, further amended 93/59/EEC,
- EURO 2 (1996) - introduced by Directive 94/12/EC, further amended by 96/69/EC,
- EURO 3/4 (2000/2005) - introduced by Directive 98/69/EC, further amended by 2002/80/EC,
- EURO 5/6 (2009/2014) - introduced by EC Regulation 715/2007 and EC Implementing Regulation 692/2008.

The Euro 5 standard introduced particulate filters (DPF/FAP) for all new diesel vehicles as the first standard. DPF/FAP is the filter mounted in the exhaust system and supplemented by the catalytic converter, which aims to capture particles up to 99 %.

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[38] EUR – Lex, an official website of the European Union. Available at https://eur-lex.europa.eu, last accessed February 2022.

To meet the new Euro 6 emission standards, some manufacturers have introduced selective catalytic reduction, in which AdBlue is injected into the exhaust of the diesel engine.

Table 4: Emission limits Euro 6

		Reference weight (RW) (kg)	**Limit values**					
			Mass of carbon monoxide (CO)		**Mass of all hydrocarbons**		**Mass of non - methane hydrocarbons (NMHC)**	
			L1 ($mg\cdot km^{-1}$)		**L2 ($mg\cdot km^{-1}$)**		**L3 ($mg\cdot km^{-1}$)**	
Category	**Class**		PI	CI	PI	CI	PI	CI
M	**-**	All	1 000	500	100	-	68	-
N1	**I**		1 000	500	100	-	68	-
	II		1 810	630	130	-	90	-
	III		2 270	740	160	-	108	-
N2			2 270	740	160	-	108	-
		Reference weight (RW) (kg)	**Mass of nitrogen oxide (NO_x)**		**The sum of all weights ($THC+NO_x$)**		**Particulate mass (PM)**	
			L4 ($mg\cdot km^{-1}$)		**L2+L4 ($mg\cdot km^{-1}$)**		**L5 ($mg\cdot km^{-1}$)**	
Category	**Class**		**PI**	**CI**	**PI**	**CI**	**PI (4)**	**CI**
M	**-**	All	60	80	-	170	5	5
N1	**I**		60	80	-	170	5	5
	II		75	105	-	195	5	5
	III		82	125	-	215	5	5
N2			82	125	-	215	5	5

Source [38], *(4) Particulate mass standards for positive ignition engines apply only to vehicles equipped with direct injection engines.*

PI = spark ignition, CI = diesel ignition

EMISSION REGULATIONS FOR HEAVY TRUCKS AND BUSES

Emission regulations stipulate that vehicles must comply with emission limits over the lifetime of the vehicle, depending on the vehicle category. The EURO V standard defines the so-called an improved vehicle that should be more environmentally friendly labelled as EEV. The EURO 0 emission class is intended for an emission class that we cannot determine on the basis of the table.

If it isn´t possible to determine the emission class of the vehicle from the technical license or from the vehicle registration certificate, etc., the emission class is determined according to the European Union directive on the basis of the marked parameter in the technical certificate or vehicle registration certificate. "Emission ES/EHK” [39].

Table 5:Norms EURO 0, I, II, III, IV, V, EEV

Class	**Year of manufacture / Date of first registration**
EURO 0, I, II	1992, <85kW
	1992, >85kW
	1996.10
	1998.10
EURO III	1999.10 EEVs
	2000.10
EURO IV, V, EEV	2005.10
	2008.10
	2013.01

Source [39]

Table 6: Vehicle service life

Vehicle category	Stage	
	Euro IV-V	Euro VI
M_1 N_1 M_2	100 000 km / 5 years	160 000 km / 5 years
N_2 N_3≤16 t M_3 class I, class II, class A and class B≤7.5 t	200 000 km / 6 years	300 000 km / 6 years
N_3>16 t M_3 class III and class B>7.5 t	500 000 km / 7 years	700 000 km / 7 years
Explanations: class I – city bus (>22 seats) class II – regional bus (>22 seats) class III – coach (>22 seats) class A – city bus (≤22 seats) class B – coach (≤22 seats)		

Table 6 shows the lifetime of each vehicle for proper emissions. The reduction of exhaust emissions is regulated in the most detailed emission regulation EURO VI.

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[39] Determination of emission class. Available at https://www.emyto.sk/files/2017-03/SVOP_03_Emisna_trieda_v4.0_svk.pdf. Last accessed February 2022

It regulates them especially in:

- Introduction of an ammonia emission limit,
- Implementation of the limit for particulate matter, which will lead to the decrease of up to 95 %,
- Introduction of emission standards for Europe, North America and Japan,
- Extension of emission requirements for service life up to 700 000 km or 7 years for the heaviest vehicles and the like.

Figure 19 shows the comparison of EURO I-VI emission regulations and the reduction of emission limits. EURO VI is the significant reduction in nitrogen oxides and particulate matter, and these pollutants are disproportionately interdependent. This means that the fewer solids there are, the more nitrogen oxides.

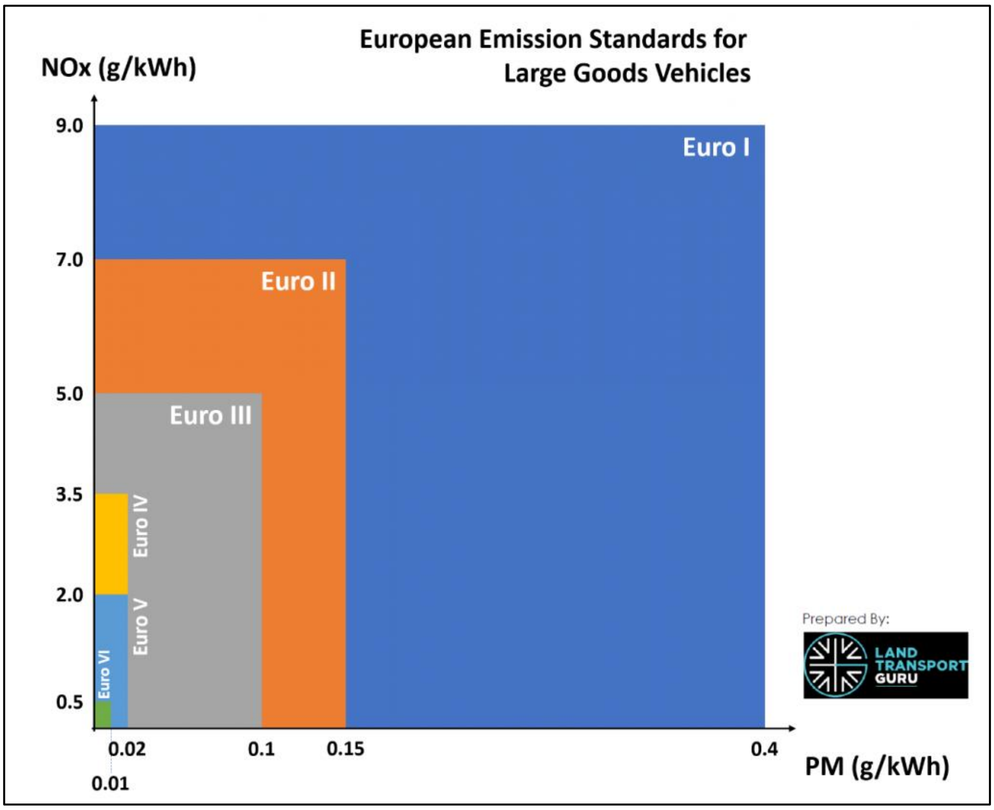

Figure 19: Prescription EURO I – VI[40]

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[40] Microsoft Bing, Images, available at https://www.bing.com/images/search?view=detailV2&ccid=fNYZb54n&id=B6F69E329823B1846872EDD149E1FB1B4B5E655A&thid=OIP.fNYZb54n7xhA1zplKJJxAAHaGA&mediaurl=https%3A%2F%2Flandtransportguru.net%2Fweb%2Fwp-content%2Fuploads%2F2014%2F02%2FNOx-PM-Graph-for-Euro-I-to-VI-1024x830.png&cdnurl=https%3A%2F%2Fth.bing.com%2Fth%2Fid%2FR.7cd6196f9e27ef1840d73a6528927100%3Frik%3DWmVeSxv74UnR7Q%26pid%3DImgRaw%26r%3D0&exph=830&expw=1024&q=re

3.3 METHODS OF MEASURING FUEL CONSUMPTION

When determining consumption, it is necessary to follow the methodology that sets the procedure and conditions of measurement. It should be as accurate as possible and should express the consumption of the vehicle as objectively as possible. In an effort to ensure the required measurement results, several types have been created that can be divided:

1. according to the place of execution:
   a) exterior - driving tests,
   b) interior - dynamometer tests;

2. according to the modes of operation of the vehicle:
   a) defined operating modes,
   b) normal operation of the vehicle;

3. according to the method of determining the amount of fuel consumed:
   a) volumetric (possible to perform in laboratories and outside),
   b) by weight (mostly subject to laboratory conditions).

EXTERIOR AND INTERIOR MEASUREMENTS

The driving tests

This type of test is performed on the road or test track. This is the test in which the operating conditions are simulated. The resistances acting on the vehicle are of the real nature; therefore, it is necessary to choose the right measurement procedure so that it comes as close as possible to the required operating conditions.

The dynamometer tests

Dynamometer tests are the substitute for driving tests and are performed when the suitable test track isn´t available or when the large number of measurements are made. That's why it's used by today's car manufacturers. In this measurement, the vehicle is placed on resistance cylinders, which are set to simulate the pre-calculated theoretical driving resistance of the vehicle. Subsequently, the measurement is performed with the vehicle, which must overcome the resistance force of the cylinders and thus consume the measured amount of fuel. These are less accurate measurement results than those obtained from driving test measurements.

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duction+of+NOx+by+HGV+emission+standsrds&simid=608027649944589771&form=IRPRST&ck=DE5E86C463D10ECE80DC16DF16AB62CD&selectedindex=0&ajaxhist=0&ajaxserp=0&vt=0&sim=11. Last accessed in July.

CONSUMPTION MEASUREMENT OPERATING MODES

Operating modes of consumption measurement are carried out according to predetermined conditions so that it is possible to quantify consumption and individual effects on it according to the results. These are most often certain operating modes that represent "points" on which to base comparisons. Most often it is the measurement of consumption at different speeds. For trucks, it can be, for example, at 40 $km \cdot h^{-1}$, 60 $km \cdot h^{-1}$, 80 $km \cdot h^{-1}$, 90 $km \cdot h^{-1}$ and the like. However, conditions such as the slope of the road on which the measurement is made and the actual weight of the vehicle and load must be defined. These must be observed in each measurement in order to obtain comparable results.

DRIVING CYCLES IN EUROPE

Driving cycles determine the dependence of vehicle speed on time. They are created by different countries and organizations to suit urban or extra-urban traffic. Driving cycles can be divided from several points of view:

- depending on the legislation:
  - legislative driving cycles
  - research and development driving cycles,
- in terms of shape - dependence of speed on time:
  - about actual driving cycles,
  - polygonal.

There are number of differences between driving cycles that affect the amount of pollutants produced and the amount of fuel consumption. Driving cycles developed in Europe are polygonal, which means that they are composed of constant accelerations, decelerations and speeds.

The driving cycles in Europe:

- ECE 15,
- EUDC,
- EUDCL,
- NEDC,
- WLTP.

Directive 70/220/EC lays down the procedure by which emissions testing of compression-ignition and compression-ignition engines of vehicles is carried out. This Directive is in accordance with UNECE Regulation 83 - Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants by the fuel requirements of the engine.

ECE 15

Driving urban cycle consisting of four identical parts. Each section has the length of 1.013 km and the vehicle will cross this track in 195 s. The total distance travelled during the cycle is 4.052 km in 780 s. The vehicle accelerates from rest to the steady speed of 15, 32 and 50 $km \cdot h^{-1}$, with an average speed of 19 $km \cdot h^{-1}$.

EUDC

This cycle is an extra-urban cycle lasting 400 s and during which the vehicle travels 6.955 km, reaching an average speed of 62.6 $km \cdot h^{-1}$. The maximum speed during this cycle is 120 $km \cdot h^{-1}$. During this cycle, the vehicle accelerates to 70 $km \cdot h^{-1}$, then decelerates to 50 $km \cdot h^{-1}$ and accelerates again to 70, 100 and 120 $km \cdot h^{-1}$.

EUDCL

This is the similar cycle to EUDC, except that it applies to motor vehicles with lower engine power. The maximum speed reached in this driving cycle is 90 $km \cdot h^{-1}$ and the average speed is 59.5 $km \cdot h^{-1}$.

NEDC

This driving cycle consists of four parts of the ECE 15 urban cycle and one extra-urban part of the EUDC cycle. The total duration of this cycle is 1 180 s. During this time, the vehicle will cover 11.007 km. The average vehicle speed during the driving cycle is 33.6 $km \cdot h^{-1}$. The vehicle starts with an engine with the temperature of 20 °C – 30 °C and the vehicle must have driven at least 3.000 km but no more than 15.000 km. The tests are performed on the vehicle with the driver weighing 75 kg and the load weighing 100 kg.

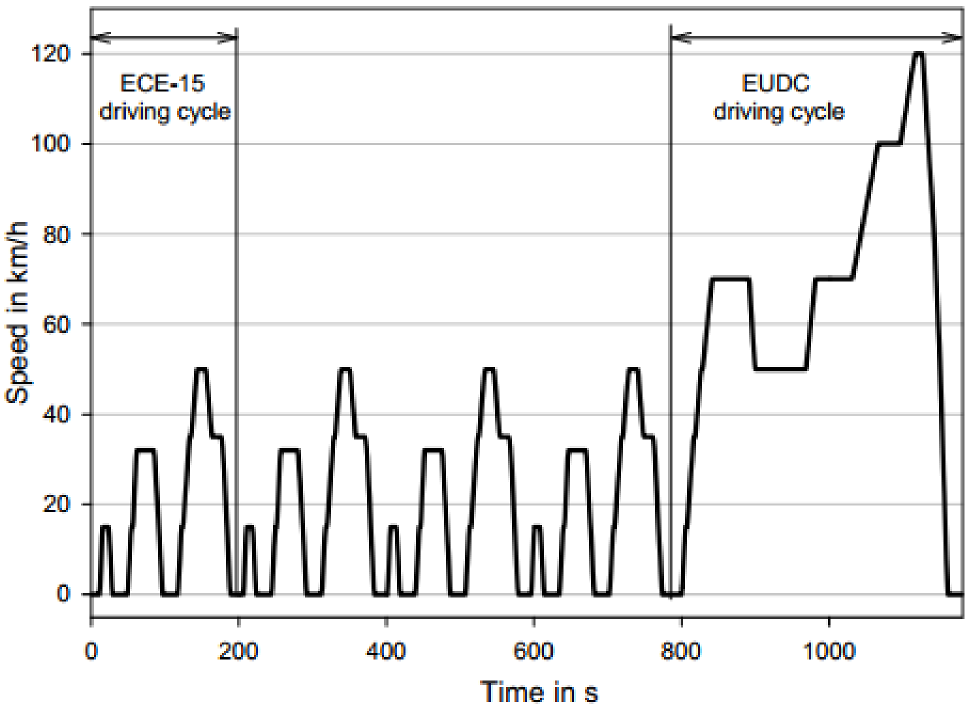

Figure 20:Driving cyclus NEDC

All mentioned cycles are model, because they don´t represent the real operation of the vehicle in road traffic.

WLTP

Since September 2017, the new methodology for determining fuel consumption and pollutants WLTP has entered into force. This driving cycle corresponds more realistically to the actual operation of vehicles in road traffic. This cycle is divided into three classes, which express the power-to-weight ratio of the vehicle.

Class 1

The cycle consists of low and medium speeds. The total duration is 1 022 s, the total distance covered is 8.091 km with an average speed of 28.5 $km \cdot h^{-1}$.

Class 2

The cycle includes low, medium and relatively high vehicle speeds. The total duration is 1 477 s, the distance is 14.66 km and the average speed is 35.7 $km \cdot h^{-1}$.

Class 3

This driving cycle consists of four parts of different types of traffic: urban traffic, extra-urban traffic, relatively high speeds, highway zone. The distance travelled during the cycle is 23.262 km, the duration is 1 800 s and the average speed is 46.5 $km \cdot h^{-1}$.

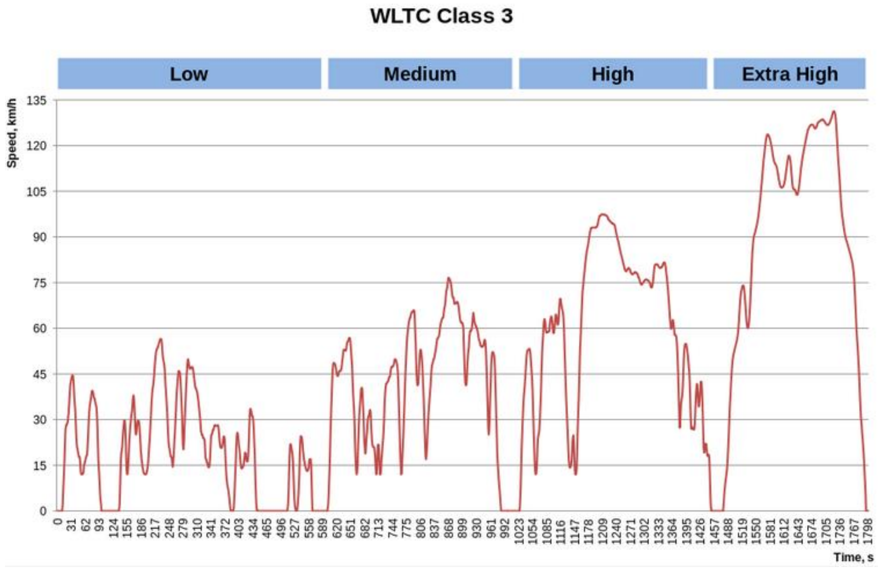

Figure 21:Driving cyclus WLTP - class 3

Normal vehicle operation

The results of such the measurement have the most accurate informative value from the point of view of the vehicle operator, as it provides results corresponding to the actual consumption of the vehicle during actual operation. Such measurements may be made by imitating the actual traffic, in particular the route, the weight of the load, the speed profile and the operating time, or by taking measurements during the actual operation of the vehicle. With such measurement methods, it is advisable that the driver isn´t familiar with the fact that the measurement is being performed in order to avoid influencing the measurement results.

METHODS OF DETERMINING FUEL CONSUMPTION

Mass (gravimetric) method

The amount of energy in the fuel depends on its weight, therefore the consumed weight of the fuel directly determines the energy intensity. The principle is most often that the fuel in the tank is weighed before and after the measurement and the difference in weight represents the weight of fuel consumed. The weight can also be monitored at some specified intervals or continuously during the measurement. It is used more often to determine engine consumption or total vehicle consumption when determining steady state consumption. Eliminates the difference in specific gravity of fuel in the incoming and outflow branches caused by fuel heating. Therefore, it is mainly used for scientific and research purposes and is mostly tied to laboratory conditions.

Volumetric method

This method, as the name implies, is the measure of the volume of fuel consumed. The amount of fuel is expressed in units of volume. The consumption of road motor vehicles is most often expressed in $l \cdot 100km^{-1}$, in the case of special vehicles litres per engine hour. This method is more flexible due to the measurement procedure and the instrument used. Therefore, it is used for driving tests outside laboratories.

Due to the changing fuel density due to ambient temperature and atmospheric pressure, it is necessary to convert the volume of fuel consumed to the volume at standardized values.

We can measure the volume of fuel consumed by measuring devices, the so-called flow meters. They work on the principle of mechanical measurement of the volume of fuel flowed. This movement of mechanical parts is converted into electrical pulses at the certain frequency (the higher, the more accurate and better), which is processed by the evaluation electronics and thus provides outputs in the form of consumption units. Due to the complexity of flow meters and evaluation electronics, the outputs can represent the total fuel consumption per measurement, the instantaneous consumption in litres per hour or if they cooperate with the vehicle speed sensor in $l \cdot 100km^{-1}$. The flow meter is connected directly to the vehicle's fuel system so that all the fuel flowing to the injectors flows through them, but also back (overflow branch). In high-pressure injection systems, the flow meters are connected to the low-pressure part. Specifically, before the feed pump if it is the vacuum pump. If it is the pressure pump, it is connected to it. Simpler one-way flow meters can be used with feed pumps with an internal fuel return loop. In these systems, the exact dose of fuel injection is regulated directly in the feed pump, so only one branch with one direction of fuel flow goes to the injectors. Unidirectional flow meters measure the volume of fuel flow in only one direction. In systems with fuel injection control in the injector (e.g., Common Rail system) there are two branches of the fuel line and therefore it is necessary to use bidirectional flow meters. These measure the volume of fuel flowing from the tank to the injector and also the volume of unconsumed fuel returning in the return branch from the injectors. The difference between these two measured volumes represents the actual consumption of the vehicle. The flowmeters measure with an accuracy of approximately 0.5 %.

Fuel consumption monitoring

In addition to vehicle monitoring, telematics applications also serve to monitor fuels. The basis of this monitoring is the prevention of fuel theft and the acquisition of objective data on their consumption. Such an analysis has the effect of reducing carriers' costs and fuel consumption by an average of 5.5 %. Fuel consumption measurement solutions can be performed by collecting data from the vehicle control unit using CAN/FMS buses, the level probe or the flow meter. The resulting course of fuel consumption as the function of time and distance travelled is displayed on the dispatcher's desk in the form of the graph. The analysis should focus on the sharp drop in fuel in the tank. It is about control and protection against their theft and illegal evacuation. However, they can also be caused by the vehicle's on-site performance.

3.4 LIFE CYCLE ASSESSMENT OF CONVENTIONAL FUEL VEHICLES - A CASE STUDY

Here we present a case study that can help students in understanding a practical case study of a life cycle assessment (LCA) of vehicles. We conducted LCA for internal combustion engine vehicles (ICEVs), which include: petrol-fuelled and diesel-fuelled passenger cars.

We analysed carbon footprint, water footprint and resource footprint of these vehicles. We conducted LCA in accordance with the ISO 14040:2006 guidelines using the SimaPro v. 9 software with the Ecoinvent v.3 database (for more details on LCA tools, please refer to “5. TOOLS FOR LCA AND ENVIRONMENTAL IMPACT ASSESSMENT”). Environmental assessment of petrol and diesel passenger cars was carried out according to four phases of LCA:

- Defining the goal and scope
- Defining the life cycle inventory
- Life cycle impact assessment
- Interpretation.

For LCA analyses, we assumed a functional unit (FU) equal to 100 km. We performed a comparative analysis between the environmental impacts of petrol-fuelled

ICEVs and diesel-fuelled ICEVs. The system boundaries for the analysed passenger car life cycle are shown in Figure 22.

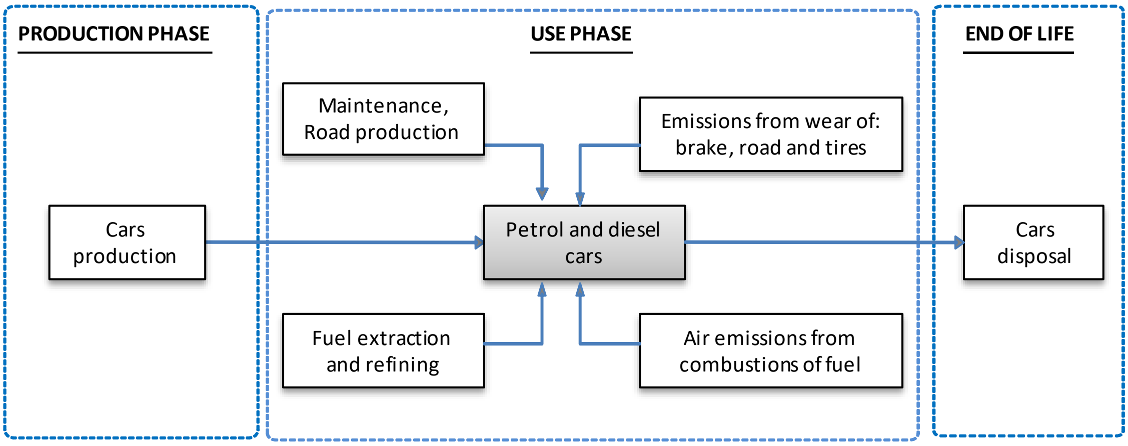

Figure 22:System boundaries of the analysed passenger car life cycle [41]

The system boundaries extend over a cradle-to-grave range: production of passenger cars, fuel production (diesel and petrol), car operation phase (including car maintenance), emissions related to the operation of cars, road construction, disposal of cars, and maintenance (Figure 22). We conducted LCA for transport by small passenger cars with internal combustion engines, both petrol and diesel fuelled. We have chosen small cars for the analysis, because small engines are more common than medium-size and large engines in the European Union countries. The average weight of small cars was estimated at 1,200 kg. The assumed engine size was up to 1.4 l. The analysis is comprised of small passenger cars of the Euro 5 class.

In the second phase of LCA - defining the life cycle inventory – we analysed the inputs and outputs data for car life cycle. The data included the construction, operation, maintenance and disposal of cars. To LCA analysis we needed all the direct emissions caused by fuel combustion and non-exhaust emissions, such as those generated by the wear of tyres and brakes as well as road pavement.

The data for the LCA are from Simapro. The main inputs for electric vehicles include: li-ion battery, electric passenger car production, maintenance, electricity production. The main outputs include: brake wear emissions, road wear emissions and tire wear emissions.

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[41] Burchart-Korol D.; Folęga P.: Comparative life cycle impact assessment of chosen passenger cars with internal combustion engines, *Transport Problems* 2019 vol. 14 iss. 2 s. 69-76

The main inputs for internal combustion engine vehicles fuelled by petrol and diesel include: passenger car maintenance, passenger car production, fuel production. The main outputs for internal combustion engine vehicles fuelled by petrol and diesel include: emissions to air carbon dioxide, carbon monoxide, non-methane volatile organic compounds, nitrogen oxides, particulates and sulphur dioxide, brake wear emissions, road wear emissions and tire wear emissions.

The next phase, namely the life cycle impact assessment (LCIA), enabled calculation of values of the environmental impact categories according to the assessment methods selected in Simapro software. We have chosen the LCIA methods which enabled us to perform the assessment of individual environmental footprints: carbon footprint, water footprint and resource footprint of petrol-fuelled and diesel-fuelled passenger cars.

The carbon footprint enables the analysis of greenhouse gas emissions taking into account direct and indirect impacts on human activities, expressed in a reference unit of kg CO_2. Carbon footprint is calculated on the basis of the global warming potential (GWP).

Water footprint enables the analysis of water use over the life cycle of a product. This indicator is applied to the volume of consumed water, and it only assesses used water. The total amount of water footprint is expressed in a reference unit of m^3.

What also matters from the perspective of circular economy is **resource footprint**, which covers depletion of fossil fuels, metals and minerals. The total amount of resource footprint is expressed in a reference unit of MJ.

Our LCA analysis allowed us to identify the main negative factors that influence individual environmental footprints. We called the main negative factors as **determinants** - these are the main elements in the entire life cycle of a vehicle that have the most negative impact on a given environmental footprint. The results of the LCA for individual footprints we presented in the form of diagrams. Below is a diagram description for all LCA analysis.

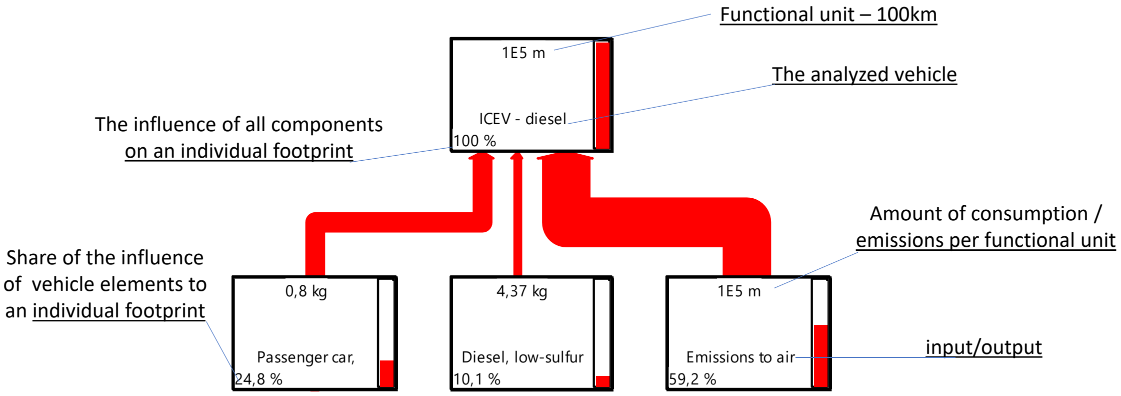

Figure 23: diagram description for LCA analysis

The red colour of the arrow indicates a negative impact on the environment. The arrows are directed from the input / output to the vehicle being analysed. The thickness of the arrow indicates the magnitude of the negative environmental impact, in this case the magnitude of the individual environmental footprints. The thicker the red arrow, the greater the negative impact. The main determinant of the environmental impact is the element from which the thickest arrow comes out. The functional unit is 100 km. The amount of consumption of all inputs is converted into the functional unit - for example for diesel ICEV - 4.37 kg means consumptions of diesel for 100 km in the case of a passenger car. The amount 10.1% means that diesel production constitutes 10.1% of whole GHG emission in the life cycle of ICEV.

RESULTS OF CARBON FOOTPRINT ASSESSMENT OF CONVENTIONAL FUELED VEHICLES

We established the determinants of carbon footprint for petrol-powered vehicles and diesel-powered vehicles. The results of the assessment of the carbon footprint have been illustrated in Figure 25.

The main determinants of carbon footprint for ICEVS (diesel and petrol) are emissions to air, accountable for 59.2% and 59.8 % of the footprint, respectively (Fig 24 and Fig 25). Much of carbon footprint is also connected with the production of vehicles (determinant expressed as passenger car) and fuels (determinant expressed as petrol low-sulphur).

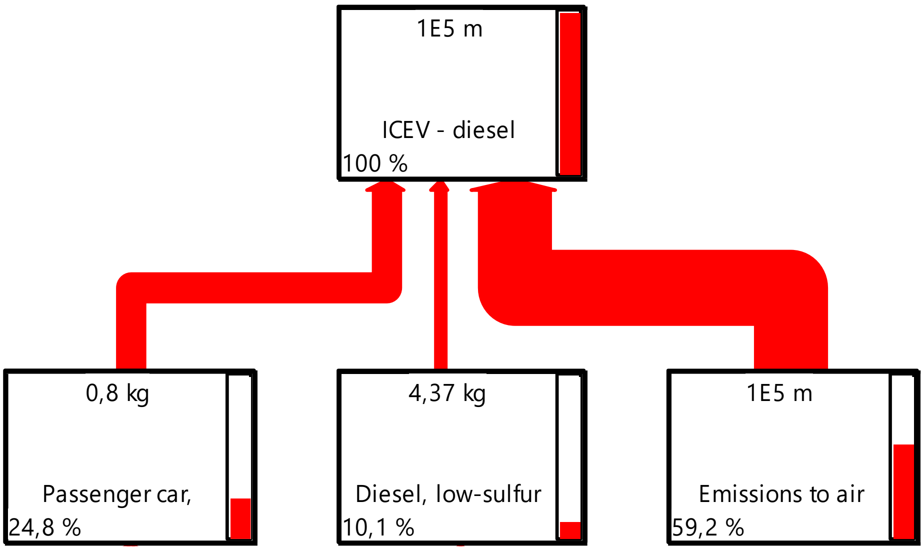

Figure 24: Determinants of the carbon footprint of diesel-powered vehicles (diesel ICEVs)

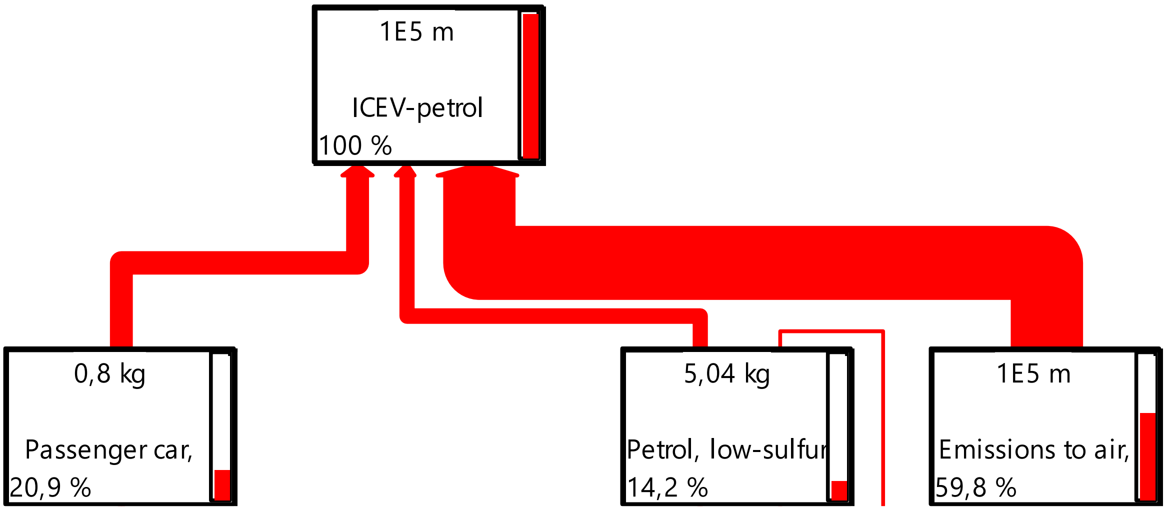

Figure 25: Determinants of the carbon footprint of petrol-powered vehicles (petrol ICEVs)

Our comparative life cycle analyses of petrol-powered vehicles and diesel-powered vehicles showed that the carbon footprint attributable to diesel-fuelled passenger cars is lower than that of petrol-fuelled passenger cars, which is primarily affected by the higher carbon footprint caused by petrol production as well as direct CO_2 emission related to the operation of petrol-fuelled cars. The main carbon footprint determinant for these conventional fuel vehicles is the direct atmospheric emission of carbon dioxide associated with operation of cars. The carbon footprint of petrol- and diesel-fuelled passenger cars is primarily attributable to the operation of these vehicles. Therefore, in order to reduce their impact on the environment, one should undertake specific efforts aimed at increasing the share of alternative fuels in the mix of fuels powering passenger cars.

RESULTS OF WATER FOOTPRINT ASSESSMENT OF CONVENTIONAL FUELED VEHICLES

We established the determinants of water footprint for petrol-powered vehicles and diesel-powered vehicles. The results of the assessment of the water footprint are presented below.

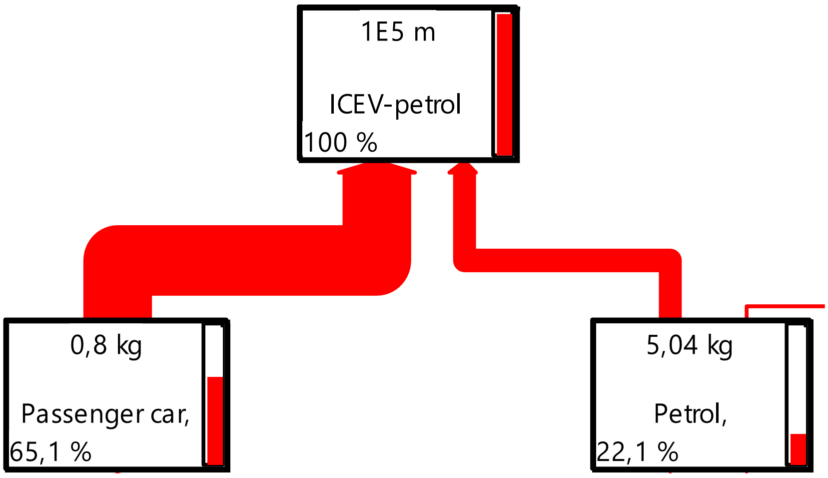

Figure 26:Determinants of the water footprint of ICEVs-petrol

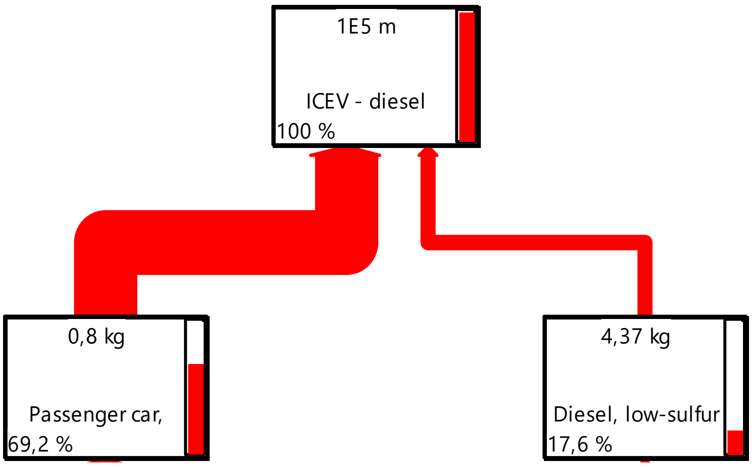

Figure 27: Determinants of the water footprint of ICEV- diesel

As previous analysis implies, the main determinant of the water footprint of ICEVs is vehicle production. A large influence of water footprint is also attributable to fuel production.

RESULTS OF RESOURCE FOOTPRINT ASSESSMENT OF CONVENTIONAL FUEL VEHICLES

We established the determinants of resource footprint for petrol-powered vehicles and diesel-powered vehicles. The results of the assessment of the resource footprint are presented in Figure 28, Figure 29.

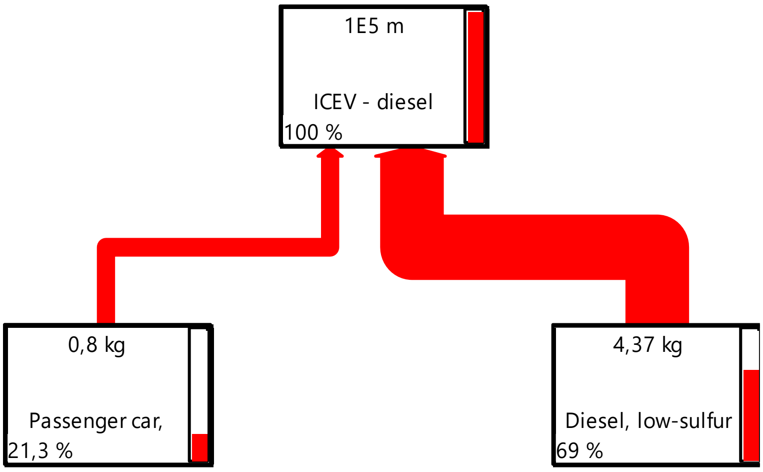

Figure 28:Determinants of the resource footprint of diesel-powered vehicles

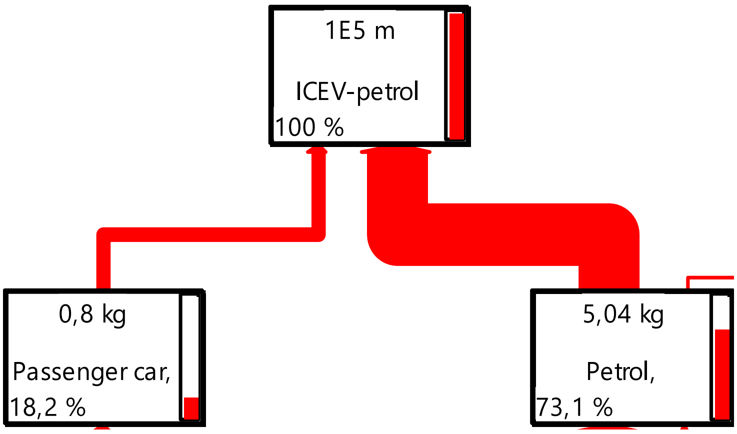

Figure 29:Determinants of the resource footprint of petrol-powered vehicles

Regarding ICEVs, the fuel production stage is the main determinant of resource footprint.

3.5 COMPARISON OF INDIVIDUAL AND PUBLIC PASSENGER TRANSPORT

The results of practical consumption measurements in real operation are presented on consumption, passenger train, bus and passenger car. Indicators such as energy consumption and greenhouse gas production were monitored, taking into account the W-t-W principle.

Consumption was calculated on the Žilina - Rajec route and back in the Slovak Republic, comparing rail passenger, bus and individual transport.

The railway line between Žilina and Rajec, Slovakia is non-electrified. At present, regional trains of independent traction run on it in one to two-hour cycles. The railway line as well as the road run along the river Rajčanka. The length of the track is 21.3 km.

The difference in altitude between Žilina (340) and Rajec (450) causes the ascent of the line to reach the highest value of 13 ‰, except for the short ascent behind the railway station in Žilina, where the ascent reaches 17 ‰ for the short time. The average climb between terminals is 5 % Figure 30 [42].

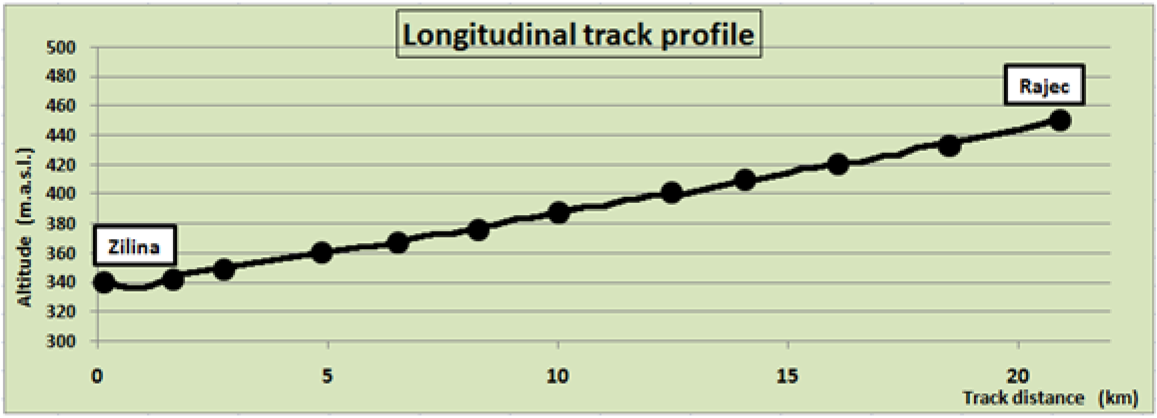

Figure 30:Longitudinal profile of the railway line with stops

There are 12 railway stops and stations on the line, Žilina is the first at the beginning and Rajec is the last at the end of the line. The maximum line speed is 60 km·h^{-1}, but on

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[42] Skrúcaný T., Ponický J., Kendra M., Grenčík J. Energy consumption and GHG production on chosen railway track in regional passenger transport. 22-nd international conference: Current problems in rail vehicles, VOL II, Žilina, 2015

some line sections the speed is limited to only 50 or 40 km·h^{-1}. Travel time between terminals is approximately 37 minutes. The average number of passengers carried in 2014 per train was approximately 32 people.

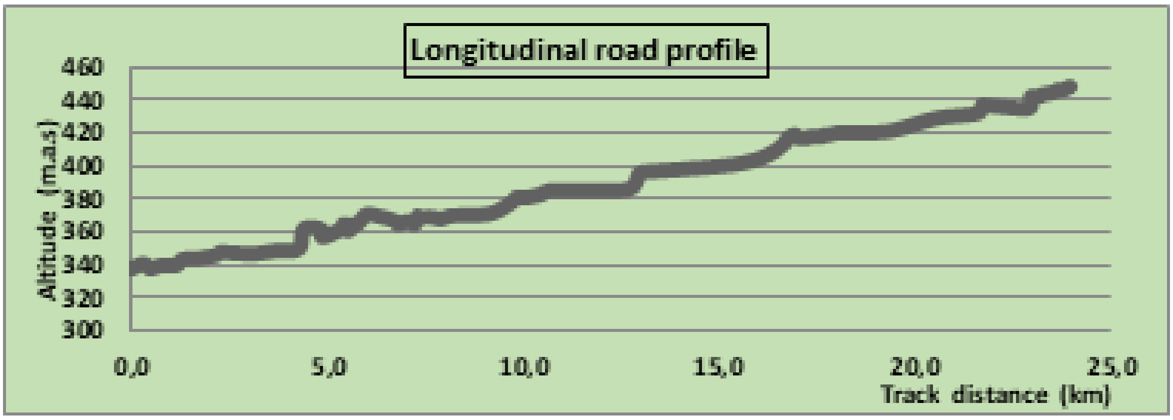

Figure 31: Longitudinal profile of the road

The 813-913 series engine unit, which was manufactured in ŽOS Zvolen (Slovakia) by the reconstruction of the old 810 series wagons, was used to measure train consumption.

The Karosa C954 bus manufactured by Karosa Vysoké Mýto (Czech Republic) in the period from 2001 to 2006 was used to measure bus consumption.

More detailed technical parameters of vehicles are given in Table 7.

Figure 32: compared vehicles (left: the train motor unita 813-913, right: bus Karosa C 954)

The simulation software Railway Dynamics was used to calculate the energy consumption of the train (Figure 33). Energy consumption by train was calculated on the basis of pre-selected and defined parameters on the defined route. The software works with imported track direction and altitude guidance. Based on the defined parameters (engine unit series, train weight, train length, axle load, number and location of stops), the energy consumption in kWh was calculated. This software can be used to calculate the energy consumption and travel time of any train on any railway line. It is only necessary to import the basic train parameters and track data for the calculation.

Table 7: basic technical parameters of bus and train

Vehicle	Motor unit 813-913	bus Karosa C 954
Drive arrangement	1´A´ + 1’1’	-
The energy source	Diesel	Diesel
Power transmission	hydromechanical	mechanical
Max. speed	90 km·h^{-1}	105 km·h^{-1}
Combustion engine	MAN D 2876 LUE 21	Iveco Cursor F2 B
Engine power	257 kW	228 kW
Weight of empty vehicle	39 t	10.8 t
Loaded vehicle weight	53 t	18 t
Vehicle length	28 820 mm	11 990 mm
Number of seats	78 + 5	49
Maximum number of standing passengers	120	39

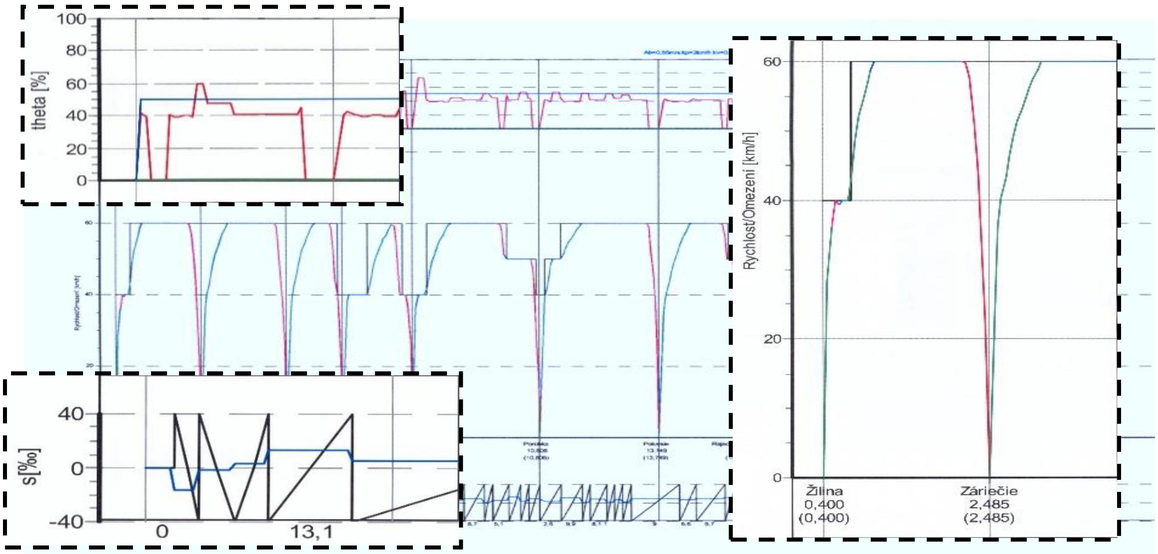

Figure 33: Output data from the Railway Dynamics software (Source: software Railway dynamics)

The calculation in this case study was made for driving in both directions, i. one to climb and the other to descend. Consumption results for both directions are included in the final evaluation (Table 8). Table 8 shows the advantage of bus transport. This is that despite the parametrically very similar engines (power, consumption) of the train and bus, as well as the lower difficulty of the railway line, the railway vehicle achieves higher fuel consumption on the monitored line than the bus. This is due to the own weight of the railway vehicle of 39 t, which is 28 t more than the weight of the bus (cca 11 t).

Table 8: Train - bus calculation results

Vehicle occupancy	Vehicle	Fuel consumption [L]	Total energy consumption [MJ]	Total production of CO_{2e} [kg]	Number of passengers	Energy consumption per passenger [MJ·person^{-1}]	Production of CO_{2e} [kg·person^{-1}]
Full occupancy	Train	22.98	981.2	74.4	83	11.82	0.90
	Bus	12.48	532.9	40.4	49	10.88	0.83
Actual number of passengers	Train	19.23	821.3	62.3	32	25.66	1.95
	Bus	11.76	502.2	38.1	26	19.31	1.47

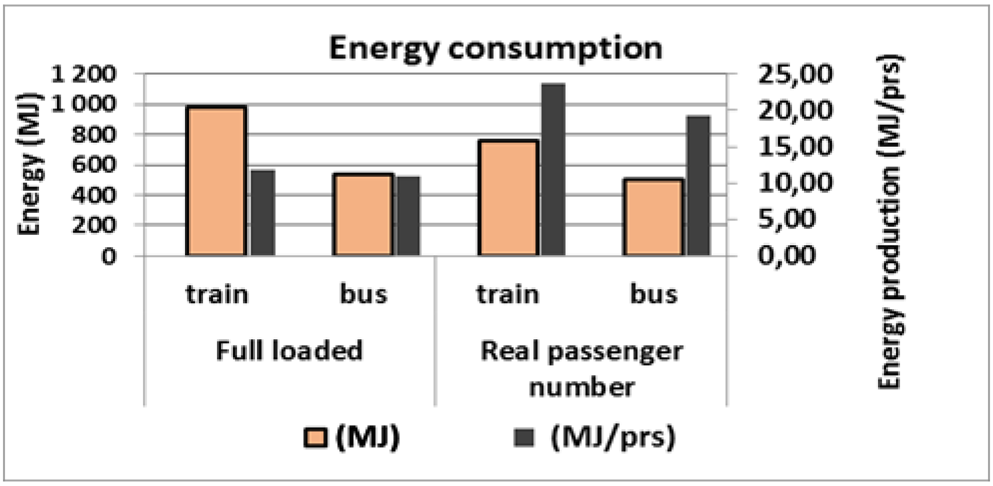

Figure 34: Comparison of train and bus energy consumption

The result of the simulation of the fuel consumption of the motor train was compared with the real consumption of this unit on the line in question. The result of the simulation was confirmed, as the difference compared to real consumption was only - 8.5 %. Therefore, all consumption results were increased by 8.5 % to bring it closer to reality.

Although the motor train achieves higher values of the actual number of passengers, it doesn´t achieve higher efficiency than the bus. As mentioned earlier, this is due to the higher dead weight of the train. When calculating the total energy consumption in the actual use of the vehicles, the energy consumption of the bus represents only 54 to 66 % of the train consumption. When calculating energy consumption per passenger (MJ·person^{-1}), the difference is significantly lower (75 to 92 %) due to the higher capacity of the train. Regardless, the efficiency of bus transport is more efficient in terms of energy consumption, but with maximum use of train capacity, or the use of parking spaces, rail transport would be closer to road efficiency, in some cases it could be more efficient in terms of the number of people transported.

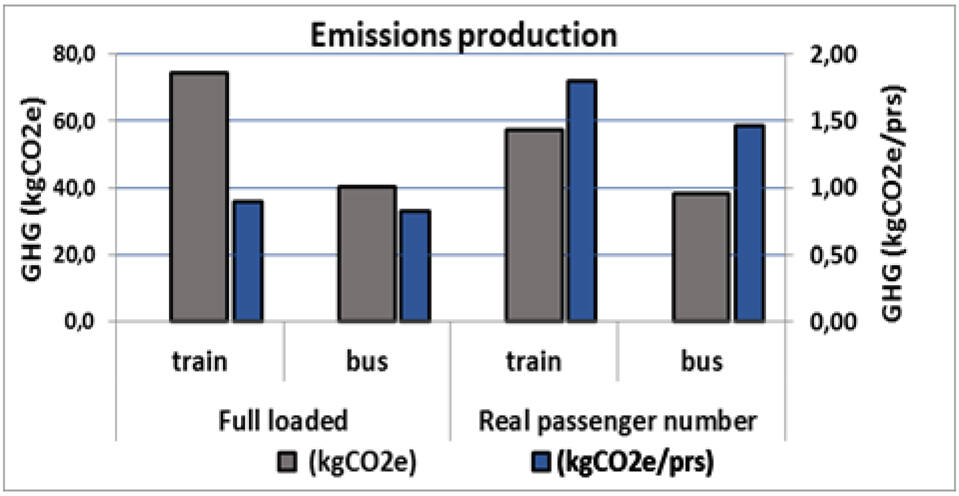

Figure 35: Comparison of greenhouse gas emissions by train and bus operation

Similar to energy consumption, it is also possible to calculate greenhouse gas emissions. The ratio between vehicle GHG emissions is similar to energy consumption, as it was calculated according to EN 16 258:2012, where GHG production is the product of fuel consumption and emission factor.

The next section compares the consumption of the passenger train with the passenger car. The technical parameters of the car are listed in Table 9.

Table 9: Technical parameters of vehicle [43]

Skoda Fabia III	
Year of production	2016
Engine	1.2 TSI, DOHC
Fuel	gasoline
Overfilling	turbocharger
Engine code	5J
Transmission	Mechanical (manual)
Number of gears	5
Speed power	66 kW / 4 400 min^{-1}
Torque at speed	160 Nm / 1 400 min^{-1}
total weight	1 564 kg
Standby weight	1 133 kg
Fuel consumption in the city (manufacturer's data)	6 l·100km^{-1}
Fuel consumption in the city (manufacturer's data)	4 l·100km^{-1}

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[43] Kendra M., Skrúcaný T., Synák F., Škorupa M., Grenčík J.: Energy intensity of railway and road passenger transport and its breaking point according to vehicle capacity usage. 7th Transport Research Arena TRA 2018, Vienna. https://doi.org/10.5281/zenodo.1421671

Figure 36: Škoda Fabia III – car used for measurement

The results of the passenger car measurements showed the large discrepancy between the manufacturer's declared fuel consumption and that actually measured. The measured one represents higher values in the range of 8 to 11.5 % compared to the declared fuel consumption of the car. In absolute terms, fuel consumption on the monitored route ranged from 4.33 to 4.56 l·100km^{-1}. All sections were measured in triplicate.

The very small deviations between the measurements were due to the driver's driving style as similar as possible. The measurement was performed in the early morning hours without traffic of other vehicles, the average section speed of the car was constantly monitored and adjusted, and the car's cruise control was used as much as possible. By this procedure, the minimum deviation of the results of individual measurements, repeatability, was achieved. The measured differences therefore represent the effect of the car's load.

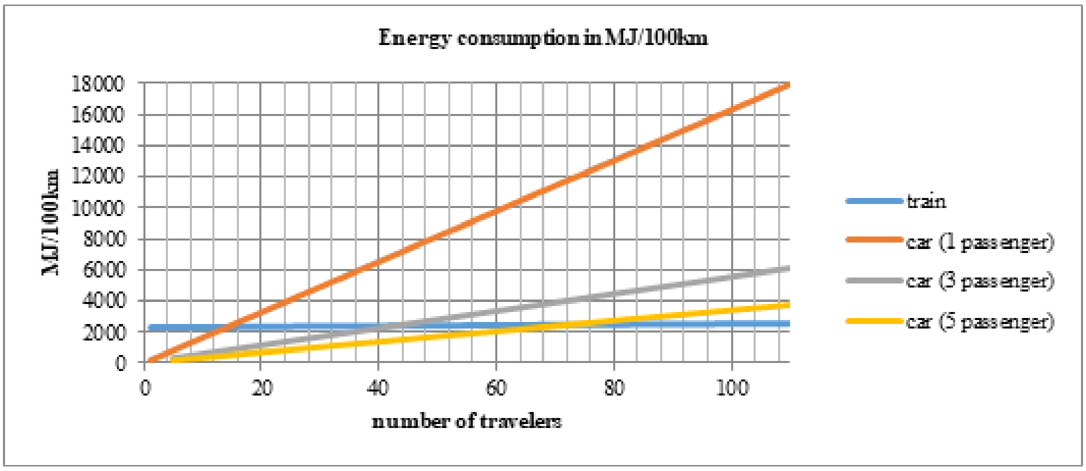

Figure 37: Comparison of train and car energy consumption

Figure 37 testifies to the energy consumption per 100 km of individual means of transport (train, passenger car) with regard to their occupancy, resp. required number of transported persons. The worst case in terms of energy efficiency is the transport of only one person in the car (the driver himself). The required number of used cars is equal to the number of transported persons, which represents the steep slope of the line (red). Efficiency increases many times as the number of people in the car increases. Although the car's fuel consumption increases in terms of instantaneous weight and thus the number of passengers, taking into account three to five times less required number of vehicles than in the first case, this is an increase in efficiency. This fact can be seen in absolute terms in Figure 37 and in relative terms in Figure 38.

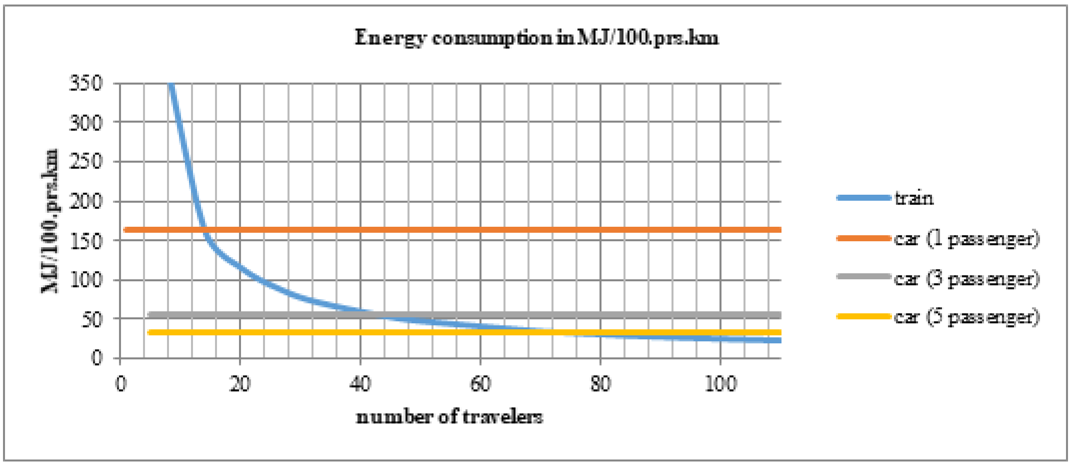

Figure 38: Relative comparison of energy consumption

The intersections of the curves in Figure 37 represent the limit values of train and car use efficiency according to the number of transported persons. If the train were the standard, it would be more efficient than the car in carrying more than 14 passengers. In practice, this means that on an evaluated transport route, the car with the driver is more efficient than the train occupied by less than 14 people. When using the car for the full number of seats, i. 5 people, the train becomes more efficient when transporting about 73 people, which is almost 90 % of the capacity of the seats (83 seats).

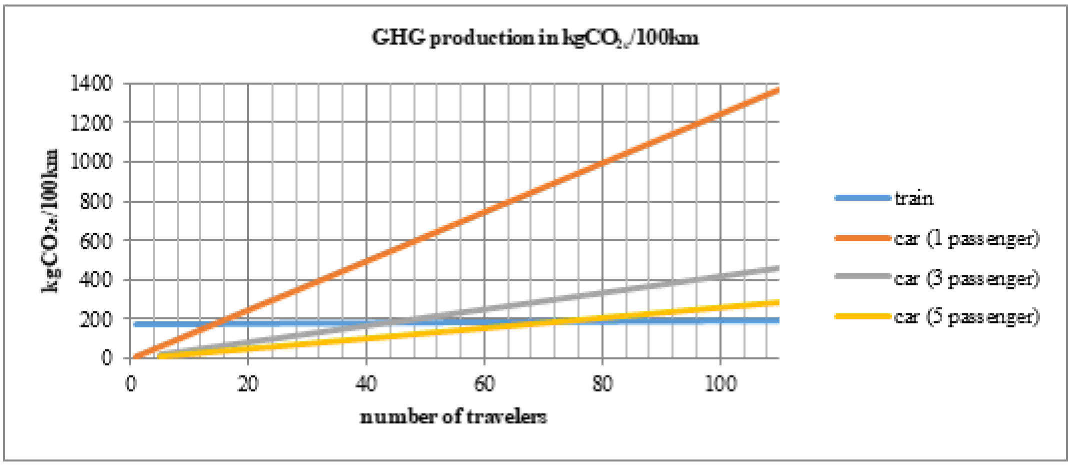

Figure 39: Comparison of greenhouse gas emissions from train and car operation

The rate of greenhouse gas emissions from the operation of the train and the passenger car in the measured area is directly related to the consumption of energy, i.e., fuel. It is also noticeable on both graphic expressions in Figure 39 and Figure 40.

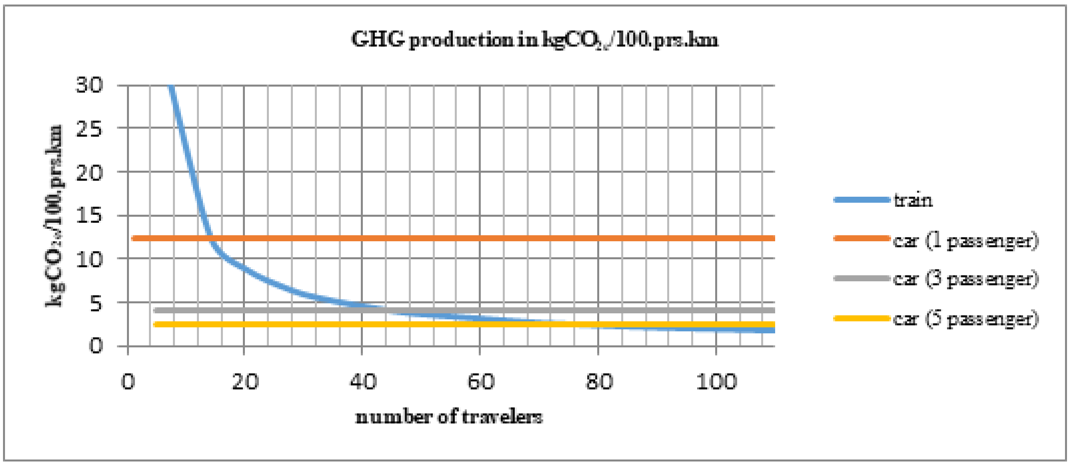

Figure 40: Relative comparison of greenhouse gas emissions

The amount of greenhouse gases produced was calculated on the basis of the standard. It takes into account greenhouse gas production coefficients ew (emission factor) constant with respect to the volume of fuel consumed ($kgCO_{2e}{\cdot}l^{-1}$), the amount of fuel consumed ($kgCO_{2e}{\cdot}l^{-1}$) or the amount of energy consumed in the fuel ($gCO_{2e}{\cdot}MJ^{-1}$), in this case petrol, or diesel. Thus, the amount of greenhouse gases produced is directly proportional to the amount of fuel burned.

Due to the value of emission factors of the compared fuels, petrol (75.2 $gCO_{2e}{\cdot}MJ^{-1}$) is at the slight disadvantage compared to diesel, which has the slightly lower value of the emission factor (74.5 $gCO_{2e}{\cdot}MJ^{-1}$). However, with the amounts of energy consumed in the means of transport considered and rounded to the nearest whole, this does not affect the change in the results of the relative expression of the greenhouse gas production of vehicles versus the relative expression of energy consumption. Therefore, also in terms of greenhouse gas production, the train is more efficient when it is occupied by more than 14 people compared to the car with only the driver. In relation to the car carrying 3 or 5 people, the train becomes more efficient only from the occupancy of 44, resp. 73 people.

The results of these practical measurements were not intended to determine which mode of transport is better or more environmentally friendly. This cannot be said unequivocally, as energy efficiency and greenhouse gas production depend not only on fuel and energy consumption but also on the capacity utilization of the means of transport. It is important to ensure the highest possible usability of means of transport by passengers, e.g., appropriate choice of vehicle for the particular traffic flow. The efficiency of ecological transport also decreases with the decreasing real usability of the means of transport. Therefore, an appropriate combination of the size of the traffic flow and the vehicles in operation is one of the steps to ensure environmentally friendly public passenger transport.

3.6 CHAPTER REFERENCES

Summarization

At the end of this chapter, students will understand following terms:

- Internal combustion engine
- European emission standards
- Emission regulations
- Emission limits
- Fuel consumption measuring
- Driving cycles
- Energy consumption
- Greenhouse gases production

Questions

- Which fuels are used in conventional internal combustion engines?
- What are the basic phases of operation of a four-stroke engine?
- What are the advantages of a petrol engine?
- What are the advantages of a diesel engine?
- In which two basic groups are European emission standards divided?
- Which emissions are regulated by European emission standards?
- What are the differences between the specific European driving cycles?
- What are the methods of fuel consumption measuring?
- Which environmental footprints of internal combustion engines do you know?
- Which technical characteristics of the vehicles affect its operational efficiency in terms of energy consumption and greenhouse gas production?

Abbreviations

BSFC - Brake Specific Fuel Consumption

CAN - Controller Area Network

CI - Diesel Ignition

CO - Carbon Monoxide

CO_2 – Carbon Dioxides

DALY - Disability-Adjusted Life Year

DPF/FAP - Diesel Particulate Filter

EC - European Community

ECE 15 - United Nations Economic Commission for Europe specification for urban driving cycle simulation

EEC - European Economic Community

EEV - Enhanced Environmentally friendly Vehicle

EHK - United Nations Economic Commission for Europe

EN - European standard

ES - European Communit*y*

EU - European Union

EUDC - Extra Urban Driving Cycle

EUDCL - Extra Urban Driving Cycle applies to motor vehicles with Lower engine power

FMS - Functional movement screen

FO - Functional Unit

GHG - Greenhouse Gas

GWP - Global Warming Potential

HC - Hydrocarbons

ICEV - Internal Combustion Engine Vehicle

IPCC - Intergovernmental Panel on Climate Change

ISO - A network of national standards institutes from 148 countries (derived from the Greek word "*isos*" meaning "equal")

LCA - Life Cycle Assessment

LCIA - Life cycle impact assessment

LPG - Liquefied Petroleum Gas

NEDC - New European Driving Cycle

NMHC - Non-methane Hydrocarbons

NO_x - Nitrogen Oxides

PI - Spark Ignition

PM - Particulate Matter

RW - Reference Weight

THC - Tetrahydrocannabinol

UNECE - United Nations Economic Commission for Europe

WLTC - Worldwide harmonized Light-duty vehicles Test Cycle

WLTP - Worldwide harmonized Light-duty vehicles Test Procedure

W-t-W - Well-to-Wheel

ŽOS - Company for railway repairs and engineering (Železnične opravovne a strojárne)

4. LCA IN AUTOMOTIVE: ALTERNATIVE FUEL VEHICLES

Time to study 120 minutes

Objectives

WHAT KNOWLEDGE STUDENTS WILL ACQUIRE

Students will acquire knowledge about application of life cycle assessment LCA in automotive, specially LCA of alternatively fuelled vehicles like battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEV)

HOW IT WILL HELP THEM TO UNDERSTAND THE TOPIC

Students will learn the methodology of LCA analysis, various environmental footprints and the essence of these environmental assessment methods for the automotive industry

WHAT SKILLS THE CHAPTER WILL DEVELOP

The chapter guarantees the acquisition of the necessary skills that will be useful in future professional work related to the automotive industry. Students will learn the determinants of environmental assessment of the life cycle of vehicles and alternative fuels.

WHERE THE STUDENTS CAN USE THE KNOWLEDGE

Students can use the knowledge in their future work related to environmental protection in the automotive industry, especially in the greenhouse gas emissions analysis departments. The LCA analyses have provided new knowledge to be used in further analyses concerning the development of alternative fuels in the European Union as well as their potential environmental impact.

Theory

4.1 INTRODUCTION TO ELECTRIC VEHICLES

Battery electric vehicle (BEV), has an electric motor instead of an internal combustion engine. The vehicle uses a large traction battery pack to power the electric motor and must be plugged in to a wall outlet or charging equipment, also called electric vehicle supply equipment (Figure 41).

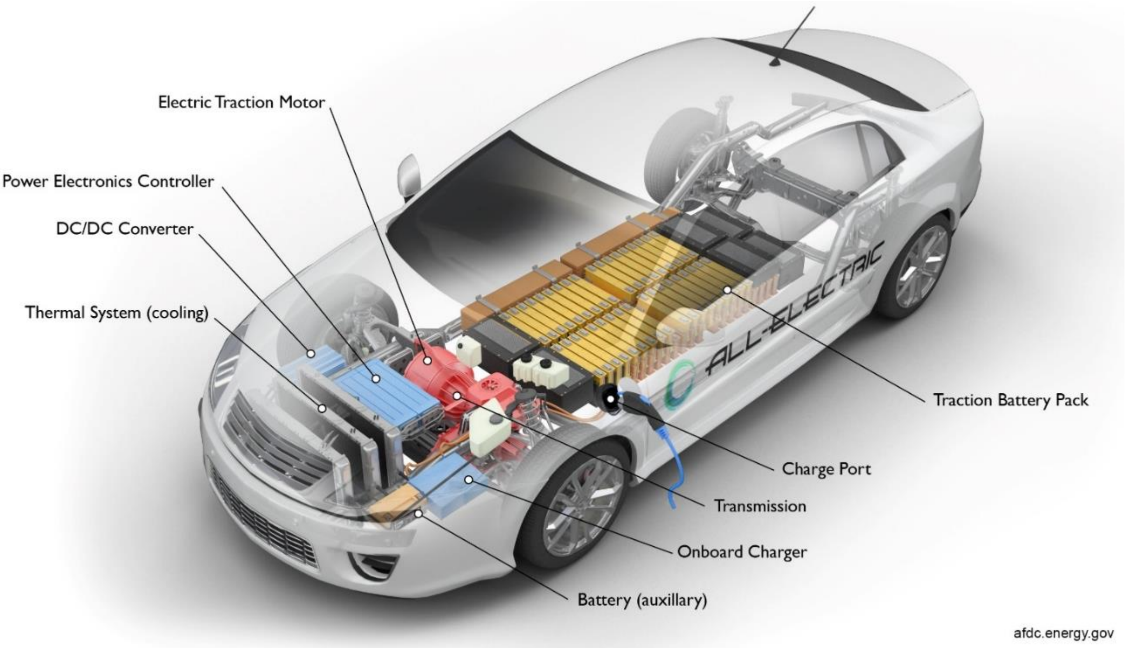

Figure 41: Electric vehicle construction

An electric vehicle consists of elements which are shown in Figure 42:

Battery	•The main purpose of the battery is providing electricity to power vehicle accessories in an electric vehicle
Charge port	•Charge port in electric vehicle allows the vehicle to connect to an external power supply in order to charge the traction battery pack
DC/DC convertor	•Vehicle accessories work need a low-voltage DC power. Electric vehicle has mounted DC/DC converter. It`s important because device provides normal vehicle accessories work and recharge the auxiliary battery.
Onboard charger	•Onboard charger converts electricity to DC power for the traction battery charging and has control function of main battery characteristics such as voltage, temperature, current, and state of charge while charging the pack
Power electronics controller	•Power electronics controller manages the flow of electrical energy delivered by the traction battery. Also it controlling the speed of the electric traction motor and the torque it produces.
Thermal system	•Thermal system (cooling system) maintains a proper operating temperature range of the electric motor, power electronics, and other components.
Traction battery pack	•Electric traction motor drives the electric vehicle’s wheels with using power from the traction battery pack. Traction battery pack provides stores electricity for use by the electric traction motor.
Electric transmission	•Electric transmission transfers mechanical power from the electric traction motor to the drive wheels.
Electric traction motor	•Electric vehicle have an electric motor instead of an internal combustion engine. Electric traction motor drives the electric vehicle’s wheels with using power from the traction battery pack.

Figure 42: Elements of an electric vehicle [44]

The U.S. Environmental Protection Agency categorizes battery electric vehicles as zero-emission vehicles, because they produce no direct exhaust or tailpipe emissions. Both

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[44] Own analysis based on https://www.newkidscar.com/electric-car-construction/

heavy-duty and light-duty all-electric vehicles are commercially available. Battery electric vehicles are more expensive than similar internal combustion engine vehicles. Battery electric vehicles have a shorter range than comparable internal combustion engine vehicles have. The efficiency and driving range of battery electric vehicles varies substantially based on driving conditions. All-electric vehicles are more efficient under city driving than highway travel.

Road transportation accounts for nearly a quarter of the greenhouse gases emission. Recently, electric vehicles have become an important element in the development strategies of the automotive industry in European Union. Electric vehicles are the future of road transport and offer significant potential for reducing air pollution and increasing life comfort, especially in crowded city centers. In European Union countries government actions, as well as a regulatory package, are aimed at increasing the use of alternative fuels and supporting the development of electromobility. Battery electric vehicles charged with renewable electricity seems to have almost no environmental impact in Well-to-Wheel.

4.2 LIFE CYCLE ASSESSMENT OF BATTERY ELECTRIC VEHICLES (BEVS)

In chapter 3.4 we presented a case study of the life cycle assessment of conventional fuel vehicles, here we present a case study of the life cycle assessment of alternative fuel vehicles.

We conducted LCA for battery electric vehicles (BEVs). For this purpose, as with the LCA analysis for conventional fuel vehicles, here we also performed analyses for carbon footprint, water footprint and resource footprint. In the case of the LCA of electric vehicles, we took into account the battery charging options given the energy mix available between 2020 and 2050. We conducted life cycle assessment in accordance with Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 2 (ISO 14044: 2006 / Amd 2: 2020). We defined the functional unit, system boundaries and basic assumptions. The environmental footprints assessment we conducted using the SimaPro v. 9 software with the Ecoinvent v.3 database. As with the LCA analysis for conventional fuel vehicles, we also defined the functional unit for electric vehicles as 100 km.

The system boundaries for battery electric vehicles included the cycles of an electric passenger car service life (including passenger car production, battery production, road construction, car use, maintenance, and disposal) and battery charging, taking into account the trends in the electricity supply for battery charging purposes between 2015 and 2050.

The electric vehicle operation itself does not cause emission of any harmful compounds into the atmosphere; it is the battery charging that entails its actual environmental impact. The charging is performed using the public power grid, and so the EV's environmental impact will be directly affected by the manner in which the electricity consumed to charge the vehicle's built-in battery is generated.

Therefore, in order to perform LCA analysis for electric vehicles, we have developed the computational model of LCA for electric vehicle battery charging, which is to help in the analysis of the environmental impact of electric vehicles.

We conducted analysis for individual electricity sources. The following eight main energy sources used to produce electricity were shown in Figure 43.

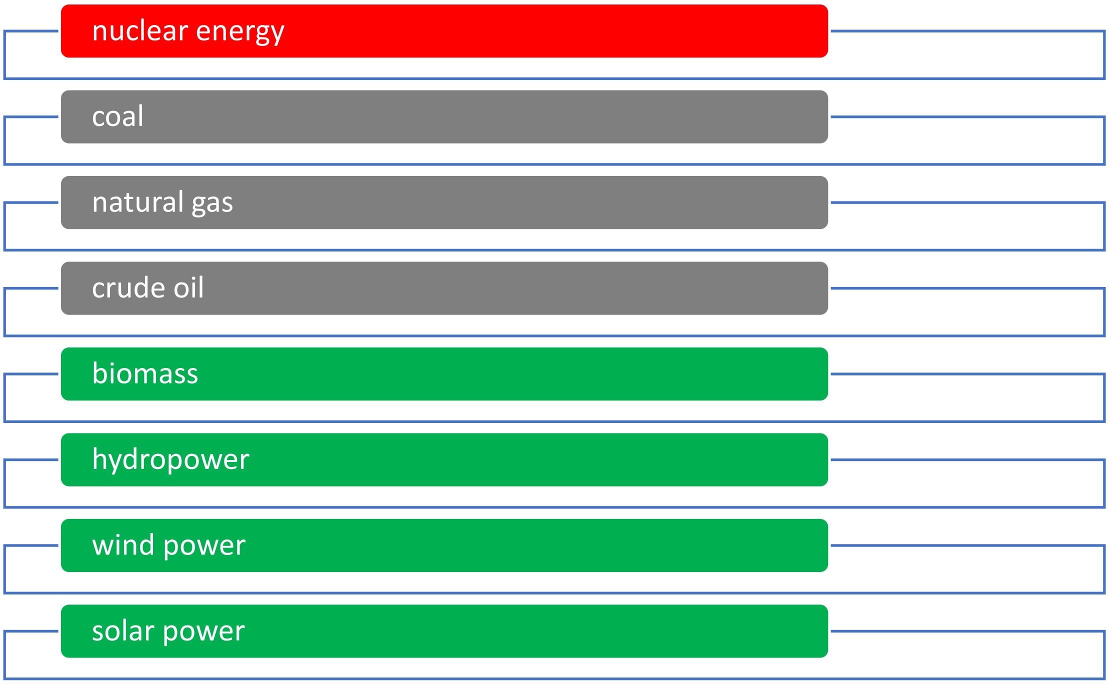


Figure 43: Main energy sources used to produce electricity

We calculated environmental footprints for individual electricity sources (Table 10).

Table 10: Carbon footprint, water footprint and resource

	Environmental footprint	**Carbon Footprint**	**Water Footprint**	**Resource Footprint**
	Abbreviations	**CF**	**WF**	**RF**
Lp.	**Unit**	**g CO_2 eq/ kWh**	**m^3 /kWh**	**MJ/ kWh**
1	Biomass	4.77E+01	1.96E-04	5.52E-01
2	Hard coal	1.19E+03	1.58E-02	1.43E+01
3	Hydro	4.15E+00	1.00E-04	3.69E-02
4	Lignite	1.15E+03	5.90E-03	1.29E+01
5	Natural gas	5.49E+02	1.70E-03	8.91E+00
6	Nuclear	1.19E+01	3.50E-03	1.37E-01
7	Solar	7.69E+01	8.00E-04	9.38E-01
8	Wind	1.58E+01	2.00E-04	1.93E-01

We conducted a literature review of the forecasts for the development of power engineering in European Union in the years to come and we have found that energy based on fossil fuels would be gradually replaced by renewable sources, mainly by wind power plants. The related changes would involve development of RES-based power stations, mainly wind power plants, along with the growth of the nuclear power sector.

The LCA calculation model for charging electric vehicle batteries that we have developed requires the following data: the percentage share of individual energy sources in the total mix in the selected country and energy consumption per 100 km for the selected vehicle. The value of the environmental footprint for each energy source was calculated by us and presented in Table 10.

We developed the following computational model of environmental footprints (Formulas 1 – 3) in order to calculate the three environmental footprints for electric vehicle battery charging:

$$CF_{EV} = (CF_{ES\,1-8} * S_{\mathrm{ES}\,1-8}) * E_{EV}CF_{EV} = (CF_{ES\,1-8} * S_{\mathrm{ES}\,1-8}) * E_{EV} \qquad (1)$$

where:

CF_{EV} – carbon footprint for electric vehicle battery charging [g CO_2 eq/100 km];

$CF_{ES\,1\text{-}8}$ – carbon footprint from production of 1 kWh of energy for individual energy sources [g CO_2 eq/kWh];

$S_{ES\,1\text{-}8}$ – percentage share of the energy source (S – share, ES – energy sources) in the energy mix of the given country or of individual sources;

E_{EV} – vehicle energy consumption [kWh/100 km];

1-8 – means individual energy source: biomass, hard coal, hydro, lignite, natural gas, nuclear, solar and wind

$$WF_{EV} = (WF_{ES\,1-8} * S_{ES\,1-8}) * E_{EV}WF_{EV} = (WF_{ES\,1-8} * S_{ES\,1-8}) * E_{EV} \qquad (2)$$

where:

WF_{EV} – water footprint for electric vehicle battery charging [m^3/100 km];

$WF_{ES\,1\text{-}8}$ – water footprint from production of 1 kWh of energy for individual energy sources [m^3/kWh];

$S_{ES\,1\text{-}8}$ – percentage share of the energy source (S – share, ES – energy sources) in the energy mix of the given country or of individual sources;

E_{EV} – vehicle energy consumption [kWh/100 km];

1-8 – means individual energy source: biomass, hard coal, hydro, lignite, natural gas, nuclear, solar and wind

$$RF_{EV} = (RF_{ES\,1-8} * S_{ES\,1-8}) * E_{EV}\, RF_{EV} = (RF_{ES\,1-8} * S_{ES\,1-8}) * E_{EV} \qquad (3)$$

where:

RF_{EV} – resource footprint for electric vehicle battery charging [MJ/100 km];

$RF_{ES1\text{-}8}$ – resource footprint from production of 1 kWh of energy for individual energy sources [MJ/kWh];

$S_{ES\,1\text{-}8}$ – percentage share of the energy source (S – share, ES – energy sources) in the energy mix of the given country or of individual sources;

E_{EV} – vehicle energy consumption [kWh/100 km];

1-8 – means individual energy source: biomass, hard coal, hydro, lignite, natural gas, nuclear, solar and wind

LIFE CYCLE ASSESSMENT OF BATTERY ELECTRIC VEHICLES – CASE STUDY FOR POLAND

Here we conducted the life cycle assessment for battery electric vehicles in Poland. For this purpose, we analysed the structure of the Polish electric energy generation mix, both at present and in the future. We established that electric energy is the main determinant of the environmental impact of electric vehicles. We conducted analysis of the environmental footprints due to electric vehicle battery charging for Poland based on the computational life cycle analysis model which we developed.

In our LCA analysis we took into account life cycle of electric car - the construction, operation, maintenance and disposal of cars. We have chosen a lithium-ion battery for the analysis because it is the most frequently used battery for BEVs.

Into our LCA analysis, we took into account the energy for battery charging fed from the current and the future electricity grid in Poland over the years 2020–2050.

We have analysed three environmental footprints: carbon footprint, water footprint, and resources footprint for battery electric vehicles in Poland. A description of these environmental footprints is provided in chapter 3.

RESULTS OF CARBON FOOTPRINT ASSESSMENT OF BATTERY ELECTRIC VEHICLES

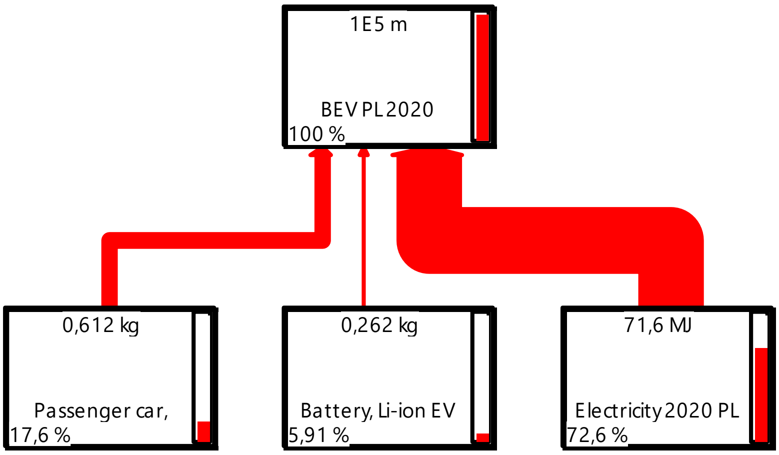


Figure 44: Determinants of the carbon footprint of battery electric vehicles in Poland in 2020

The results of the LCA for individual footprints we presented in the form of diagrams.

We established the determinants of carbon footprint for battery electric vehicles used in Poland in 2020. The results of the assessment of the chosen environmental footprint have been illustrated in Figure 44.

Based on our LCA analysis we found that the main determinant of carbon footprint for BEVs in Poland is the electricity used to charge vehicle batteries (Figure 44). The electricity consumed to charge batteries represented 71.6% of the carbon footprint for BEVs in Poland in 2020. A large share of carbon footprint is related to the production of passenger cars (17.6%).

RESULTS OF WATER FOOTPRINT ASSESSMENT OF BATTERY ELECTRIC VEHICLES

We established the determinants of water footprint for battery electric vehicles used in Poland in 2020. The results of the assessment of the water footprint are presented in Figure 45. The main determinant of the water footprint for BEVs is related to the electricity used to charge vehicle batteries, and its share was 73.1% in 2020.

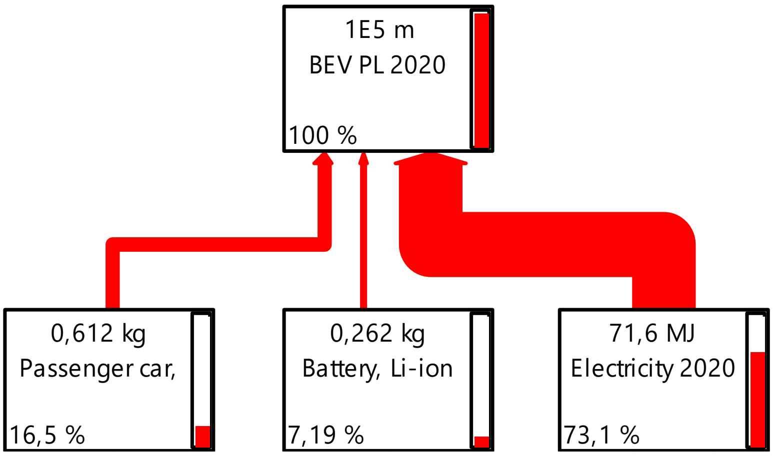


Figure 45: Determinants of the water footprint of electric vehicles in Poland in 2020

RESULTS OF RESOURCE FOOTPRINT ASSESSMENT OF BATTERY ELECTRIC VEHICLES

We established the determinants of the resource footprint of battery electric vehicles in service in Poland in 2020. The results of the assessment of the chosen environmental footprints have been presented in Figure 46.

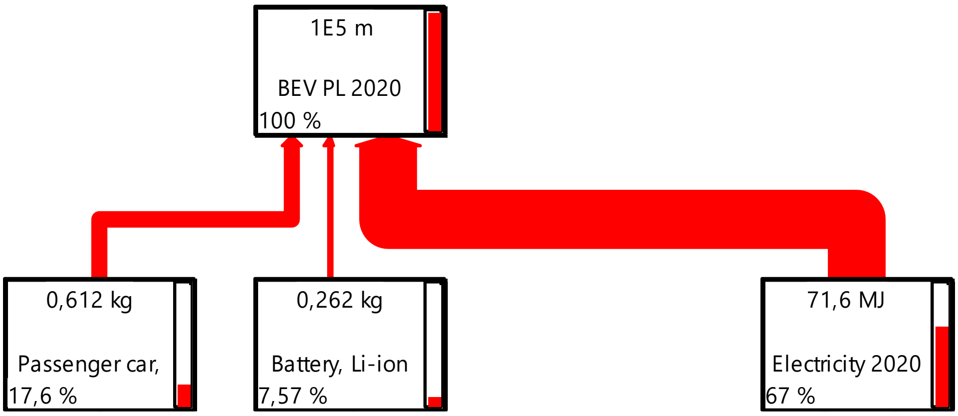


Figure 46: Determinants of the resource footprint of electric vehicles in Poland in 2020

The comparative analyses of the environmental footprints of both current and future electric passenger cars were performed by considering the changes in the sources of electricity forming the Polish mix. We found that the main determinant of environmental footprints for the electric vehicles in Poland is the electricity used to charge the vehicles. In the future, an increase is expected in the generation of electricity from alternative sources as well as from nuclear power, starting from 2035, while the volume of electricity produced from solid fuels is projected to drop, which affects the results. On the example of Poland and Polish electricity mix, determinants calculation of the footprints of electric vehicles in other countries can be applied. The LCA analysis of the electricity sources used for vehicle battery charging showed that the main determinant of the negative environmental impact of energy systems in Poland was the consumption of solid fuels, both hard coal and lignite.

4.3 LCA OF ELECTRIC VEHICLE BATTERY CHARGING IN EUROPEAN UNION COUNTRIES - CASE STUDY

ASSUMPTIONS

This chapter deals with analysis of the electric energy produced in individual EU Member States and used for charging of electric vehicle batteries in European countries. We performed the LCA analysis on the categories of environmental impact related to greenhouse gas emission, accumulated water consumption, as well as resources depletion. Our analyses cover the year 2015, and also include forecasts of energy production in all EU countries for 2020, 2030 and 2050.

We analysed electricity generation mix structure in Europe, both at present and in the future. Energy production is very diversified across Europe in terms of the energy sources used, which involves diversified environmental impact. The **function of the system** was the amount of electric energy in the power grid used to charge an electric battery of a passenger car assuming a distance of 100 km. For the sake of comparison, all the analyses referred to the same functional unit (FU) of 100 km. Within its **boundaries**, the system extended over all the technologies encompassing the electricity mix of all countries. The system boundary is *from cradle to gate (the explanation and details about this approach are in chapter 2.5)*. In order to perform the life cycle analysis, the system boundary was defined and data sets were identified with reference to the structure of electricity generation for individual EU countries. The main **source of data** for the analyses concerning the current and the projected structure of electricity production in all European Union countries was the documentation released by the European Commission. The structure of electricity production in the power grid applied in the battery is one of the most important parameters taken into account when analysing an electric vehicle.

We assumed that the basic variable determining the impact of electric vehicles on the environment in European Union countries would be the structure of electricity generation for purposes of electric car battery charging. For this reason, environmental analyses of the forecasted changes in energy sources in all EU countries were performed. The analyses cover the years 2015–2050 and address the basic assumptions related to the change in the energy sources, as forecasted for individual countries. The analyses concerned the types of energy production forecasted in the analysed countries for the years 2015–2050.

The environmental impact analyses we conducted by considering the assessment of the greenhouse gas emission due to electricity generation, taking the structure of energy sources in all EU countries into account. We analysed other categories of regarded as significant in terms of the environmental impact of electric vehicles, including cumulative water consumption and resources depletion.

RESULTS

Analysis of energy generation sources in the EU countries

Firstly, we analysed electricity sources in EU. The share of individual electric energy sources in the European Union is presented in Figure 47. Changes in the share of individual energy sources used for electricity production in the European Union in the years 2015–2050 was shown in Figure 49.

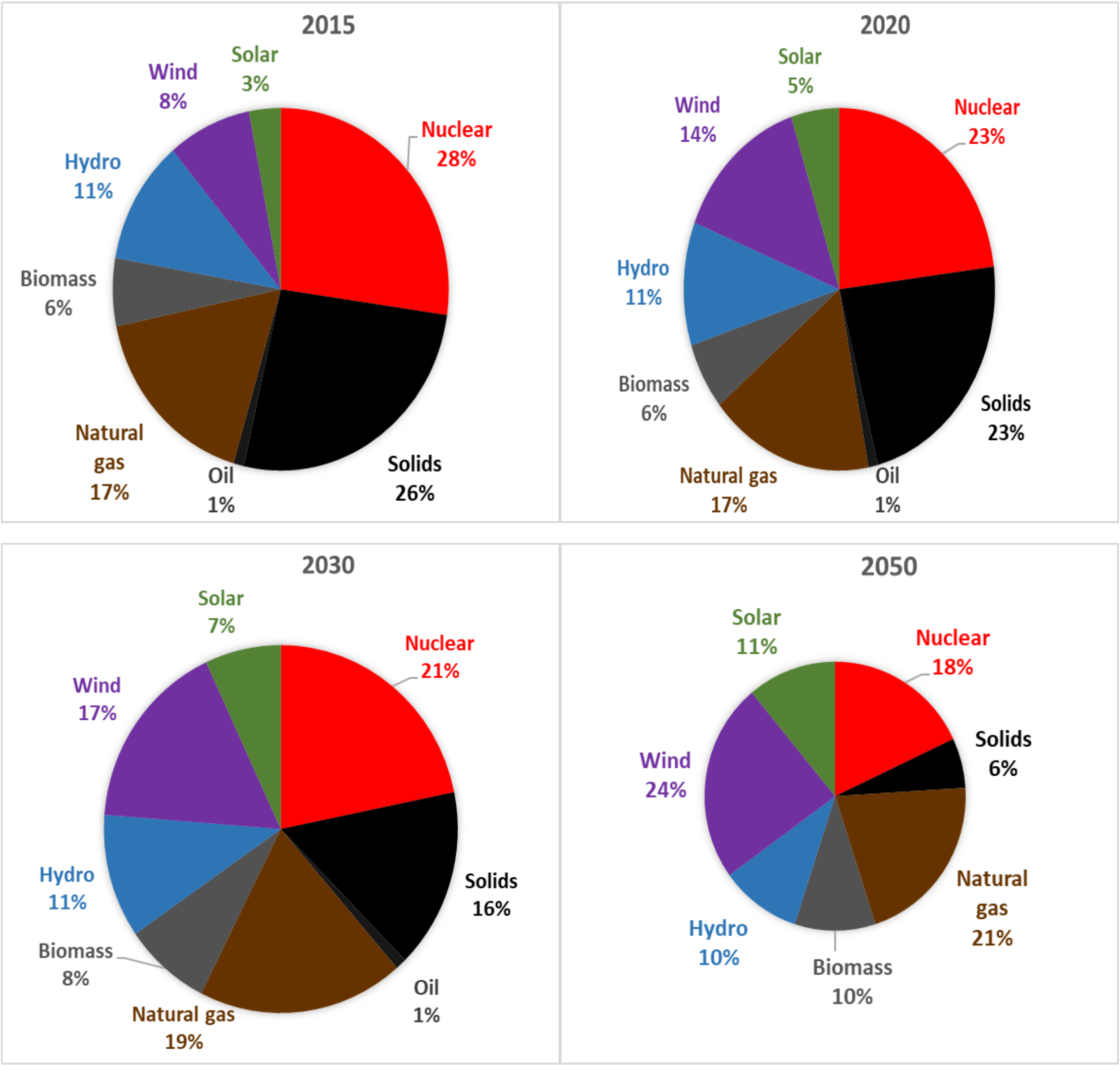


Figure 47 a: Share of individual electric energy sources in the European Union

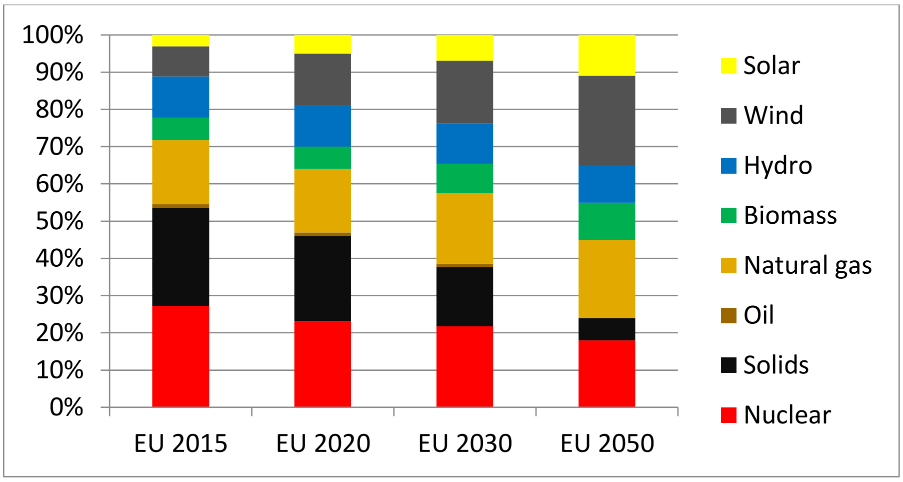


Figure 48 b: Share of individual electric energy sources in the European Union

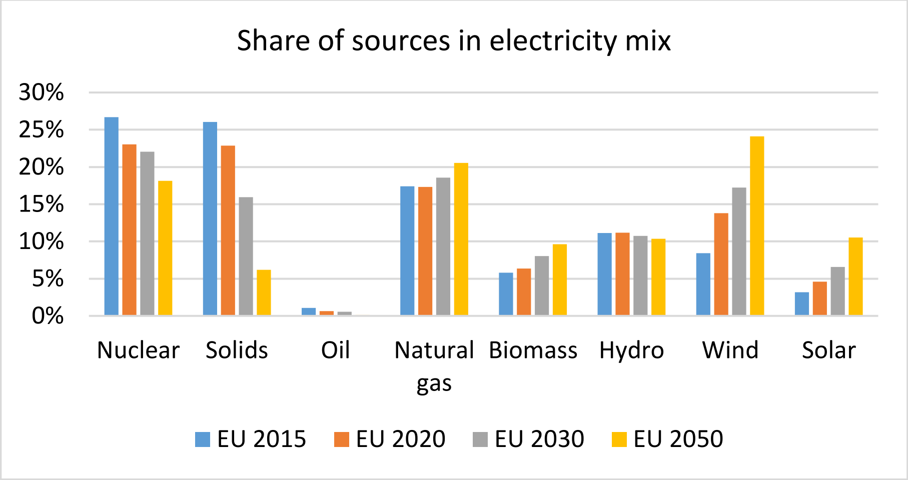


Figure 49: Changes in the share of individual energy sources used for electricity production in the European Union in the years 2015–2050

We found that in EU countries in 2015, the accumulated share of nuclear power, solids and natural gas accounted for 70% (where the individual share of these sources came to 27%, 26% and 17%, respectively), while the share of renewable energy sources (RES) accounted for only as much as 29%. In the years to come, the share of solids is forecasted to drop to 6% in 2050, and that of nuclear power to 18%, while the share of RES is expected to increase to 55%, with the highest share attributable to wind energy (24%). A slight increase in the share of natural gas consumption for purposes of electricity production is also expected in the European Union. A detailed review of the energy policy of individual EU countries has been provided in publication (Energy Policies of IEA Countries - www.iea.org).

Life cycle assessment of EV battery charging in the European Union

Based on analysis of electric vehicle battery charging against electricity consumption from the power grid in the European Union, we calculated indicators for greenhouse gas emission (Figure 50), cumulative water use (Figure 51), and resources depletion (Figure 52), considering 100 km driven by an electric passenger car, assumed as a functional unit of measure. These indicators were calculated for individual European Union countries.

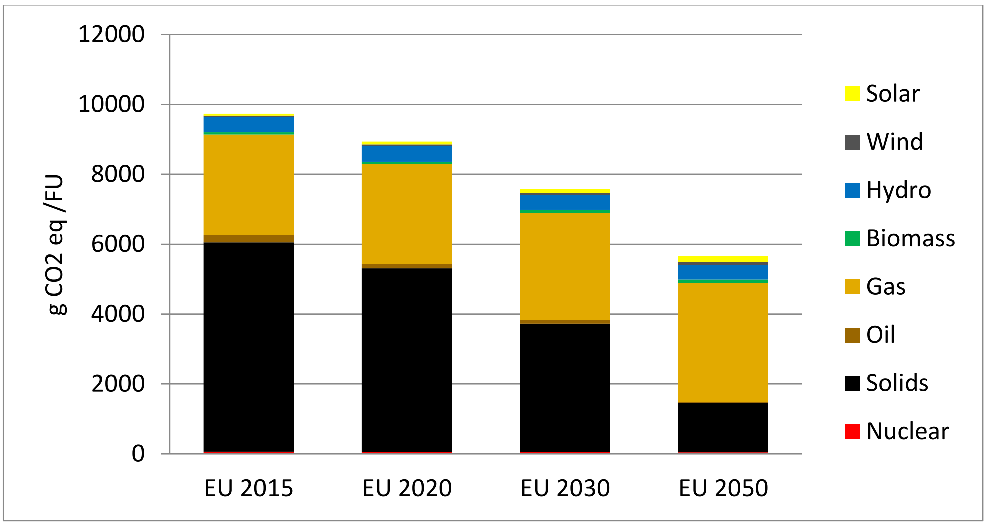


Figure 50: Impact of EV battery charging on greenhouse gas emissions in European Union

Based on our analysis of the greenhouse gas emission (GHG) of electric vehicle battery charging, we established that the GHG emission is declining, equalling: 9,727.67 g of CO_2 eq. per 100 km in 2015, 8,934.34 g of CO_2 eq. per 100 km in 2020, 7,579.62 g of CO_2 eq. per 100 km in 2030, and 5,661.96 g of CO_2 eq. per 100 km in the year 2050. As Figure 50 implies, the highest impact on the GHG emission is attributable to the use of coal (solids) and natural gas in electricity production. We also found that despite the increase in the share of renewable energy sources, they exert no impact on the GHG emission (the impact of RES on the GHG emission is negligible). Also, despite the large share of nuclear power in the electric energy mix in the European Union, it has no impact on the greenhouse gas emission.

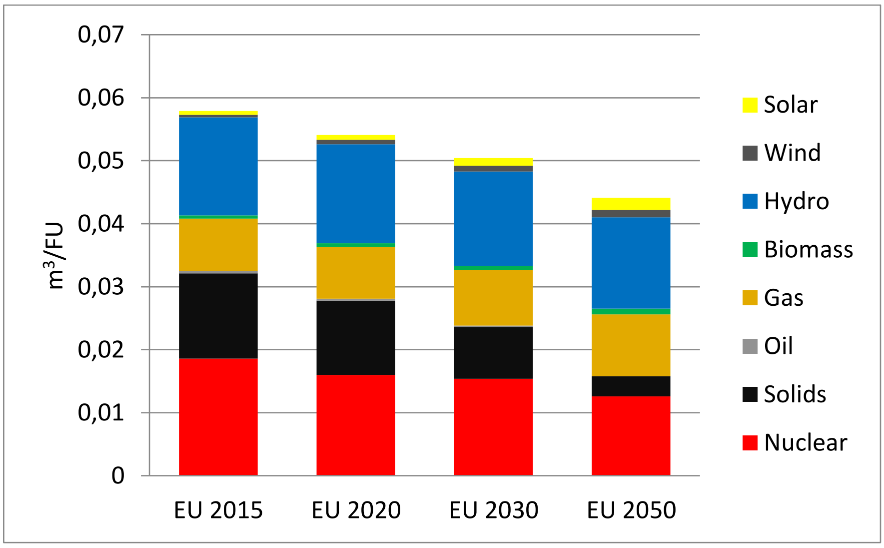


Figure 51: Cumulative water use of EV battery charging in European Union

Based on the cumulative water use analysis for electric vehicle battery charging against electricity consumption from the power grid, we calculated cumulative water use for 100 km driven by an electric passenger car. We demonstrated that the ratio of accumulated water consumption will decrease from 0.0579 m^3/100 km in 2015, 0.0541 m^3/100 km in 2020, and 0.0505 m^3/100 km in 2030, to 0.0442 m^3/100 km in 2050. As Figure 51 illustrates, the greatest influence on the CWU coefficient comes from the consumption of hydro power, nuclear power, natural gas and solids for electricity production.

We found that the increase in the share of natural gas in the electric energy production structure triggers increased water consumption, and further, that despite the increase in the share of other renewable energy sources (wind, solar and biomass), they still exert no impact on the indicator subject to analysis. The high water consumption attributable to electric energy production based on nuclear power, coal and natural gas is associated with the very high water consumption for cooling processes in these technologies.

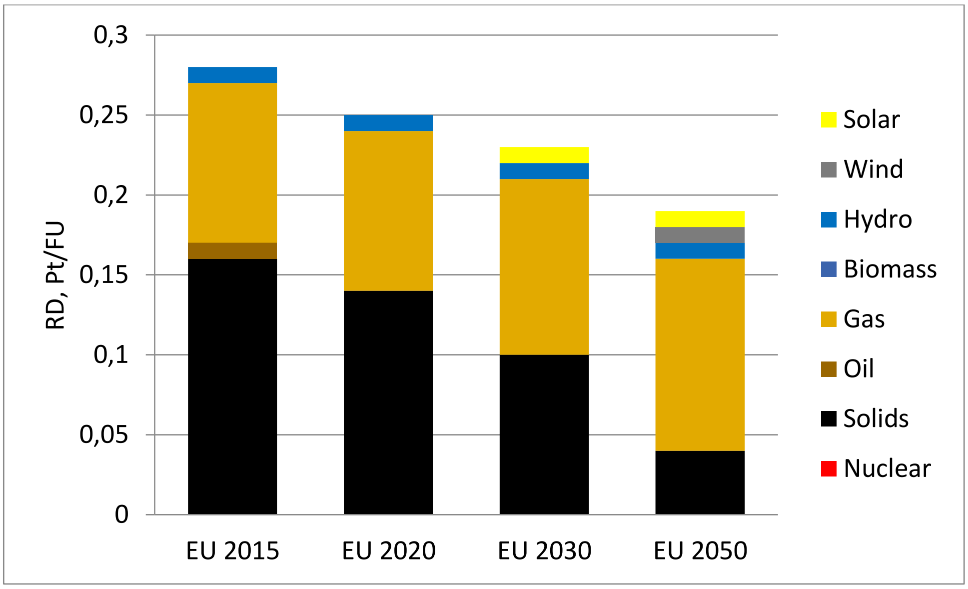


Figure 52: Impact on resources depletion from EV battery charging in the European Union

Based on the analysis of the resource's depletion for electric vehicle battery charging, we demonstrated that this indicator is decreasing from 0.29 Pt/100 km in 2015, 0.27 Pt/100 km in 2020, and 0.24 Pt/100 km in 2030, to 0.19 Pt/100 km in 2050. Figure 52 shows that the greatest impact on the consumption of resources is attributable to the consumption of solids and natural gas in electricity production. The consumption of solids is decreasing, causing this indicator to decline, while the consumption of natural gas is increasing, which results in an increase in the resources depletion indicator.

With regard to the analyses of all environmental indicators for the production of the electric energy used in the European Union to charge batteries of electric vehicles, we established that all these indicators are declining. This is mainly due to the reduction in the share of solids in the electricity production. However, as for the increase in the share of natural gas, this has an impact on the increase in the environmental efficiency indicators, and particularly on the depletion of resources (raw materials, i.e., fossil fuels and minerals) and greenhouse gas emissions.

The analysis of the impact of using renewable energy sources to generate electricity has shown that the most eco-friendly energy source is wind power. The analysis of hydro power, on the other hand, has revealed its negative impact on the cumulative water consumption. Compared to the electric energy from wind, the environmental indicators established for the solar power-based electricity production are also higher.

Based on our LCA analysis of life cycle of electric energy generation in the power grid for purposes of charging electric vehicle batteries, we reached the following findings:

- In most European Union countries, the analysed environmental indicators have been found to decline in the successive years of the analyses (from 2015 to 2050).
- The determinants of the GHG emission from electricity generation are solids and natural gas consumption. Other energy sources used in the EU countries have little impact on the GHG emission.
- It has been demonstrated that the greatest impact on the CWU indicator due to electricity production is exerted by the consumption of hydro power, nuclear power, natural gas and solid fuels. The high water consumption indicator attributable to the electric energy production based on the nuclear, coal and natural gas technologies is associated with the high water consumption for cooling processes required by these technologies.
- The greatest impact on the resource's depletion is attributable to the consumption of solids and natural gas in electricity production. Reducing the consumption of coal in the electricity production structure has a positive effect on the resource's depletion, while an increase in the consumption of natural gas in the successive years in some EU countries negatively affects the environment by triggering an increase in the resource depletion indicator.

- The environmental impact analysis of the use of renewable energy sources in electricity production has shown that the most eco-friendly energy source is wind power.
- Greenhouse gas emissions and water footprint are lower when charging electric vehicle batteries using renewable energy compared to other sources. Hence the conclusion that the European Union countries should definitely rely on renewable energy sources for purposes of electric vehicle battery charging.

4.4 COMPARATIVE LIFE CYCLE ANALYSIS OF PETROL ICEVS, DIESEL ICEVS, AND BEVS – CASE STUDY

ASSUMPTIONS

Here we compared the environmental impacts of internal combustion engine vehicles (ICEVs), versus battery electric vehicles (BEVs) by taking the life cycle of these cars into account. For this purpose, we analysed carbon footprint, water footprint and resource footprint of these vehicles. System boundaries for the life cycle of BEVs and ICEVs (diesel- and petrol-powered) is shown in Figure 52. We carried out LCA on the example of Polish energy mix.

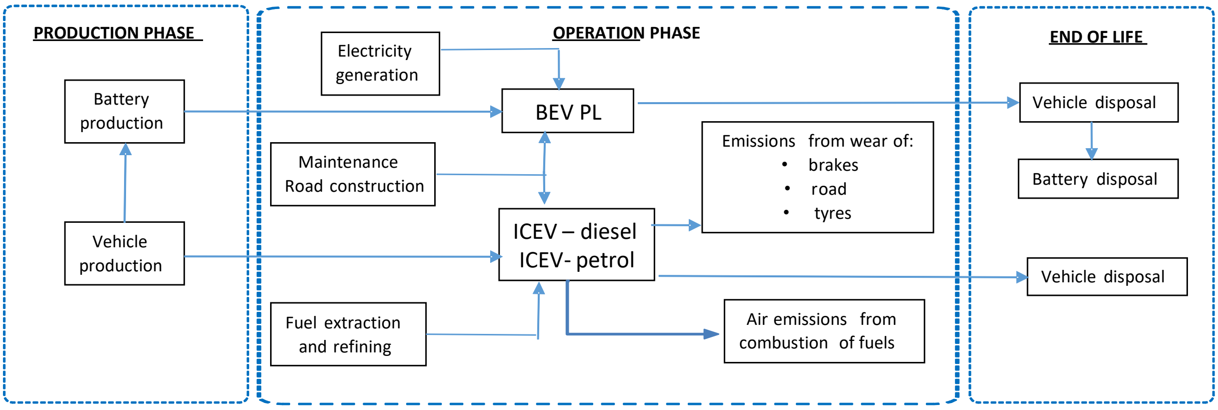


Figure 53: System boundaries for the life cycle of BEVs and ICEVs (diesel- and petrol-powered)

COMPARATIVE LCA OF VEHICLES – THE RESULTS

Figure 54 illustrates individual factors affecting the carbon footprint of the diesel ICEVs, petrol ICEVs, and BEVs subject to analysis, considering battery charging using the energy mix available between 2020 and 2050.

We found that the current and future carbon footprint indicators of BEVs in Poland are lower than those for diesel ICEVs and petrol ICEVs. In the case of petrol- and diesel-powered ICEVs, direct emissions into the air at the vehicle use stage are the main determinants of carbon footprint, while in the case of BEVs, the corresponding determinant is electricity production.

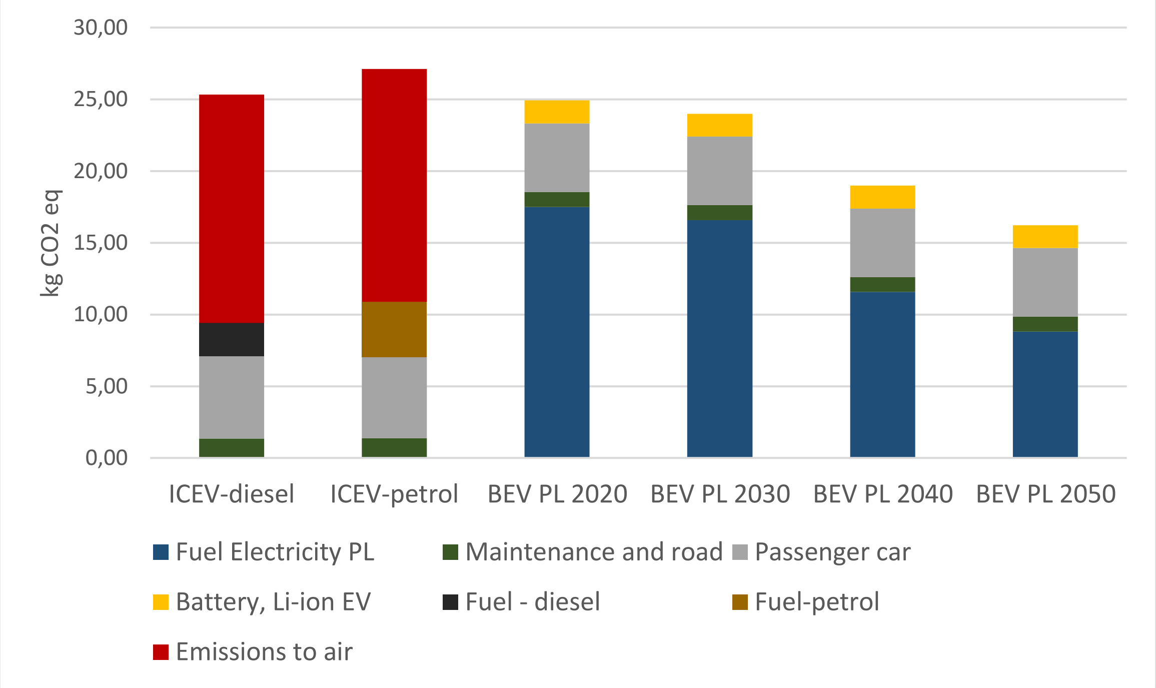


Figure 54: Analysis of the carbon footprint of petrol ICEVs, diesel ICEVs, and BEVs

Figure 55 depicts the factors affecting the water footprint of diesel ICEVs, petrol ICEVs, and BEVs, if the battery charging process is based on the domestic energy mix available in the years 2020–2050.

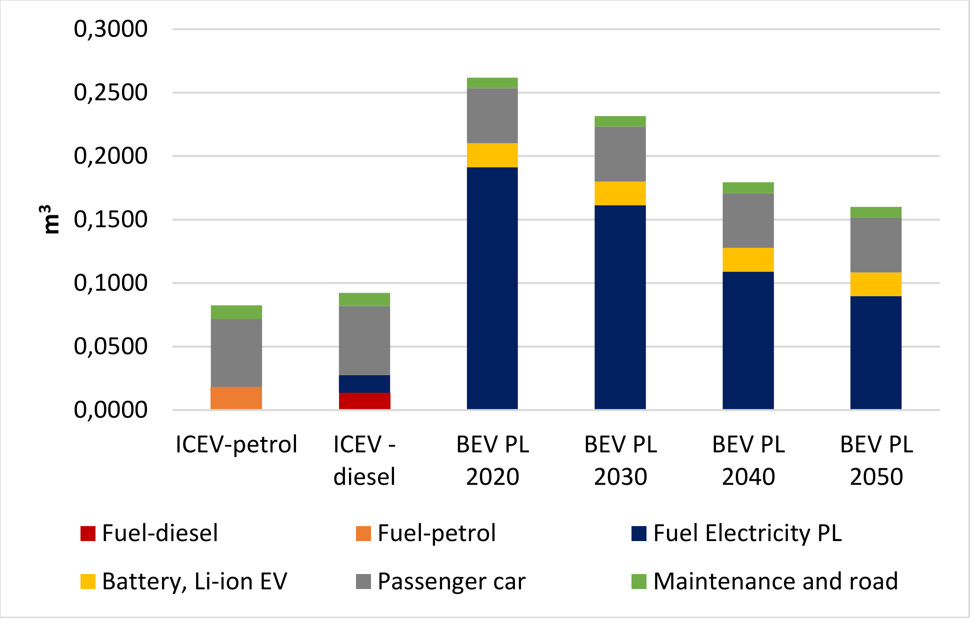


Figure 55: Analysis of the water footprint of petrol ICEVs, diesel ICEVs, and BEVs

We found that both current and future water footprints of BEVs in Poland are higher than those of ICEVs (Figure 55). For ICEVs, the car production stage is the main determinant of the water footprint, while in the case of BEVs, this determinant is electricity.

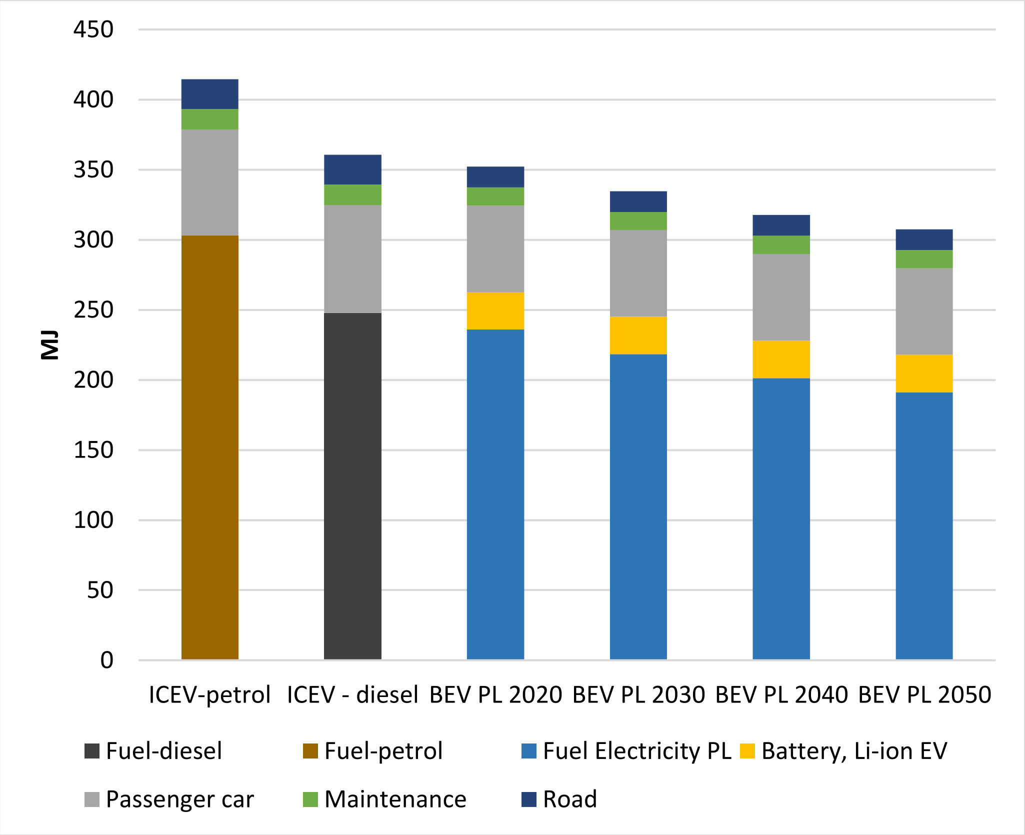


Figure 56: Analysis of the resource footprint of petrol ICEVs, diesel ICEVs, and BEVs

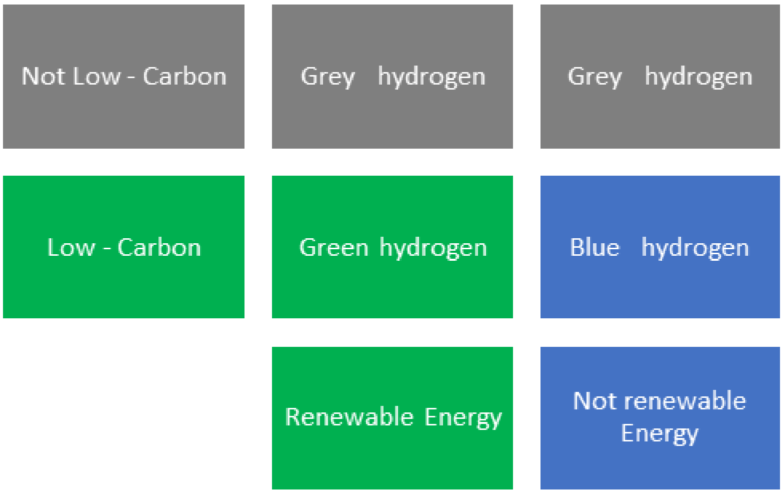
Figure 56 illustrates individual factors affecting the resource footprint of the diesel ICEVs, petrol ICEVs, and BEVs subject to analysis, considering battery charging using the energy mix available between 2020 and 2050.

Based on the analysis, we found that the environmental footprints proposed are adequate and useful tools which can serve the purpose of decision making for the assessment of transport sustainability according to the life cycle approach. However, further research is needed to refine these methods. The environmental metrics thus obtained can be utilised to support decision making in circular economy.

4.5 LIFE CYCLE ASSESSMENT OF FUEL CELL ELECTRIC VEHICLES

HYDROGEN AS THE MOST PROMISING DECARBONISATION OPTION FOR VEHICLES

Climate change and fossil fuel depletion are the main reasons leading to development of methods of hydrogen technology. There are many processes for hydrogen production from conventional and alternative resources, such as natural gas, coal, nuclear, biomass, solar and wind. Hydrogen can be derived from different sources. It may be either green, blue or grey (Figure 57).



Not Low - Carbon	Grey hydrogen	Grey hydrogen
Low - Carbon	Green hydrogen	Blue hydrogen
	Renewable Energy	Not renewable Energy

Figure 57: Indicative colours for hydrogen production from non-renewable and renewable sources

Hydrogen can be produced using renewable sources such as wind and solar energy, but it may well be produced from fossil fuels, including gas and lignite. Colours, in this case, perform the role of utility markers showing how hydrogen has been obtained, enabling governments, businesses and communities to judge about their drawbacks vis-à-vis the advantages of clean emission-free products:

- Green hydrogen is 100% derived from zero-emission renewable sources such as wind and sun;
- Hydrogen is blue when no additional emission is generated in the production process (e.g., when using nuclear power), which is the case of processes using specific technologies (e.g., CCS) to achieve net zero emission;
- Grey hydrogen is produced with additional emissions (typically from natural gas or lignite). Unfortunately, this category accounts for ca. 95% of all the hydrogen currently produced worldwide.

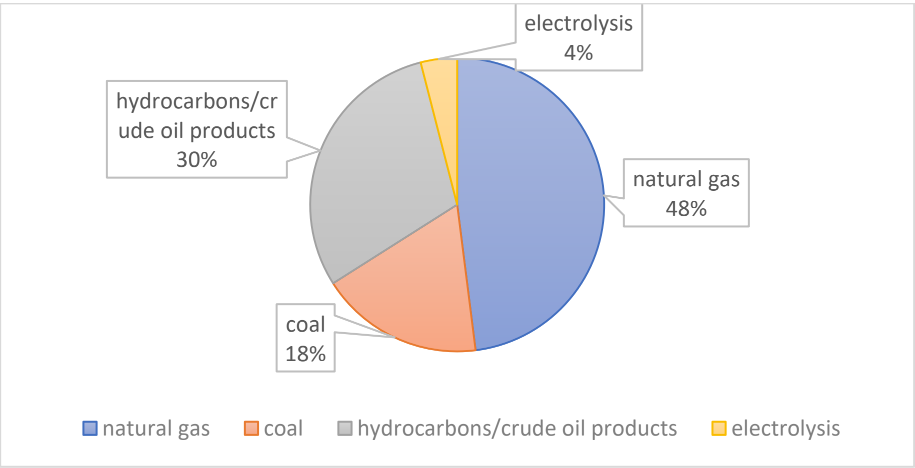
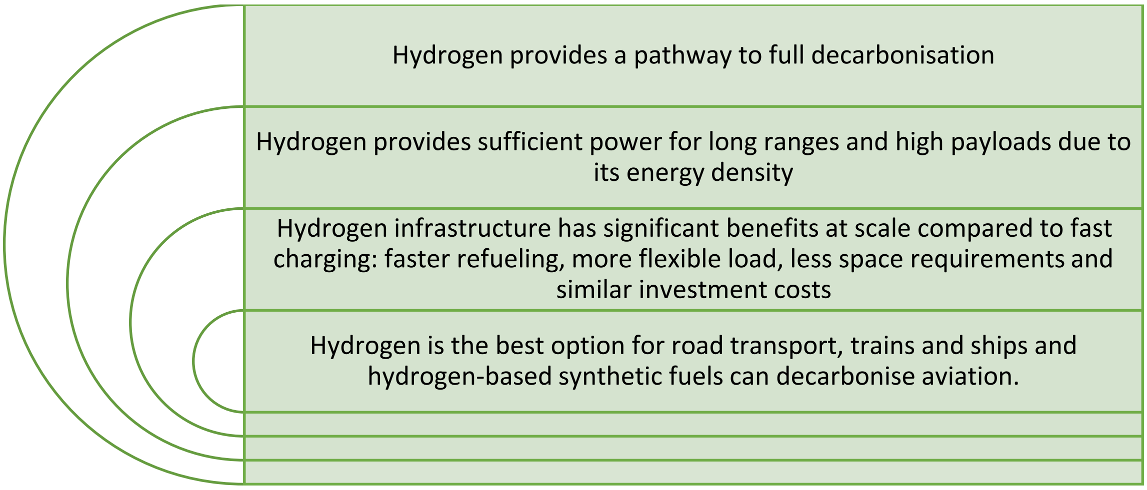


Figure 58: Sources used for hydrogen production

The most popular hydrogen production methods are conversion of natural gas and light hydrocarbons, gasification of coal and biomass, recovery of coke-oven gas and water electrolysis, photoelectrolysis photobiological processes.

On 8 July 2020, as part of the implementation of the European Green Deal, the European Commission announced its hydrogen strategy whose main goal is to foster development of RES-based production of hydrogen, namely green hydrogen obtained by way of electrolysis using renewable energy sources. Hydrogen is by far the most promising decarbonisation option for heavy goods vehicles, buses, ships, trains, large cars and commercial vehicles for four reasons (Figure 59).



Hydrogen provides a pathway to full decarbonisation

Hydrogen provides sufficient power for long ranges and high payloads due to its energy density

Hydrogen infrastructure has significant benefits at scale compared to fast charging: faster refueling, more flexible load, less space requirements and similar investment costs

Hydrogen is the best option for road transport, trains and ships and hydrogen-based synthetic fuels can decarbonise aviation.

Figure 59: Reasons why hydrogen is the most promising decarbonisation option for various vehicles

According to the 2020 report entitled "*Fuelling the Future of Mobility: Hydrogen and Fuel Cell Solutions for Transportation," developed by Deloitte China and Ballard Power Systems*, from the point of view of life cycle emissions, the future of transport is hydrogen fuel cell-powered vehicles.

The growing interest in and demand for hydrogen, commonly referred to as the *fuel of the future*, is triggered by its increasing consumption in transport. Hydrogen used in transport is perceived as a low-carbon fuel, alternative to petroleum-based and gas products. FCEVs could reduce air pollution because they cause no direct exhaust emission, similarly to BEVs.

Hydrogen is considered a low-emission fuel. The only compound released from the exhaust pipe of a vehicle powered by this gas is steam. However, the actual emission related to hydrogen production depends on how it has been obtained. Hydrogen is one of the most crucial sources of clean energy supported by the European Union, but in order for hydrogen to be recognised as green under the EU policy, it should be produced using renewable energy only. Meanwhile in Europe and Poland, the main topic of discussion is the industrial-scale production of hydrogen using fossil fuels, or in other words – grey hydrogen. However, the hydrogen production performed in Poland has so far used coal-based technologies to a considerable extent, and therefore it is necessary that RES-based technology should be developed so that the hydrogen thus obtained is green.

4.6 LIFE CYCLE ASSESSMENT OF FUEL CELL ELECTRIC VEHICLES - CASE STUDY

Here we conducted analysis of the greenhouse gas emissions of fuel cell electric vehicles (FCEVs) powered by hydrogen produced from coal. For this purpose, we performed LCA analyses for hydrogen production and we used the results of the GHG analysis of the production and operation of FCEVs from the literature.

The following results of the GHG emission analyses were obtained from the literature for both the production and operation of FCEVs [45,46]:

- PEMFC stack – 5 g CO_2 eq/km,
- Vehicle infrastructure (without PEMFC stack) – 40 g CO_2 eq/ km, and
- Vehicle operation (without hydrogen) – 10 g CO_2 eq/km.

We performed a comparative analysis of GHG emission for FCEVs powered by hydrogen produced from coke oven gas (COG) and for FCEVs powered by hydrogen produced from coal gasification. The GHG emissions analysis of hydrogen production by gasification incorporated the processes of coal extraction, mechanical treatment, transport of coal to the gasification plant, the gasification itself, CO_2 capture, and carbon storage. The results of the GHG emissions analysis of hydrogen production from coal gasification with CCS and without CCS in Polish conditions were presented [17]. We extended the system boundary to the FCEV and applied the obtained hydrogen to the FCEV. In our case study the functional unit was 1 km, and the system boundary was extended. The analysis of the GHG emissions of FCEVs revealed that GHG emissions of hydrogen production from COG were lower than for hydrogen production from coal gasification. Furthermore, FCEVs powered by hydrogen obtained from coal gasification (without CCS technology) were characterised by the highest GHG emissions indicator, while the biomass gasification technology utilised for hydrogen production showed the lowest GHG emissions indicator – therefore, this is the best hydrogen production alternative.

System boundary of the life cycle of FCEV powered by hydrogen produced from coke oven gas is presented in Figure 60.

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[45] Evtimov I. & Ivanov R. & Stanchev H. & Kadikyanov G. & Staneva G. Life cycle assessment of fuel cells electric vehicles. *Transport Problems.* 2020. Vol. 15, No. 3, P. 153-166

[46] Valente, A.& Iribarren, D.& Candelaresi, D.& Spazzafumo, G.& Dufour, J. Using harmonised life-cycle indicators to explore the role of hydrogen in the environmental performance of fuel cell electric vehicles. *International Journal of Hydrogen Energy* 2020. Vol. 45. P.25758-25765

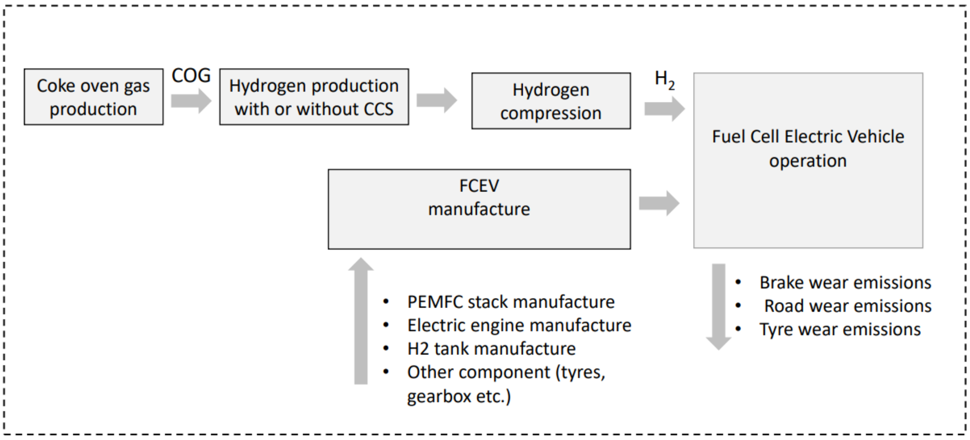

Figure 60: System boundary of the life cycle of FCEV

Our results were compared against an FCEV life cycle assuming such diverse sources of hydrogen as natural gas, biomass, and electrolysis (Table 11).[47],[48],[49],[50], [51]

Table 11: Comparative analysis of the results of original studies

Hydrogen production system	GHG emissions from FCEV life cycle [g CO_2 eq/km]	Sources
Hydrogen from coke oven gas without CCS	156	[52],[17]
Hydrogen from coke oven gas with CCS	97	
Hydrogen from coal gasification without CCS	215	
Hydrogen from coal gasification with CCS	121	
Hydrogen from steam methane reforming	140	[45]
Hydrogen from biomass gasification	60	
Hydrogen from electrolysis – wind power	70	[53]

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[47] Heo E., Kim J., Cho S.: Selecting hydrogen production methods using fuzzy analytic hierarchy process with opportunities, costs, and risks. International Journal of Hydrogen Energy, Vol. 37, 2012, p. 17655-17662.

[48] Chang P.L., Hsu C.W., Chang P.C.: Fuzzy Delphi method for evaluating hydrogen production technologies. International Journal of Hydrogen Energy, Vol. 36, 2011, p. 14172–14179

[49] Kügemann M., Polatidis, H.: Multi-Criteria Decision Analysis of Road Transportation Fuels and Vehicles: A Systematic Review and Classification of the Literature. Energies, Vol.13, Issue1, 2020

[50] Nikolaidis P., Poullikkas A.: A comparative overview of hydrogen production processes. Renewable and Sustainable Energy Reviews, Vol. 67, 2017, p. 597-611

[51] Staffell I., Scamman D., Abad W.A., Balcombe P., Dodds P. E., Ekins P., Ward K. R.: The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science, Vol. 12, 2019, p. 463-491.

[52] Piotr Folęga, Dorota Burchart, Paweł Marzec, Simona Jursova, Pavlina Pustejovska: Potential environmental life cycle impacts of fuel cell electric vehicles powered by hydrogen produced from polish coke oven gas, Transport Problems, issue 1, vol 17, 2022

[53] Evtimov I. & Ivanov R. & Stanchev H. & Kadikyanov G. & Staneva G. Life cycle assessment of fuel cells electric vehicles. *Transport Problems.* 2020. Vol. 15, No. 3, P. 153-166

GHG emissions were evaluated for BEVs whose batteries were charged with electricity supplied from the power grid, namely, the Polish electric energy mix [54, 55]. In the case of BEVs in Poland, the GHG emissions were 41.4 kg CO_2eq/150,000 km (in 2015). By 2050, these emissions are expected to decrease to 25.8 kg CO_2eq/150,000 km. From 2015–2050, the GHG emissions attributable to BEVs range between 172 and 276 gCO_2eq/km, depending on the electricity source, for the years 2015–2050.

GHG emissions from FCEVs range between 60 and 215 g CO_2eq/km, meaning that the use of hydrogen, even if produced using fossil fuels, is a better solution for transport than electric vehicles. The exception is hydrogen from coal gasification without CCS technology.[56]

FCEVs do not generate local emissions of compounds such as NO_X, nor do they emit any CO_2. At the tank-to-wheel (TTW) stage, only FCEVs and BEVs are completely carbon-neutral, whereas other decarbonisation options – such as vehicles powered by biofuels, natural gas, and hybrids – are not. Compared to diesel and petrol ICEVs, emissions should be considered in the same way as emissions from fuel production at the TTW stage and well-to-tank (WTT) stage. The WTT emissions for ICEVs include emissions from petroleum extraction, transport, refining and processing, and distribution to service stations. Regarding BEVs, the WTT emissions depend on the electricity mix of the country where the vehicle is usually charged. An advantage of FCEVs over BEVs is that fuel cells are less energy-intensive than batteries. The environmental impact of FCEVs at the WTT stage depends on how the hydrogen is produced.

In the subchapter, we analysed the carbon footprint of the hydrogen supply chains for fuel cell vehicles. Notably, not only do FCEVs reduce GHG emissions when compared to petrol-powered vehicles, but these vehicles release almost no emissions during their operation, which can improve air quality, particularly in urban areas.

Fossil fuels consumed to produce hydrogen (i.e., hydrogen pathways based on natural gas, coal, and grid power), which are intended to be the fuel of the future, cannot be

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[54] Zhang, B., Chen, Y., Kang, B., Qian, J., Chuai, X., Peng, R., Zhang, J., Hydrogen production via steam reforming of coke oven gas enhanced by steel slag-derived CaO *International Journal of Hydrogen Energy* 2020. Vol. 45. P.13231-13244

[55] Valente, A.& Iribarren, D& Dufour, J. Harmonising methodological choices in life cycle assessment of hydrogen: A focus on acidification and renewable hydrogen. *International Journal of Hydrogen Energy* 2019. Vol. 44. P.19426-19433

[56] Fueling the Future of Mobility Hydrogen and fuel cell solutions for transportation. Vol. 1, Deloitte China 2020.

regarded as a green alternative. Only fuel cell vehicles powered by hydrogen produced by RES-based techniques – in particular, wind and hydropower – can reduce GHG emissions. LCA is a useful tool for assessing the environmental impact of fuel cell vehicles using different fuels. A well-to-wheel hydrogen life cycle analysis demonstrated that hydrogen is a promising solution for reducing GHG emissions. However, concerning hydrogen fuel cell vehicles, this solution can cause even higher GHG emissions than those attributable to internal combustion engine vehicles if the hydrogen is produced using fossil fuels. Hydrogen-powered vehicles represent one of the three main options for low-carbon transport, along with vehicles that run on biofuels and electric vehicles. Unlike biofuels, hydrogen imposes no impact on land use or air quality; also, hydrogen offers larger running ranges and shorter charging times than BEVs. However, electric cars are more advanced than hydrogen-powered cars because of their lower costs and easily accessible infrastructure [[57],[58]].

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[57] Chen, Y.& Ding, Z.& Wang, W.& Liu, J. Life-cycle assessment and scenario simulation of four hydrogen production schemes for hydrogen fuel cell vehicles. *China Journal of Highway and Transport* 2019. Vol. 32. No.5. P.172-180

[58] Burchart D. Application of advanced environmental life cycle assessment methods to pathways of alternative transport fuels. Monograph. Politechnika Śląska, Gliwice 2021, 170 p.

4.7 CHAPTER REFERENCES

Summarization

At the end of this chapter, students will understand following terms:

- Importance of LCA in automotive sector
- LCA of battery electric vehicles (BEVs)
- LCA of fuel cell electric vehicles (FCEVs)
- Environmental footprint assessment
- LCA for electric vehicle battery charging
- Carbon footprint, water footprint and resource footprint of energy sources
- Computational model of environmental footprints for electric vehicle battery charging
- Comparative LCA of petrol ICEVs, diesel ICEVs, and BEVs
- Hydrogen as the most promising decarbonisation option for vehicles

Questions

- What is the importance of LCA for the automotive sector?
- How does the life cycle of BEVs affect carbon footprint?
- How does the life cycle of BEVs affect water footprint?
- What are the sources of hydrogen production?
- What is an environmental footprint?
- How do individual energy sources influence environmental footprints?
- What are the results of the LCA of petrol ICEVs, diesel ICEVs, and BEVs?
- Why is hydrogen the most promising decarbonisation option for vehicles?

Abbreviations

BEVs – Battery Electric Vehicles
CCS – carbon capture and storage
CF – Carbon footprint
CWU – cumulative water use
DALY – disability-adjusted life years
EF – Ecological footprint
FCEVs – Fuel Cell Electric Vehicles
FU - Functional Unit
GHG emissions – Greenhouse Gas emissions
GWP – Global Warming Potential
ICEVs – Internal Combustion Engine Vehicles
LCA – Life Cycle Assessment
LCI – Life Cycle Inventory
LCIA – Life Cycle Impact Assessment
RES – Renewable Energy Sources
RF – Resource Footprint
TTW – tank-to-wheel
WF – Water footprint
WTT – well-to-tank

5. TOOLS FOR LCA AND ENVIRONMENTAL IMPACT ASSESSMENT

Time to study 120 minutes

Objectives

WHAT KNOWLEDGE STUDENTS WILL ACQUIRE

Students will acquire knowledge about different LCI databases and several LCA software tools which can be used for LCA analysis

HOW IT WILL HELP THEM TO UNDERSTAND THE TOPIC

Student can gain an overview of several available LCA tools and related LCI databases used for life cycle assessment.

WHAT SKILLS THE CHAPTER WILL DEVELOP

The chapter will help students in acquiring skills and knowledge about LCA software tools which can be useful in future professional work related.

WHERE THE STUDENTS CAN USE THE KNOWLEDGE

Students can use the knowledge in their future work related to LCA analysis and use of LCA software tools and various LCI databases.

Theory

5.1 INTRODUCTION TO LCA TOOLS

To help with the LCA analysis several LCA tools are available in the market which can be purchased or are free. There is significant difference between the tools in the area of user-friendliness, modeling principles and included databases which can be used.

WHAT TO CONSIDER WHEN SELECTING LCA SOFTWARE

When selecting LCA software tool for use in a project, there are several criteria which should be considered in order to select the best option for your needs.

First of all, you should identify which needs the tool must fulfil. Do you want to calculate LCA of newly created product or are you evaluating and improving already established product?

Secondly, you should consider if the delivered results are applicable to your conditions:

- Which software environment do you have available?
- Will the tool be operated by single person or multiple persons will share the data?
- Which type of data is available in the software?
- Will the tool be used only by your company or you will share the source and results with others?
- How the tool cooperates with other possible tools and system which are you using in your company?
- How long will the calculations take?
- Will you be able to use the data and outputs directly for presentation and further evaluation?
- Does the tool support desired certification?

You should also consider a financial side:

- Does the company already own LCA tool or new tool will be bought?
- What kind of budget do you have?
- How many manhours will it take to learn the tool?
- It is possible to pay for a course, which will help you in learning the tool?
- Is there enough examples and adequate documentation about the tool?

Last but not least, you should also consider features which LCA software tools provides. These five categories should be considered:

- Database – the database used for calculation and the methodology is the main element of the tool to consider. There exist multiple databases which are available for one or more LCA software tools. More about LCI datasets will be described later.

- Uncertainty analysis – because variation through statistical modeling methods may result in potential distortions, the uncertainty and variability analysis should be incorporated in LCA software tools.
- Sensitivity analysis – LCA software tools should include sensitivity analysis for studying robustness of results and their sensitivity to uncertain factors. This step is essential part of the final interpretation, because input parameter for LCA is often uncertain.
- Impact assessment methods – LCA tools should include methods used to evaluate potential environmental impacts. Two prevalent and internationally recognized methods for LCA are the CML 2001[59]method and Eco-Indicator 99[60]
- Presentation – a user-friendly presentation style is a necessity in a good LCA software tool. The results should be presented in a structured hierarchy and allow interactivity with the presented results.

5.2 LCI DATABASES

Life Cycle Inventory (LCI) database supports various types of sustainability assessment. There are many commercial and free LCI databases which contains information and datasets on one or multiple sectors and which can be imported and used by the previously described tools. In the following text we will focus only on several of these databases.

When selecting database, we need to focus if the database is well defined and regularly updated given that technological advances cause the premature aging of the validity of existing data. From the point of view of environmental impact measurement, two parameters are critical:

- The volume, quality, accuracy and relevance of data available to the user in the software,
- The software package’s user-friendliness.

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[59] Guinée, J., Heijungs, R., Huppes, G., Koning, A.D., Oers, L., Sleeswijk, A.W., Haes, U.D., Duin, R.V. & Lindeijer, E. 2001. Life cycle assessment—An operational guide to the ISO Standards Ministry of Housing. Spatial Planning and the Environment (VROM), and Centre of Environmental Science, Leiden University (CML), The Netherlands

[60] Goedkoop, M., Effting, S. & Collignon, M. 2000. The Eco-Indicator 99: Manual for designers: A damage-oriented method for life cycle impact assessment. Amersfoort: PRé Consultants.

ECOINVENT

Ecoinvent[61] database contains around 18 000 lifecycle inventory datasets, covering range of sectors on global and regional level:

- Accommodation services – the database includes data covering the construction and operation of tourist accommodation facilities, as well as related consumer goods.
- Agriculture, fishery and animal husbandry – the database consists of datasets covering the grow of crops, production of oil from crops, supporting agricultural activities, transportation, production of animal feeds, animal husbandry, and end-of life of various by-products.
- Building and construction – the database covers extraction, processing, transportation and manufacturing of construction minerals and materials and end-of life treatment of construction materials.
- Chemical and plastics – the database consists of over 1900 datasets covering board spectrum of substances which are subsequently used in other sectors. In the database we can find datasets on fertilizers, pesticides, ink and paints, plastics and rubber and many others.
- Energy – the database contains data on electricity and heat which are supporting many different activities, used in, and consumed for, operating households, offices and facilities, for manufacturing, transportation and operation of machines.
- Forestry and wood – the database covers growing of forests, production of wood, transportation and processing of wood and supporting activities and the end-of life of various by-products.
- Fuels – the database contains data on extradition and processing technologies, transportation of crude or refined fuels, production and distribution of most common fuel types – fossil such as hard coal, lignite, petroleum, refined petroleum products and natural gas – renewable fuels such as biogas, biomethane, bioethanol, biodiesel and various solid biofuels from biomass.

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[61] Ecoinvent Dabase, available at https://ecoinvent.org/the-ecoinvent-database/. Last accessed February 2022.

- Infrastructure – the database covers dataset on immobile infrastructure for construction, transport, agriculture, manufacturing, energy generation and transport, mining, waste treatment and hospitality sector.
- Metals – the database describes activities related to production of semi-fabricated metal products such as billets, ingots and rods and well as activities that produce finished metal goods. The database covers production of 35 different metals.
- Pulp and paper – the database includes about 160 datasets covering supply chain from initial forestry to the manufacturing of different paper and board products and also end of life treatment of waste paper and waste paperboard.
- Textiles – the database contains about 150 dataset covering cultivation of raw materials, their processing and transportation of various by-products.
- Transport – the database contains about 600 datasets covering production, maintenance and operation of transportation vehicles, the infrastructure and end of life treatment.
- Waste management and recycling – the database contains more than 1600 datasets related to collection, sorting, disposal and recovery of wasters from variety of sectors.
- water supply – the database comprises over 150 databases which cover extraction, treatment and distribution of tap water, processed water and irrigation water.

Each dataset is attributed to a geographic location – state, country or continent. Geography coverage is dependent on data quality and availability. For almost every dataset there is also geographical location global or Rest-of-the-World location, representing the average global production. The global location and Rest-of-the-World location can be used in cases when there is no desired local representation. The global dataset is created to reflect the global average conditions based on international data. If no such data exists, then the global location is created as weighted average of available local datasets.

FEDERAL LCA COMMONS

The Federal LCA Commons [62] is a database providing US representative LCA data. The database contains datasets developed in different US governmental agencies such as

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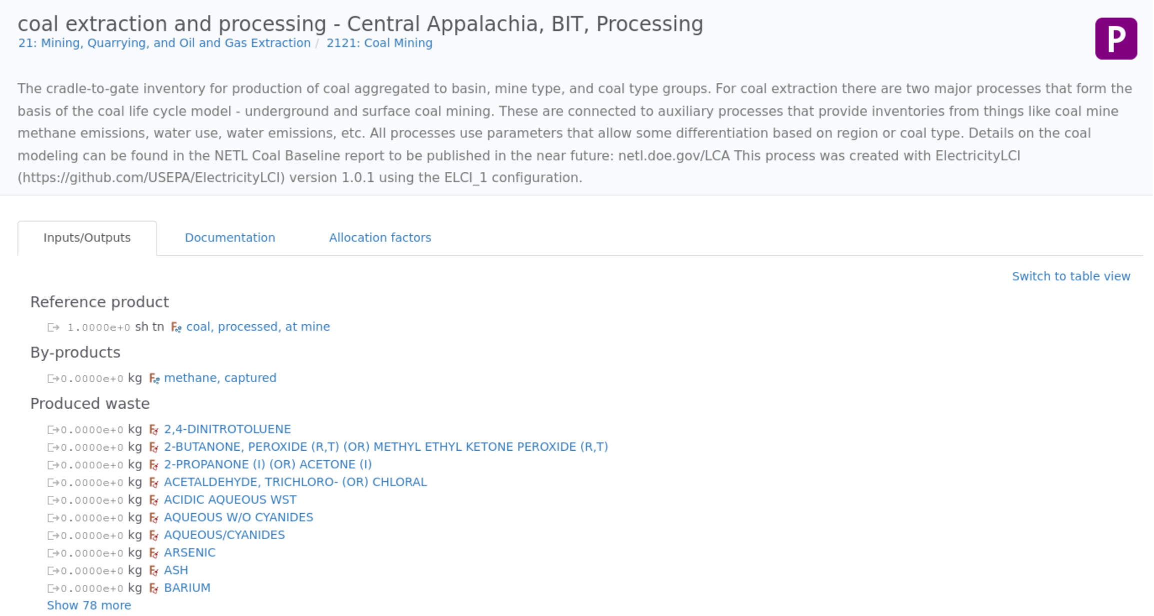
[62] Federal LCA Commons, available at https://www.lcacommons.gov/, last accessed February 2022.

United States Department of Agriculture (USDA), Department of Energy and Environmental Protection Agency (EPA). Moreover, other agencies, such as National Renewable Energy Laboratory (NREL), National Agriculture Laboratory (NAL), US Forest Service and National Institute of Standards and Technology (NIST), participate in supporting and creating various datasets.

The goal of Federal LCA Commons, as stated on their website [63], is:

1. Advance Federal LCA data, research, and information systems by leveraging multi-agency resources and expertise,
2. Improve consistency in LCA methods developed by each agency to develop LCA results for decision-making and public disclosure, and
3. Enhance public and agency access to Federal LCA data in a standardized searchable format from a common repository.

Federal LCA Commons database can be accessed and downloaded from LCA commons website [64] or is available for OpenLCA,



coal extraction and processing - Central Appalachia, BIT, Processing

21: Mining, Quarrying, and Oil and Gas Extraction / 2121: Coal Mining

The cradle-to-gate inventory for production of coal aggregated to basin, mine type, and coal type groups. For coal extraction there are two major processes that form the basis of the coal life cycle model - underground and surface coal mining. These are connected to auxiliary processes that provide inventories from things like coal mine methane emissions, water use, water emissions, etc. All processes use parameters that allow some differentiation based on region or coal type. Details on the coal modeling can be found in the NETL Coal Baseline report to be published in the near future: netl.doe.gov/LCA This process was created with ElectricityLCI (https://github.com/USEPA/ElectricityLCI) version 1.0.1 using the ELCI_1 configuration.

Reference product

1.0000e+0 sh tn coal, processed, at mine

By-products

0.0000e+0 kg methane, captured

Produced waste

0.0000e+0 kg 2,4-DINITROTOLUENE
0.0000e+0 kg 2-BUTANONE, PEROXIDE (R,T) (OR) METHYL ETHYL KETONE PEROXIDE (R,T)
0.0000e+0 kg 2-PROPANONE (I) (OR) ACETONE (I)
0.0000e+0 kg ACETALDEHYDE, TRICHLORO- (OR) CHLORAL
0.0000e+0 kg ACIDIC AQUEOUS WST
0.0000e+0 kg AQUEOUS W/O CYANIDES
0.0000e+0 kg AQUEOUS/CYANIDES
0.0000e+0 kg ARSENIC
0.0000e+0 kg ASH
0.0000e+0 kg BARIUM

Figure 61: Example of dataset in LCA Commons [63]

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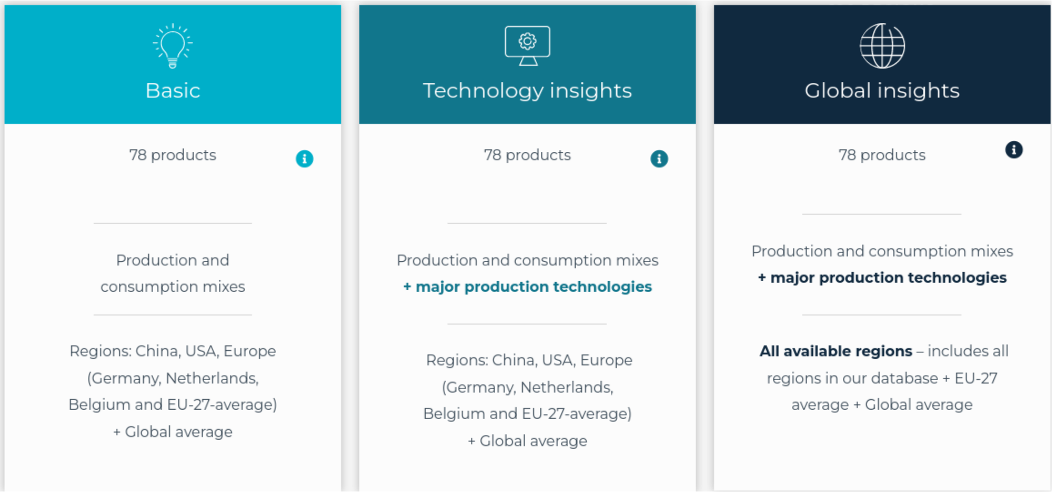
[63] Federal LCA Commons, available at https://www.lcacommons.gov/about-us-0. Last accessed February 2022.

[64] Federal LCA Commons, available at https://www.lcacommons.gov/lca-collaboration/. Last accessed February 2022.

CARBON MINDS DATABASE

Cm.chemicals database by Carbon Minds[65] is a large-scale dataset for the environmental assessment of chemicals and plastics. Backed by a consistent methodology and annual updates, cm.chemicals is a one-stop data source for ISO 14040/14044:2006/AMD 2:2020 compliant life cycle assessment studies for chemicals and plastics. The database covers over 1000 products in up to 190 geographical regions.

Carbon Minds Database can be purchased as Standard Data Packages – Basic, Technology insights, Global insights which consists of 78 common chemicals or as Data-on-Demand.



Basic

78 products

Production and consumption mixes

Regions: China, USA, Europe (Germany, Netherlands, Belgium and EU-27-average) + Global average

Technology insights

78 products

Production and consumption mixes
+ major production technologies

Regions: China, USA, Europe (Germany, Netherlands, Belgium and EU-27-average) + Global average

Global insights

78 products

Production and consumption mixes
+ major production technologies

All available regions – includes all regions in our database + EU-27 average + Global average

Figure 62: Carbon Minds database available options [64]

GABI

GaBi LCA databases[66] offers around 17000 processes and plan models, based on data collected by GaBi when working with companies, associations and public bodies. GaBi offers several databases:

- Organic intermediates – database contains 184 processes covering basic products of industrial synthesis (e.g. methanol, formaldehyde), oxidation products of ethylene (e.g. ethylene oxide), alcohols, components for polyamides (e.g. adipin Acid, caprolactam, hexamethylene diamine), conversion products of propene (e.g.

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[65] Carbon minds, available at https://www.carbon-minds.com/. Last accessed Februarz 2022.
[66] Sphera Solutions GmbH, available at https://gabi.sphera.com/databases/gabi-databases/, last accessed February 2022.

acrylonitrile, acetone, epichlorhydrin, bisphenol A), aromatics and conversion products of benzene (e.g. BTX, ethylbenzene, styrene, cumene, cyclohexane, MSA), oxidation products of xylene (e.g. phatalic anhydride, dimethyl terephtalate).

- Inorganic intermediates – contains 126 processes covering hydrogen, nitric acid, hydrocyanic acid, ammonia and many more.
- Energy – 1460 process covering natural gas, power, hard coal, crude oil, lignite mixes from different countries, thermal energy from steam, crude oil, natural gas from several countries and many more.
- Steel – 33 processing covering frequently used steel aloys.
- Aluminum – 86 processes covering primary and secondary ingots, extrusion profiles, aluminium sheets and others.
- Non-ferrous metals – 13 processes covering titanium, cadmium, nickel, copper, manganese, high and low carbon ferro-chrome and others.
- Precious metals – 28 processes covering silver, silver mix, gold, rhodium, platinum, palladium and others.
- Plastics – database contains 107 processes covering mass plastics (e.g., PE with various densities, PP, PS), vinyl polymers (e.g., PVC, PVAL), technical plastics (e.g., ABS, PMMA, PTFE), polyamide (e.g., PA 6, PA 6.6, PA 6.12), special plastics (e.g., PPS, PEEK, SMA).
- Coatings – contains 80 processes covering various solvent, powder and water coats, slurry clear coat, plans for the modelling of automotive and industrial coating.
- End of Life – database contains 520 processes covering granulators, landfill, incineration, dynamic process models.
- Manufacturing processes – 68 processes covering machining, riveting, deep drawing, grinding, molding, laser cutting, galvanization.
- Electronics – database contains 251 processes covering assembly lines, coil, diodes, ICs, PWBs, solder pastes, capacitors, transistors, LED SMDs, resistors, ring core coils, FR4 substrates, thermistors and others.
- Renewable raw materials – 157 processes covering fertilizers & pesticides, tractors & passes, agricultural equipment, industrial intermediate products, different crops like corn, wheat, hemp, flax, rape seat, soybean and many more.

- Construction materials – database contains 2640 processes covering additives, glue, concrete, mortar, plaster, paints, lightweight aggregate con-crete, brick, foam mortar, lime sand brick, building slabs, wood, insulating material, heat insulating bonding systems, metals, plastics, windows, lighting and plumbing, heating and ventilation, elevators and many more.
- Textile finishing – 147 processes covering pre-treatment (dry processes such as singeing, or wet processes like desizing, bleaching and scouring), dyeing and/or printing (e.g., acids, cationic, direct, disperse, and reactive dyes), finishing, fabrics.
- Seat covers – 46 processes covering leather, PET fabric, cutting and sewing, synthetic leather, non-woven fabric.
- Bioplastics – 128 processes covering bioplastics from different sources, e.g., sugar cane, corn, wheat etc.
- Food & feed – database includes 434 processes representing the most commonly used food and feed products in different geographical regions: crops and animals, e.g., corn, tapioca, rapeseeds, beef, sheep, manufacturing of food products (incl. dairy, starch, and grain mill products, sugar, meat, chocolate, animal feed, vegetable and animal oils, etc.) and by-products.
- Carbon composites - database contains 137 processes for the most common manufacturing and processing technologies in different geographical regions: data sets for the production of carbon fibers (CF) under various technological boundary conditions (standard process, energetically optimized, renewable energies) and regional boundary conditions (production mixes Global, EU28, DE, US, JP, CN, TW, HU, KR, FR, GB, ES, BR, CA), data sets for the production of components made of carbon fiber-reinforced plastics (CFRP) with thermoset or thermoplastic matrix using the most common processing technologies, processing processes (unit processes) for carbon fiber-reinforced plastics for modelling specific production process chains.

OTHER DATABASES

There are many other databases, which can used as sources for LCA analysis. Many of these databases are supported by one or many of LCA tools. Please consult corresponding tool for further info.

WEEE LCI DATABASE

WEEE LCI Database [67] is a French database dedicated to the end-of-life of electrical and electronic equipment, which contains over 900 system processes combining 86 materials.

EXIOBASE database

EXIOBASE database [68] – global, detailed Multi-regional Environmentally Extended Supply and Use / Input Output Database. The database provides data of sectors, products, emissions and resources for 43 countries, and over 200 product categories.

Environmental Footprint database

Environmental Footprint database [69] – designed to support the use of product environmental footprint category rules (PEFCR) and organization environmental footprint sector rules (OEFSR). It contains secondary EF-compliant life cycle inventory datasets and a compatible EF impact assessment method. The Environmental Footprint database is part of the European Commission's Single Market for Green Products Initiative[70].

ESU world food LCA database

ESU world food LCA database [71] – includes about 1900 data sets covering global impacts of food-related areas of interest such as agricultural production services, vegetable production, fruits, animal products, fish, dairy products, meat alternatives, staple food, drinks, sweets, meals, household appliances, food consumption and pet food.

DATASMART LCI Package

DATASMART LCI Package [72] – consists of wide range of materials and processes inclusive of U.S. natural gas mix, geothermal electricity generation, textile production processes, waste treatment processes for white goods and electronics, packaging, bio-materials and dairy; for all 50 U.S. states, 13 Canadian provinces and territories and 10 U.S. eGRID electricity mixes.

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[67] Ecosystem LCI Database, available at https://weee-lci.ecosystem.eco/, last accessed February 2022.

[68] Exiobase consortium, available at https://www.exiobase.eu/, last accessed February 2022.

[69] European Platform on Life Cycle Assessment, available at https://eplca.jrc.ec.europa.eu/LCDN/contactListEF.xhtml, last accessed February 2022.

[70] European Commission, Environment. Available at https://ec.europa.eu/environment/eussd/smgp/, last accessed February 2022.

[71] ESU-sevices Ltd. Available at http://esu-services.ch/data/fooddata/, last accessed February 2022.

[72] Long Trail Sustainability, available at https://ltsexperts.com/services/software/datasmart-life-cycle-inventory, last accessed February 2022./

IDEA Japanese Inventory database

IDEA Japanese Inventory database [[73]] – The Inventory Database for Environmental Analysis is a hybrid inventory database that features both statistical and process-based data. It comprehensively covers nearly all economic activities in Japan and contains about 3800 processes that are classified based mainly on the Japan Standard Commodity Classification. It covers many sectors such as: agriculture, forestry and food, chemical, rubbers and plastics, steel and non-ferrous metals, textile, electronics and machinery, transportation equipment, energy, water, waste treatment, civil engineering, retail and wholesale services.

Social hotspots database

Social hotspots database [[74]] – provides great insight into social hotspots in product supply chains, covering 140 countries and regions and 57 economic sectors. The database includes an extensive list of indicators around labour rights, health and safety, human rights, governance, and community infrastructure.

Evah Pigments Database

Evah Pigments Database [[75]] – database introduces inventory for 51 pigments from various regions comprising 16 different coloured inorganic pigments and 10 different coloured organic pigments. Half of all inorganic pigment are used in printing, a quarter in architectural paints and the rest to colour textiles, plastics, ceramics, enamels, paper, cement, food, cosmetics, pharmaceuticals and automotive products.

NEEDS LCI database

NEEDS LCI database – contains international industrial life cycle inventory data on future electricity supply systems (advanced fossil, hydrogen, fuel cells, offshore wind, photovoltaics, solar thermal, biomass, advanced nuclear, wave energy), future material supply, future transport services. The LCI data sets available in this database are designed to be used in long-term environmental technology assessment. The data sets contain descriptive information about the technology.

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[73] IDEA Inventory Database for Environmnetal Analysis, available at http://idea-lca.com/?lang=en, last accessed February 2022.

[74] Social Hotspots Database, available at http://www.socialhotspot.org/, last accessed February 2022.

[75] The Evah Institute, available at http://www.evah.com.au, last accessed February 2022./

ProBas

ProBas [76] – German dataset library originally provided by the German Federal Environment Agency (Umweltbundesamt). It includes unit as well as aggregated processes, for the following topics: Energy, Materials & Products, Transportation services and Waste.

Worldsteel

Worldsteel Association [77] – a non-profit organisation and industry association, with members in every major steel-producing country.Worldsteel represents steel producers, national and regional steel industry associations, and steel research institutes. Members represent around 85% of global steel production. The database contains global and regional LCI data for 16 steel products, from hot rolled coil to plate, rebar, sections, and coated steels.

5.3 LCA SOFTWARE TOOLS

There many LCA software tools in the market which can be used and are more suitable than others – many of the tools are multipurpose, some are designed for specific industry.

For the purpose of this course, we selected several LCA tools which will be presented in a more detailed way. This list of LCA tools is not comprehensive and absence of specific tool should not be taken as negative recommendation.

We will look closely on these following tools:

- SimaPro
- GaBi
- OpenLCA
- Umberto

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[76] ProBas Proyessorientierte Basisdaten fur Umweltmanagementsysteme, available at https://www.probas.umweltbundesamt.de/php/index.php, last accessed February 2022.

[77] World Steel Association, available at https://worldsteel.org/steel-by-topic/life-cycle-thinking/, last accessed February 2022.

SIMAPRO

SimaPro [78] is one of the leading LCA software tools which has been and is widely used in the industry and academia for over 25 years. It was developed by PRé Consultants.

The software can be used for various applications: sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators.

SimaPro can be used to:

- Easily model and analyse complex life cycles in a systematic and transparent way.
- Measure the environmental impact of products and services across all life cycle stages.
- Identify the hotspots in every link of supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal.

The SimaPro suite of tools includes the classic desktop software and the cloud-based modules SimaPro Collect and SimaPro Share available via the online platform.

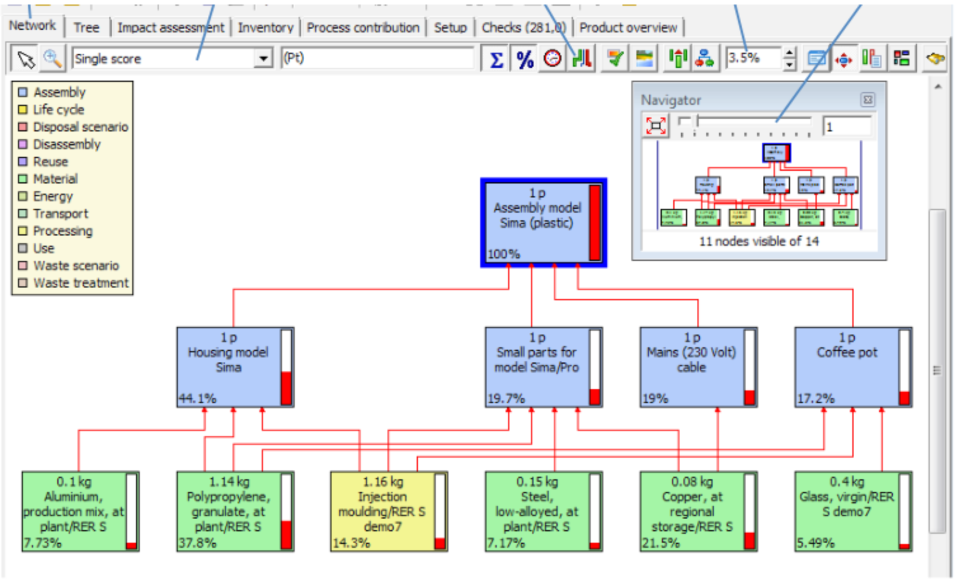

Figure 63: SimaPro example [75]

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[78] Pré Sustainability, available at https://simapro.com/, last accessed February 2022.

SimaPro contains number of impact assessment methods[79] used in calculating impact assessment results:

- European methods – CML-IA, Environment Prices, Ecological scarcity 2013, EF 3.0 Methods, EN 15804 + A2 Methods, EPD (2018), EPS 2015d and EPS 2015dx
- Global methods – IMPACT World+, LC-IMPACT, ReCiPe 2016
- North American – BEES, TRACI 2.1
- Single Issue – Cumulative Energy Demand, Cumulative Exercy Demand, Freshwater Eutrophication, IPCC 2021, Selected LCI results, USEtox 2
- Water Footprint – AWARE, WAVE, Water Scarcity [80] [81], [82], [83]

SimaPro includes [[84]] (by default or on request) many LCI databases such as Ecoinvent, Carbon minds, WEEE LCI database, Environmental Footprint database, Social hotspots database, Datasmart LCI package and many others.

SimaPro offers Business (Business User, Expert User and Power User) and educational licenses (SimaPro Phd, SimaPro Classroom, SimaPro Faculty). The licenses differ in length of the service contract and features availability.

SIMAPRO COLLECT

SimaPro Collect is a web-based tool for LCA data collection. It is designed to collect data from suppliers and other stakeholders via customizable survey templates.

SimaPro Collect is available via the SimaPro online platform. Sending out surveys is included in the Power user, Expert user and PhD packages for the duration of the service contract. Filling out surveys can be done by people with a business user access to the SimaPro online platform.

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[79] Pré Sustainability, available at https://simapro.com/wp-content/uploads/2021/12/DatabaseManualMethods930.pdf, lat accessed February 2022.

[80] Berger, Markus & Van der Ent, Ruud & Eisner, Stephanie & Bach, Vanessa & Finkbeiner, Matthias. (2014). Water Accounting and Vulnerability Evaluation (WAVE): Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting. Environmental science & technology. 48. 10.1021/es404994t.

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[83] Motoshita, Masaharu & Itsubo, Norihiro & Inaba, Atsushi. (2011). Development of impact factors on damage to health by infectious diseases caused by domestic water scarcity. The International Journal of Life Cycle Assessment. 16. 65-73. 10.1007/s11367-010-0236-8.

[84] Pré Sustainability, available at https://simapro.com/databases, last accessed February 2022.

SIMAPRO SHARE

SimaPro Share is a web-based tool for life cycle assessment experts to create product scenarios and share them with business stakeholders. Non-LCA experts can then view and compare these 'what if' scenarios, and experience the impact of their decisions first-hand with accessible, tangible results. SimaPro Share supports fact-based decision-making and sustainable product development by easily allowing LCA results to be shared.

SimaPro Share is included in the SimaPro Power user, Expert user, and PhD license packages, and is available for the duration of the service contract. Business stakeholders who will view, adapt and compare scenarios need to have a business user license.

GABI

GaBi [[85]] Solutions has over 25 years history in providing tools and consultation in LCA. GaBi offers commercial and educational licenses. GaBi Software Suite offers several software tools:

- GaBi ts – is as sustainability solution which offers building product plans for entire lifecycle and calculation of result which represent environmental impacts according selected LCI datasets and relevant LCIA methods. GaBi ts also offers to compare design scenarios and run what-if analyses to identify the most sustainable and cost-efficient design.
- GaBi Envision – is an intuitive web application which enables user to compare different scenarios of the product design created in GaBi Products Sustainability Software by simply changing model parameters.
- GaBi Server – supports collaboration between LCA practitioners, by providing central database management, quality assurance workflows and user rights management. Users work with the same database and therefore can work parallel on the same model.
- GaBi DfX – is a software for compliance and sustainable product development with a view to the end of lie phase. GaBi DfX offers analysis on complex products such as from the automotive, aerospace and electronics sector. The software has following functionalities: import of BOM (Bill of materials) as basis for analysis,

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[85] Sphera Solutions GmbH, available at https://gabi.sphera.com/international/index/, last accessed February 2022.

connection diagram for visualization of order of disassembly, disassembling report, recycling costs analysis for end-of-life scenario and recycling model for modeling disassembly and recycling scenarios.

GaBi Software suite uses several of previously mentioned LCI databases such as GaBi database, Ecoinvent or Environmental Footprints. GaBi also offers “Data on demand” approach, where GaBi will compile a custom database with requested datasets.

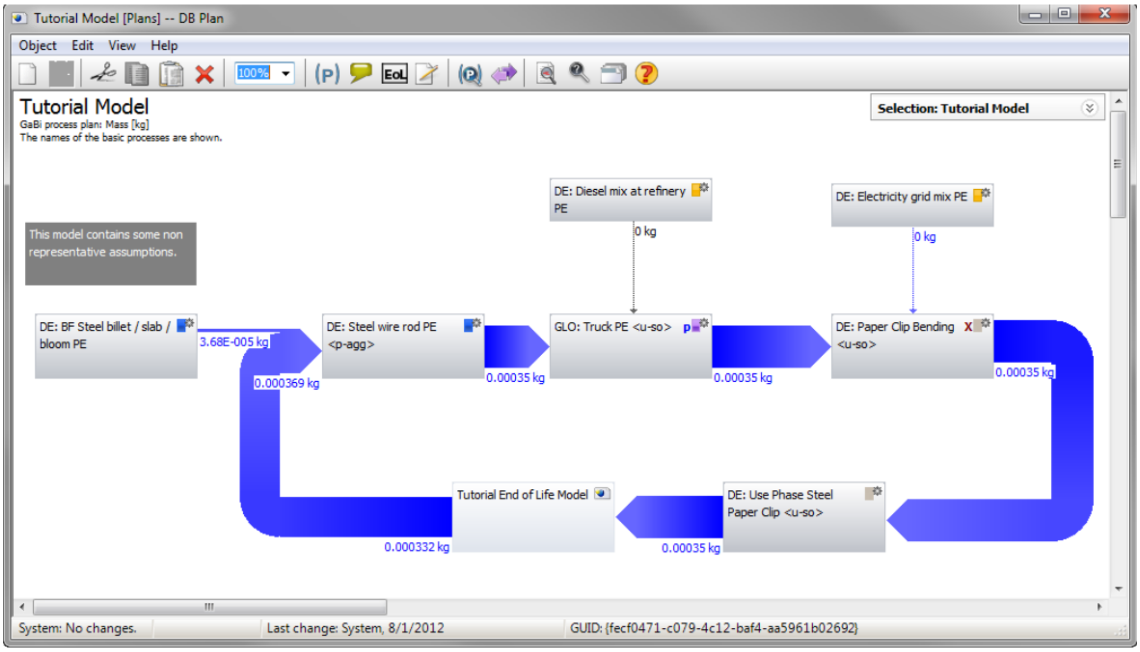


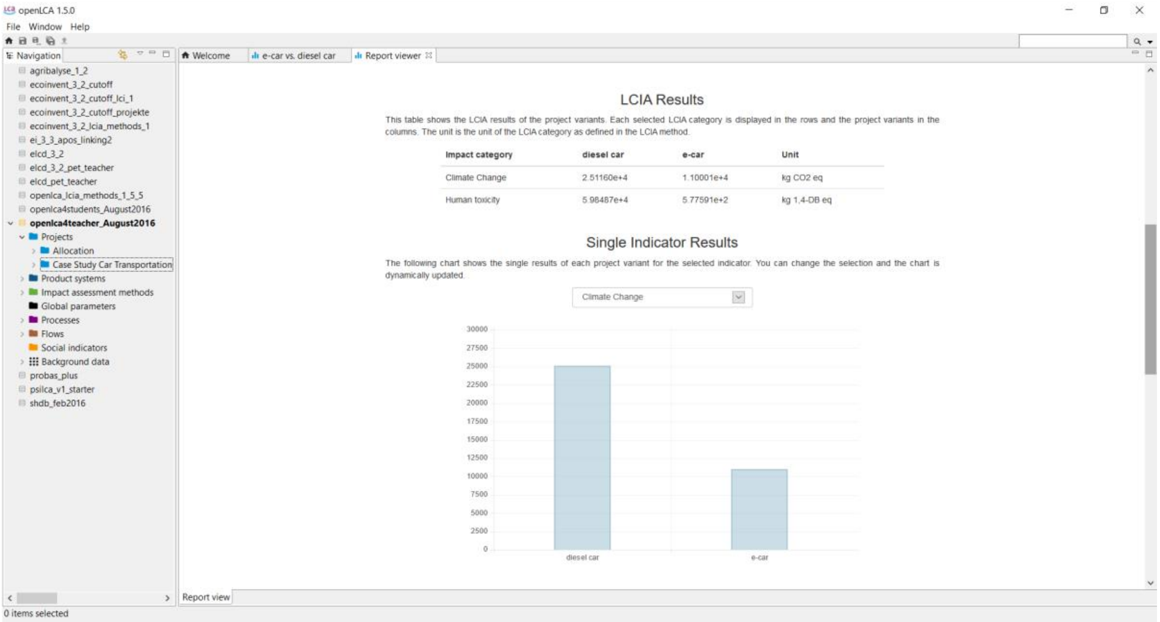
Figure 64: GaBi user interface example

OPENLCA

OpenLCA is an opensource and free software for Sustainability and Life Cycle Assessment which offers several features such as:

- Modeling LCA studies compliant to international standards such as ISO 14040 and ISO 14044:2006/AMD 2:2020.
- Data quality system defined by user or existing ones can be used to visualize data quality in inventory results, the LCIA results, impact analysis and sankey diagram. Moreover, uncertain values can also be calculated from the data quality matrices.
- Automatic and graphical creation of product systems.

- Uncertainty simulation using Monte Carlo simulation – all uncertainty distributions that are defined in the flows, parameters and characterization factors are taken into account in the simulation.
- Contribution tree provides the upstream total LCI or LCIA results per tier in the product system breaking down the results into the upstream total contributions of the providing processes within each supply chain.
- Parameters can be used to define values in openLCA. Parameters can be concrete values, formula value or complex calculation rules.
- Developer tools for skilled users are available to run Python and JavaScript programs and SQL queries.
- Product Environmental Footprint can be calculated.
- Regionalized impact assessment – in newer version of openLCA it is possible to handle GIS data allowing user to include this type of data in the process locations, as well as for defining site-specific impact factors in the method (using parametrization) and therefore making a regionalized impact assessment possible.
- Life Cycle Costing comes as a flow-based approach for calculating Life Cycle Costs and Value Added, with Value Added being considered as „negative cost“.



LCIA Results

This table shows the LCIA results of the project variants. Each selected LCIA category is displayed in the rows and the project variants in the columns. The unit is the unit of the LCIA category as defined in the LCIA method.

Impact category	diesel car	e-car	Unit
Climate Change	2.51160e+4	1.10001e+4	kg CO2 eq
Human toxicity	5.98487e+4	5.77591e+2	kg 1,4-DB eq

Single Indicator Results

The following chart shows the single results of each project variant for the selected indicator. You can change the selection and the chart is dynamically updated.

Climate Change

Figure 65: openLCA user interface example – report [79]

There are many free and commercial LCA databases available, which are provided by different institutions. You can see more information and access them through openLCA Nexus[86] – for example Ecoinvent, Federal LCA Commons, Carbon Minds cm.chemicals and many others.

OpenLCA method package contains over 40 methods such as AWARE (flow-based), BEES+, CML, Crustal Scarcity Indicator, Cumulative Energy Demand, eco-indicator 99, Ecological Scarcity 2013, Ecosystem Damage Potential, Environmental Footprint method v3.0, EN 15804 +A2, ILCD Midpoint +, IPCC 2021 AR6, ReCiPe, TRACI, USETox.

OpenLCA offers clients for multiple platform – MS Windows, Mac and Linux. openLCA also offers LCA Collaboration Server is a server application that complements openLCA (the LCA desktop application). It facilitates exchange and synchronization of LCA data (e.g., flows, processes, product systems or entire LCA models) between users who work from different computers, enabling distributed, collaborative LCA modelling. The Collaboration Server introduces industry-established concepts from software development to the LCA world, with e.g., on-demand tracking of changes as well as comparison of databases and optional merging of data. It is so far unique. The Collaboration Server is available for free.

UMBERTO

Umberto [[87]] developed by ifu Hamburg (now iPoint) is a LCA software suite with over 25 years of history. Umberto offers several LCA software tools.

Umberto LCA+ is a desktop-based software for LCA analysis, which offers transparent illustration of process chains through clear graphic elements, hierarchical modeling through subnets. Umberto LCA+ offers integration of several LCA databases – Ecoinvent, cm.chemical and others.

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[86] OpenLCA Nexus, available at https://nexus.openlca.org/databases, accessed February 2022.

[87] iPoint, availaable at https://www.ifu.com/umberto, last accessed February 2022.

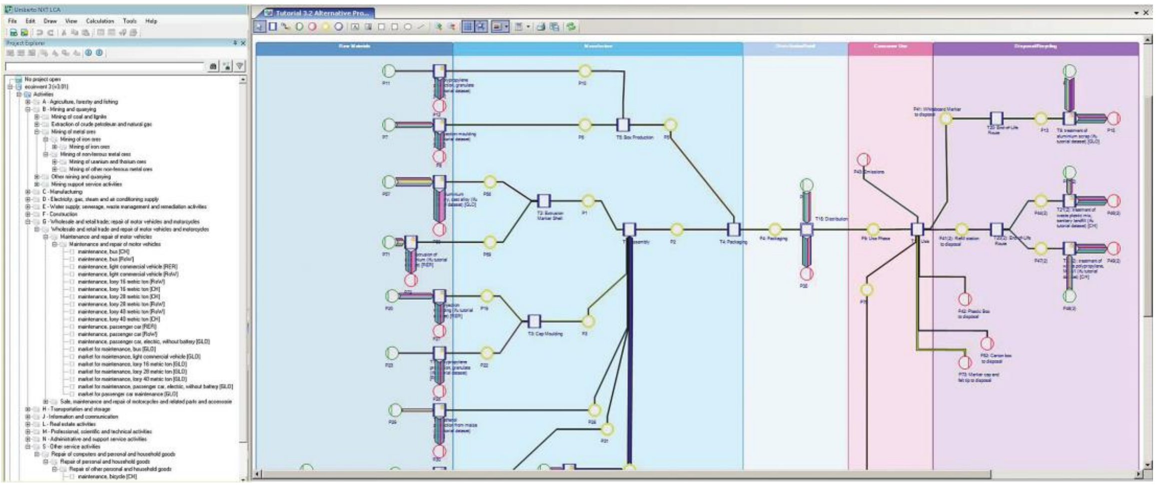

Figure 66: Umberto user interface example [80]

Umberto Efficiency+ is a software tool focused on resource efficiency and process optimalization. With Efficiency+ you can digitally map all energy and material flows. Sankey diagrams are used to visualize the material flows in your production processes.

e!Sankey is a data visualization tool which helps in many different fields of application, such as energy audits and energy management, energy flows (energy balance, energy efficiency), material flows, heat transfer and heat losses technical processes, chemical engineering, waste water and waste disposal, logistics, transport of goods, supply chain, visualization of cost flows & value streams.

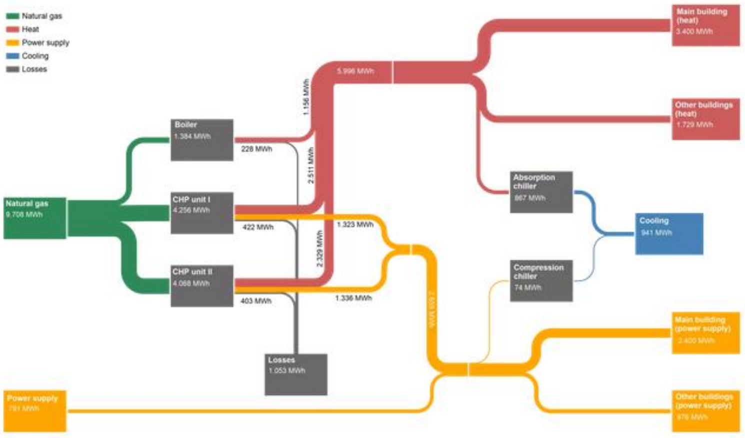

Figure 67: Umberto e!Sankey output example [80]

5.4 CHAPTER REFERENCES

Summarization

At the end of this chapter, students will understand following terms:

- What is a LCA database
- What is a LCA tool
- In which environment to use which LCA database
- Basic knowledge about LCA tools usage

Questions

- What is a LCA database?
- Why to use a LCA database?
- What different LCA databases are available for use?
- What is a LCA tool?
- How can LCA tool help in LCA analysis?

Abbreviations

ABS - Acrylonitrile butadiene styrene

AWARE – Available Water Remaining

BEES – Building for Environmental and Economic Sustainabilitz

BOM – Bill of Materials

BR – Brazil

BTX – Benzene, tulene, xylene

CA - Canada

CF – carbon fibre

CFRP - carbon fiber-reinforced plastics

CN - China

DE –Germany

EF - Emission Factor

EPA - Environmental Protection Agency

ES – Spain

FR – France

FR4 – flame retardant

GB – Great Britain

HU - Hungary

ICs – integrated circuits

ILC – Infinive Life Cycle

IPCC - Intergovernmental Panel on Climate Change

JP - Japan

KR – the Republic of Korea

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LED - Light Emitting Diode

MSA – Methanesulfonic acid

NAL National Agriculture Laboratory

NIST - National Institute of Standards and Technology

NREL – National Renewable Energy Laboratory

OEFSR - environmental footprint sector rules

ReCIPe - recipe

PA - Polyamide

PEFCR - product environmental footprint category rules

PEEK - Polyether ether ketone

PET - Polyethylene terephthalate

PMMA – Polymethyl methacrylate

PTFE – Polytetrafluoroethylene

PS - Polystyrene

PP - Polypropylene

PPS - Polyphenylene sulfide

PVAL – Polyvinyl alcohol

PVC - Polyvinylchloride

PWBs - Printed Wiring Boards

SMA - Styrene maleic anhydride

SMDs - Surface Mount Devices

TRACI – Tool for Reduction a d Assessment of Chemicals and Other Environmental Impacts

TW - Taiwan

US - United States

USDA - United States Department of Agriculture

WAVE – Water Accounting and Vulnerability Evaluation