Life Cycle Sustainability Assessment of the Hydrogen Fuel Cell Buses in the European Context

Evaluation of relevant measures to support low-carbon mobility in the public transport sector

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A thesis presented for the degree of
Doctor of Philosophy

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Telecomunicazioni (DITEN)
Univertà di Genova
Italy
May 2021

… to my parents and to my wife

As from my soul which in thy breast doth lie:
That is my home of love: if I have ranged,
Like him that travels, I return again;
Just to the time, not with the time exchanged,
So that myself bring water for my stain.
Never believe though in my nature reigned,
All frailties that besiege all kinds of blood,
That it could so preposterously be stained,
To leave for nothing all thy sum of good;
For nothing this wide universe I call,
Save thou, my rose, in it thou art my all.
Shakespeare, Sonnet CIX

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Acknowledgements

Firstly, I would like to express my sincere gratitude to my advisor Prof. Maurzio Mazzucchelli for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Riccardo Genova and Prof.ssa. Cristina Carnevali, for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives.

My sincere thanks also goes to Dr. Davide Lotti, who provided me an opportunity to join the team as intern, and who gave access to the laboratory and research facilities. Without they precious support it would not be possible to conduct this research.

I thank my fellow labmates in for the stimulating discussions, for the sleepless nights we were working together before deadlines, and for all the fun we have had in the last four years. Also I thank my friends in the following institution Federico Piazza and Stefan Jakimovki.

Finally, I must express my very profound gratitude to my parents and to my wife Rosalba for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Davide W. Pederzoli

Abstract

Goal and Background. Transport represents 27% of Europe's Greenhouse Gas (GHG) emissions and is the main cause of air pollution in cities. With the global shift towards a low-carbon economy, the EU set forth a low-emission mobility strategy with the aim of reducing the overall emissions in the transport sector. The High V.LO.-City project is part of this overarching strategy and addresses the integration of hydrogen fuel cell (H2FC) buses in the public transport.
Methods. In this thesis, the environmental assessment of one H2FC bus and the related refuelling station is carried out using the Life Cycle Assessment (LCA) methodology, taking into account the following phases: (1) bus production, (2) hydrogen production pathways (water electrolysis, chlor-alkali electrolysis, and steam methane reforming), (3) hydrogen consumption during bus operation, and (4) the vehicles' end of life. The potential impacts are evaluated for magnitude and significance in the life cycle impact assessment (LCIA) phase, using Environmental Footprint (EF) method which is part of the Product Environmental Footprint (PEF) method, established by the European Union (EU) in 2013. The calculated fuel economy is around 10.54 KgH_2/100Km and the energy demand of a refuelling infrastructure may vary between 6 and 9 KWh/KgH_2.
Results. The results show that H2FC buses have the potential to reduce emissions during the use phase if renewables resources are used. The expected Global Warming Potential (GWP) benefit is about 85% in comparison to a diesel bus. Additionally, the emissions of the selected patterns of hydrogen production depend on how electricity is produced and on the chemical-based or fossil-based feedstocks used to drive the production process.
Conclusions and Outlook. The improvement of the environmental profile of hydrogen production requires to promote clean electricity sources to supply a low-carbon hydrogen and to sharpen policy focus with regard to life cycle management, and to counter potential setbacks, in particular those related to problem-shifting and to grid improvement.

Executive Summary

> *A rough assessment... shows that current appropriations of natural resources and services already exceed Earth's long-term carrying capacity... If everybody on Earth enjoyed the same ecological standards as North Americans, we would require three earths to satisfy aggregate material demand, using prevailing technology... To accommodate sustainably the anticipated increase in population and economic output of the next four decades, we would need six to twelve additional planets.*[1]

Policy landscape

Anthropogenic climate change is one of the greatest challenges facing humanity, with worrisome consequences that could imperil the very foundation of modern civilization. An ever growing body of scientific researches demonstrate unsustainability of the prevailing model of development, which is largely based on combustion of fossil fuels. Modern civilization depends on extracting massive energy stores, depleting finite fossil fuels deposits that cannot be naturally replenished ones consumed and whose recovery is on time scales of order of magnitude longer than the existence of human species. Although a two-digit increase of renewable energies, by 2018 fossil fuels still account for about **85%** of world's primary energy consumption, just **3.5%** less than a generation ago, in 1990 [35].

By considering these stores, actual societies **transform unprecedented amount of energy**. Such transformation raised the average quality of life for most of world's population, but it has been the key factor behind **environmental degradation** and **uneven distribution of energy resources**. Moreover, the dependence of modern societies on incessant, reliable, inexpensive supply of fossil fuels has brought to changes well beyond local and

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[1] Wackernagel, Mathis & Rees, William (1996), Our Ecological Footprint, New Society Press. [261]

regional boundaries, generating a multitude of political concerns, above all the **concentration of decision-making power** in the hand of a few resulting from higher level of integration at institutional level (be it a government, business or military). According to Richard Adams [2]: 'more energetic processes and forms enter a society, control over them becomes disproportionately concentrated in the hands of a few, so that fewer independent decisions are responsible for greater releases of energy'.

Two events from the early 1970s in particular - the Club of Rome's report 'Limits to Growth' [219] in 1972, and the UN Conference on the Human Environment in Stockholm (the 'Stockholm Conference') in 1972 - are worth mentioning as they can be seen as **important milestones** in the development of international environmental awareness. They both remarked, though at different degree, the necessity to reconcile economic growth with the planet's carrying capacity over the long term. The book 'Limits to Growth' [219] explored via computer model different possible scenarios -and environmental outcomes-of world development over two centuries from 1900 to 2100 and warned that the never-ending pursuit of growth was incompatible with the planet's resources, leading to **overshoot the biosphere's regenerative capacity**. Whereas the Stockholm Conference called for a **treaty in the environmental field** and provided guidelines for action by Governments and international organizations designed to protect and improve the human environment [34] .

A process of visioning was set forth, shaping the very preliminary traits of the **sustainable development** which was eventually defined in the Brundtland Commission's report 'Our Common Future', in 1987.

Successive summits in the coming years further strengthened the concept of **sustainable development**, committing governments to ending poverty, protecting the planet and improving quality of life at global scale. The UN incorporated a set of sustainable development goals in paragraph 54 United Nations Resolution **A/RES/70/1** of 25 September 2015, officially known as 'Transforming our world: the 2030 Agenda for Sustainable Development'[2]. Moreover, such objectives are firmly anchored in the European Union Treaties[3] and mainstreamed in key projects, sectorial policies and initiatives. In 2010, past the 2008-2009 financial crisis, EU set out a vision of Europe's social market economy for the 21st century, called 'A strategy for smart, sustainable and inclusive growth'[334], underscoring sustainability as a key

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[2] The Agenda is a commitment to eradicate poverty and achieve sustainable development by 2030 world-wide, ensuring that no one is left behind. The adoption of the 2030 Agenda was a landmark achievement, providing for a shared global vision towards sustainable development for all.

[3] Articles 3 (5) and 21 (2) of the Treaty on European Union (TEU).

reference.

Under its umbrella, the European Parliament and the European Council backed the 'flagship initiative for a resource-efficient Europe' ([317] and [302]) for supporting a shift towards a resource-efficient, low-carbon economy. It provides a long-term framework for action in many key sectors. In particular, **transport sector is critical**, since it is hard-to-decarbonize, energy intensive, and deployment of new technologies and the development of adequate infrastructure requires successive investments over several decades.

In 2016, road transport accounted for **28.5%** of CO2 emissions from fuel use in the USA [94], while in Europe the figure was **27%** [98]. Moreover, European road transport was responsible for almost **72%** of total greenhouse gas emissions from transport (including international aviation and international shipping). Of these emissions, **44%** were contributed by passenger cars, while **19%** came from heavy-duty vehicles, including buses, [98]. To achieve the 2-degree scenario, the EU needs to eliminate about **72%** of CO2 from the EU transportation fleet by 2050, equal to roughly **825 Mt** [121]. The majority of estimated transportation emissions-related health impacts occurred in the top global vehicle markets. In 2015, **84%** of global transportation-attributable deaths occurred in G20 countries, and **70%** occurred in the four largest vehicle markets: China, India, the European Union (EU), and the United States[6].

The **Transport White Paper**[340] puts forward a wide range of options for pursing the required holistic transport policy and for limiting energy-related CO2 emissions. Additionally, in 2006 the EU had already backed the **Seventh Framework Programme** ('**7th EAP**') [318], spanning seven years from 2007 through 2013, to achieve a set of environmental objectives by adequate investments, encouraging the use of public-private initiatives.

Demonstration projects and rolling out of innovative technologies are the pillars of the implementation strategy held in specific areas of the transport sector [324]. In this view, the **mass public transport** will remain the **backbone** around which sustainable mobility solutions will thrive. To date, this has included the development of hydrogen fuel and related infrastructure for transport, led by a Public-Private Partnership – the 'Fuel Cells and Hydrogen Joint Undertaking' (FCHJU), established by a Council Regulation on 30 May 2008 [322]. According to FCHJU Strategic Research Agenda [120], demonstration 'provides evidence of the viability of a new technology that offers potential economic (and societal) advantage but cannot be commercialised directly. The act of demonstrating (i) proves the functional performance, including operability, reliability and economics and (ii) enhances public awareness and public acceptance of the applied technology'. As stated by FCHJU report on alternative fuel urban buses [124] the public transport sector sets to **double the market share** of public transport worldwide by 2025. **Hydrogen** is touted as a promising decarbonisation option in urban mobility and could potentially represent a key element in achieving the energy transition. The **formation of niches** is appropriate way to address the introduction of hydrogen technologies, that require protected spaces within which to develop momentum.

As of today, a succession of **hydrogen fuel cell** (H2FC) bus projects are underway in the public transportation: **HIGH V.LO City** (2012 - 2019), **HYTRANSIT** (2013 - 2019), **3MOTION** (2015 - 2022) and **JIVE** (2017-2022)[4].

The impact of supposed green vehicles with alternative technologies needs to be thoroughly assessed and compared with the impact of conventional vehicles using a **life cycle approach**. Such an approach ponders the impact of the **well-to-wheel** emissions, including emissions from electricity generation as well as the environmental impacts due to the production and disposal of the vehicle. The **Life Cycle Assessment** (LCA) is an overarching tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management.

DITEN department was involved in the **High V.LO. City** project as an evaluator to determine the added value of the project taking into account the performance of FC buses and of the refuelling installations as well against a defined set of targets.

That being so, the overall objective of the thesis is to **evaluate the environmental** load of hydrogen powered buses regarding several environmental categories, with a focus on climate change, as well as suggesting room of improvement for hydrogen and FC technology compared with other drive train technologies for public transport buses.

Research objectives

As stated before, transport sector requires urgent need to improve the environmental performance by controlling emissions of harmful substances into the atmosphere[5], integrating environmental protection requirements and promot-

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[4] Previous initiatives: CUTE (2001-2006), HyFLEET:CUTE (2006-2009), ECTOS (2001 - 2007), CHIC (2010-2016).

[5] In general, the road transport sector is the largest contributor to total nitrogen dioxide emissions in the EU, while fuel combustion in the commercial, institutional and households sector is the largest contributor to overall primary particulate matter emissions, particularly in some eastern European countries.

ing low-carbon mobility solutions. In order to accomplish such improvement, the assessment of the environmental impact of the hydrogen fuel cell buses through a systematic and methodical analysis have to be performed, which provides the necessary knowledge and insight to address the environmental problems concerning urban mobility.

This thesis fulfils the following main objectives:

- Report a comprehensive LCA case study that uses **real-world operations data** to investigate the environmental impacts of High V.LO-City hydrogen fuel cell bus system (i.e. H2FC bus, hydrogen production routes, and refuelling stations) against a conventional Euro-6 Diesel bus. Specifically, three methods of hydrogen production are considered: electrolysis of water, chlor-alkali electrolysis, and steam methane reforming process.
- Provide an assessment of the environmental impacts not only in terms of climate change or global warming potential, but in other impact's categories.
- Develop and implement an elaboration pipeline useful to handle hydrogen bus data more conveniently and to automate data collection and data entry in the software tool.
- Provide guidelines and orientations that could enhance the understanding of current environmental policy framework (aimed at reducing carbon dioxide emissions and supporting low carbon alternatives), and of the global energy system transition phase (increasing renewable energy deployment, energy efficiency, and showing contradictions).

Thesis Outline

This thesis is divided into seven chapters, outlined as follows:

Chapter 1 outlines the historical background of the climate change issue, showing the major milestones that have led to the rise of the environmental awareness, substantiated in the common concern of humankind concept and in subsequent environmental treaties and conventions.

Chapter 2 presents an outlook for energy use worldwide, showing major consumption patterns and energy related emissions. The excursus continues illustrating the projected changes in the global primary-energy structure over time and then the energy consumption issues in the transport sector. Eventually, it shifts towards the European context, evidencing energy use and carbon emissions trend against targets. Relevant measures to support low-carbon mobility complete the picture.

Chapter 3 describes the emergence of the Sustainability Science as a new trans-disciplinary endeavour, the Life Cycle Assessment (LCA) theoretical framework, namely its concept, methodology and computational structure. The 'well-to-wheel' analysis is presented as complementary to LCA.

Chapter 4 discusses the elaboration pipeline that was designed and implemented to handle hydrogen bus data more conveniently, to automate data collection and data entry in the software tool.

Chapter 5 discusses the Labview application developed to calculate the performance indexes of the hydrogen buses involved in the High V.LO. City project.

Chapter 6 reviews the most recent LCA studies on alternative fuels for vehicles, placing special emphasis on hydrogen production processes impacts assessment. Main gaps in literature are determined and described. In response to existing gaps in the research field, this chapter reports a comprehensive LCA case study to evaluate the environmental impacts of High V.LO-City hydrogen fuel cell bus system against a conventional Euro-6 Diesel bus. The results are calculated using the OpenLCA software, and their interpretations are elucidated.

Chapter 7 summarises the results and conclusions. The final remarks weave together different strands of thoughts especially focusing on energy consumption patterns, hydrogen production methods, and recommendations for improving the transport environmental performance.

Chapter 1

Energy and Society in the historical development of Climate Change

> *Man of the twentieth century has become just as* ***emancipated from nature*** *as eighteenth-century man was from history. History and nature have become equally alien to us, namely, in the sense that the essence of man can no longer be comprehended in terms of either category. On the other hand, humanity, which for the eighteenth century, in Kantian terminology, was no more than a regulative idea, has today become an inescapable fact. This new situation, in which 'humanity' has in effect assumed the role formerly ascribed to nature or history.*[1]

> *The fundamental object of contention in the life-struggle, in the evolution of the organic world, is available energy. In accord with this observation is the principle that, in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favorable to the preservation of the species.*[2]

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[1] Arendt, Hannah, The Origins of Totalitarianism (1958); Cleveland and New York: Meridian Books, The World Publishing Company, 1967) p. 298 [10].

[2] Lotka, A. J. (1922). Contribution to the energetics of evolution. Proceedings of the National Academy of Science, 8, 147-151 [198].

1.1 Introduction

Inquiry into the natural phenomenon of **energy's manifestation** traces back to **Heraclitus** (c.535- c.475 a.C.) and **Aristotle** (384-322 a.C.). The former supposedly argued that everything changes, the latter, on the other hand, noticed that this was not completely true: although change happens, something also remains unchangingly the same. The energy historian **R. Bruce Lindsay** suggests that, from Aristotle onwards, a continuous line of inquiry into the concept of energy spans all the way to Einstein, with as common denominator the assumption that 'the root of the concept is the notion of **invariance** or **constancy** in the midst of change' [192]. Therefore concluding that: '[...] if we can find a single word to represent an idea which applies to every element in our existence in a way that makes us feel we have a genuine grasp of it, we have achieved something economical and powerful. This is what has happened with the idea expressed by the word energy. No other concept has so unified our understanding of experience.'[194]. Put into philosophical terms, nothing comes from nothing and becomes nothing: everything that lives and exists ultimately owes its being to this fundament. However, the word **energy** does not have a concrete grasp. Even the Nobel prize Feymann stresses this difficulty: 'It is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount'[3]. He argues that:

> *There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no known exception to this law-it is exact so far as we know. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same. (Something like the bishop on a red square, and after a number of moves-details unknown-it is still on some red square. It is a law of this nature.) Since it is an abstract idea, we shall illustrate the meaning of it by an analogy.*[4]

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[3] See /www.feynmanlectures.caltech.edu...

[4] See www.feynmanlectures.caltech.edu ➡.

In 1892, **Wilhelm Ostwald**, a leading German chemist and Nobel laureate, began his manifesto on the **Fundamentals of General Energetics** (1892) by stressing energy's unique position:

> *The concepts that find application in all branches of science involving measurement are space, time, and energy. The significance of the first two has been accepted without question since the time of Kant. That energy deserves a place beside them follows from the fact that because of the laws of its transformation and its quantitative conservation it makes possible a measurable relation between all domains of natural phenomena. Its exclusive right to rank along space and time is founded on the fact that, besides energy, no other general concept finds application in all domains of science. Whereas we look upon time as unconditionally flowing and space as unconditionally at rest, we find energy appearing in both states. In the last analysis everything that happens is nothing but changes in energy.*[5]

According to the German mathematician Deltete: 'all changes or transformations in nature can be reduced to two kinds of change: they are in part transfers (Übergänge) of energy from one body to another, in part transformations (Umformungen) of energy from one form to another'[79]. The latter kind of change governs the Earth-system, sustaining and maintaining all the biosphere's processes. Life on Earth would be impossible without the **photosynthetic conversion** of solar energy into plant biomass. **Photosynthesis** is the only significant **solar energy storage process on Earth** and has provided life-energy for the biosphere during most of the Earth's history. Wealth of evidence indicates that photosynthesis has evolved via a complex path to produce the distribution of types of photosynthetic organisms and metabolisms that are found today. The photosynthesis mechanism has risen firstly in the **Bacteria** (cyanobacteria phylum) and in a second evolution step into plants, that belong to the **Eukaryote** domain, containing **chloroplasts**, which were derived from endosymbiosis of acquired **cyanobacteria-like** organisms. A common trait for the photosynthesis is that it involves oxidation of water and evolution of molecular oxygen, O2, as a waste product and giving rise to what is now called **oxygenic photosynthesis**. The production of O2 and its quent accumulation in the atmosphere forever changed the Earth and permitted the development of advanced life that utilized the O2 during

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[5] Ostwald, W. 1892. Studien zur Energetik. II. Grundlinien in der allgemeinen Energetik. Berichte uber die Verhandlungen der Koniglich Sachsischen Gesellschaft der Wissenschaften zu Leipzig 44: 211-237. Trans. in Applications of Energy: Nineteenth Century, ed. R. B. Lindsay. Stroudsburg, Pa.: Dowden, Hutchinson and Ross, 1976. [193]

aerobic respiration. Several lines of geochemical evidence indicate that free O2 began to accumulate in the atmosphere by 2.4 billion years ago, although the ability to do oxygenic photosynthesis probably began somewhat earlier. This step increase is popularly known as the **Great Oxidation Event** or GOE (see Figure 1.1).

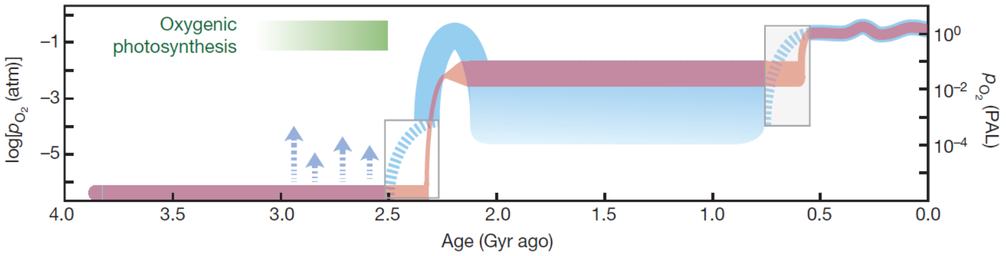

Figure 1.1: The faded red curve shows a ’classical, two-step’ view of atmospheric evolution, while the blue curve shows the emerging model (pO2 , atmospheric partial pressure of O2). Right axis, pO2 relative to the present atmospheric level (PAL); left axis, log pO2 . Arrows denote possible ’whiffs’ of O2 late in the Archaean; their duration and magnitude are poorly understood. An additional frontier lies in reconstructing the detailed fabric of ’state changes’ in atmospheric pO2 , such as occurred at the transitions from the late part of the Archaean to the early Proterozoic and from the late Proterozoic to the early Phanerozoic (blue boxes) [203].

Humans depends on such transformation for their survival and on many more energy flows for their organized existence. The evolution of human societies, as multi-individual organisms, is predicated on energy flux. From this perspective the history of successive civilizations, the largest and most complex organisms in the biosphere, resolves around building energy reserves and means for controlling greater energy flows. The mechanism of evolution is evolving as a natural consequence of the continuing evolution of energy coupling. A simple schematic of the fluxes in the solar-driven planetary heat engine is reported in Figure 1.2. The Earth (oval figure) contains and limits everything except the energy of the Sun. Solar energy (1) drives photosynthesis in green plants; cycles water from the oceans to the atmosphere and back; circulates global air masses; warms soils. Our lives and the economy depend on these ecological processes. Solar energy (2) is also available in economically useful forms (E) - e.g., hydrocarbons, hydro, wind power, etc.

These forms of energy drive the conversion processes (C) which are central to the economy and affect the environment. In addition to energy, other inputs to conversion (production factors) are natural assets (N) - natural resources and environmental services, (flowing via 3); human assets (H) - people’s skills, knowledge, intellect and vigour (flowing via 4); and phys-

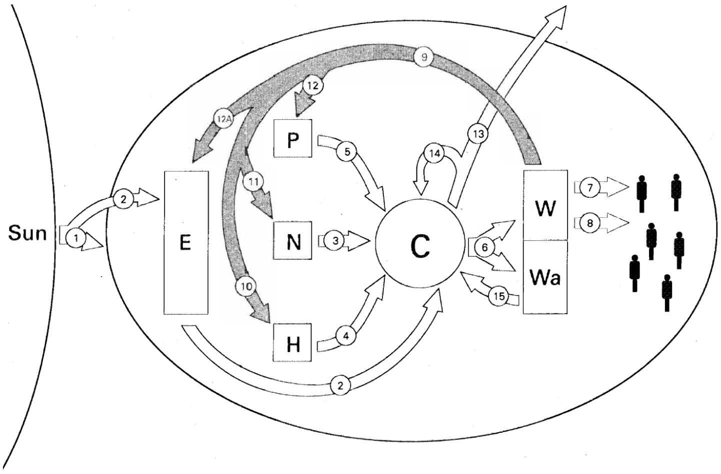

Figure 1.2: Inputs and outputs to and from the economy within the context of the environment are shown in simplified form. The Earth-system is maintained by constant solar energy flux.

ical plant and infrastructure (P) - settlements, factories, machines, systems of transportation and communication (flowing via 5). Conversion results in loss of heat (13) some of which can be recaptured (14) and used again. The visible results (6) of conversion are material wealth (W) and material wastes (Wa). Material wealth provides the goods and services that people need (7) or want (8). Material wastes can sometimes be recycled (15) to contribute to material wealth. Material wealth is used for the investment (9) needed to maintain the process of conversion and to ensure sustainability. Investment must be allocated among the production factors. There has been a tendency to run down natural assets to expand physical pliant (12), including energy extraction facilities (12a), and to allow a high level of discretionary consumption (8). Human development (10) through education, training and health care (including family planning) is often neglected, and the failure to invest in the maintenance and rehabilitation of natural assets (11) has been close to catastrophic. Many of the actions recommended in the Stategy imply the re-allocation of investment to correct those imbalances. According to **Alfred Lotka**'s (1880-1949) law of maximum energy, for biota it is not the highest conversion efficiency, but the greatest flux of useful energy, the maximum power output, which is most important for growth, reproduction, and maintenance, and species radiation. Consequently, living organisms and ecosystems do not convert energy with the highest efficiencies but rather at rates optimized for the maximum power output [199]. Odum and Pinkerton (1955) demonstrated that the efficiencies are always less than the possible maxima: they never surpass 50% of the ideal rate. Therefore, the most likely prospect is for substantially higher global energy demand. Modern civilization thus appears to follow the law of maximized energy flows, which Lotka singled out as a key evolutionary mark: 'In every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system, so long as there is presented an underutilized residue of matter and available energy.'[198].

At the beginning of the twentieth century **Ostwald** tied the availability of energy, substitution of labour by mechanical, prime movers, and increased efficiency of energy conversions to cultural progress. And the extension of Lotka's principle of maximized energy flows to human affairs would mean that the most competitive societies would struggle for the highest possible energy fluxes. Two important quotations could clarify this relationship. In a seminal paper, the anthropologist **Leslie White** called such link the first law of cultural development: 'Other things being equal, culture evolves as the productivity of human labor increases'[361]. In other words, the degree of cultural development varies in correlation with the amount of technically available energy. The physicist **Ronal E. Fox** concluded his book on energy in evolution by stating: 'A refinement in cultural mechanism has occurred with every refinement of energy flux coupling'[363]. All known form of energy are critical for human existence. However, the very basic energy source is stored in plants in form of chemical energy as a result of photosynthesis process. These stores lay down the foundation for all higher life. Metabolism rearranges nutrients into tissues and maintaining body functions, and, in all mammals, also constant body temperature. Digestion also provides mechanical (i.e. kinetic) energy of working muscles. Animals can deploy their muscles for searching food, reproduction, escape, and defence, but these functions are bounded by the size of their bodies and by the availability of accessible nutrition in the environment. On the other hand, humans can overcome these physical limits by **using tools** and **harnessing** the energies outside their own bodies. These extra somatic energies have been used for a growing variety of tasks. Above all, food acquisition practice, with a repertory of **tool-making capabilities**, is a distinguished (even if not an exclusive) mark of hominids behaviour. Tools[6] have given early hominids - a

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[6] Tool use and manufacture are given prominence by their suggested relation to human lineage. They play a central concepts in animal cognition research for the past century. Studies of tool use and tool making, both in the laboratory and in the field, continue to advance scientist's understanding of the behavioural and cognitive capabilities of animals today. An important goal in understanding the nature of tool is to develop a precise, comprehensive definition and to provide interpretive meanings concerning human behaviour and cognition from an evolutionary perspective. One of the earliest explicit definitions,

later human - a significant mechanical advantage in the survival race against adverse weather conditions and predators. The **mastery of fire** can be the climax of these capabilities, setting human ancestors, and thus the genus 'Homo', further apart from animals. The preamble of '2001' seeks to capture the first spark of human dexterity, i.e. the moment when human ancestors realized that natural objects, such bones, could be used as tools. The narrative expedient of the intervention of extra-terrestrial intelligence, in the form of a mysterious monolith, makes possible this cognitive leap. The relevant passage in Clarke's novel, which occurs at the end of Part One, is arranged to convey an ascending progression of events [59]:

> *When the ice had passed, so had much of the planet's early life - including the man-apes. But, unlike so many others, they had left descendants; they had not merely become extinct - they had been transformed. The toolmakers had been remade by their own tools.*
> *For in using clubs and flints, their hands had developed a dexterity found nowhere else in the animal kingdom, permitting them to make still better tools, which in turn had developed their limbs and brains yet further. It was an accelerating, cumulative process; and at its end was Man.*
> *The first true men had tools and weapons only a little better than those of their ancestors a million years earlier, but they could use them with far greater skill. And somewhere in the shadowy centuries that had gone before they had invented the most essential tool of all, though it could be neither seen nor touched. They had learned to speak, and so had won their first great victory over Time. Now the knowledge of one generation could be handed on to the next, so that each age could profit from those that had gone before.*

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proposed by van Lawick-Goodall ([188], page 195), focuses on abstract properties of behaviour, including functionality and goals: "[Tool use is] the use of an external object as a functional extension of mouth or beak, hand or claw, in the attainment of an immediate goal". Alcock's ([5], page 464) definition is more detailed in its specification of goals as the alteration of form and position: "Tool-using involves the manipulation of an inanimate object, not internally manufactured, with the effect of improving the animal's efficiency in altering the form or position of some separate object". Beck ([18], page 10) offers a refinement of Alcock's definition, one that has come into wide use and is a current standard in the animal cognition literature: "Thus tool use is the external employment of an unattached environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself when the user holds or carries the tool during or just prior to use and is responsible for the proper and effective orientation of the tool."

> *Unlike the animals, who knew only the present, Man had acquired a past; and he was beginning to grope toward a future.*
> *He was also learning to harness the forces of nature; with the taming of fire, he had laid the foundations of technology and left his animal origins far behind. Stone gave way to bronze, and then to iron. Hunting was succeeded by agriculture. The tribe grew into the village, the village into the town. Speech became eternal, thanks to certain marks on stone and clay and papyrus. Presently he invented philosophy, and religion. And he peopled the sky, not altogether inaccurately, with gods.*
> *As his body became more and more defenseless, so his means of offense became steadily more frightful. With stone and bronze and iron and steel he had run the gamut of everything that could pierce and slash, and quite early in time he had learned how to strike down his victims from a distance. The spear, the bow, the gun, and finally the guided missile had given him weapons of infinite range and all but infinite power.*
> *Without those weapons, often though he had used them against himself, Man would never have conquered his world. Into them he had put his heart and soul, and for ages they had served him well.*
> *But now, as long as they existed, he was living on borrowed time.*

Stone, bronze and iron became increasingly central in human practices. This conceptual blending deserves a careful analysis. Such evaluation of human technologies and culture, thus compressed in a single scenario (the ‘blend’), is founded on all-encompassing concept of energy, as a prime mover spanning the totality of human actions. The same narrative expedient appears in the sentence ‘The spear, the bow, the gun, and finally the guided missile’. These weapons, considered here individually, capture the evolution of human technology from prehistory to the cold war. The concreteness described by this passage hints at an embodied parallel between the history of mankind and physical interaction with the natural environment (‘interaction’ denoting ‘dominance’ over the Earth-system). To further underscore this progress, it is worth also to mention the ‘Dawn of Man’ sequence in **Kubrick**’s ‘2001: A space odyssey’ [185]. The film has told the story of how a primitive hordes of man-apes became human, through learning the use of tools and weapons, and how the twenty-first century descendants were able to use machine to venture beyond the Earth to other worlds among the stars. In one of the most remarkable narrative ellipse, however, the entire history of the human development (from the first murderer to the technological marvel of space flight) is covered by Kubrick's now famous jump cut, from a bone, as it flies up in the air, to the weightless fall, down screen, of a space craft, floating in the void to the strains of Johan Strauss's Blue Danube Waltz. This transition creates a direct comparison between the large, complex spaceship and the more archaic bone weapon. Yet, while tools have evolved into extremely advanced objects such as space ships, only comparable to a bone in structural form, they still remain the empowering forces that distinguish humanity from animals. With the 'Dawn of Man' Kubrick echoed the writer **Robert Ardrey**, who argued that lethal violence first made human being. In this context that the 'Territorial imperative' [9] takes form, meaning capturing a place and fending off rivals with a dead tapir's bone. Such technological advancement paved the way for a rapid societal changes that reached its climax at the early begin of the twentieth century.

1.2 Energy flows and controls

The progresses, gained during the twentieth century, were closely bound with an **unprecedented rise of total energy consumption**. This growth was accompanied by a worldwide change of the dominant energy base as hydrocarbons have relegated coal, almost everywhere, to only two essential applications: the production of metallurgical coke and, above all, the generation of electricity. The combustion of fossil fuels and the affordable generation of electricity creates a new form of high-energy civilization whose expansion has now encompassed the whole planet. However the provision and the use of fossil fuels and the electricity are the large causes of **anthropogenic pollution of atmosphere** and **greenhouse emissions** are leading contributor to water pollution and land use change. This immense increase in energy use is changing the layer of gases that constitutes the Earth 's atmosphere, which in turn controls global climate. So, for the first time in the planet's history , humans are truly involved in a change of their environment. In contrast, the understanding of the physical basis, governing the dynamic of climate change (including the contribution of anthropogenic emissions), has spread over three centuries and still today constitutes a matter of debate in the scientific community.

1.3 Historical background

In this long lively history of global environmental science, Jonathan Weiner describes the development of concern about global warming as 'a slow Eureka'[359].

The initial research associated with greenhouse focused on the understanding of the role of carbon dioxide in relation to atmospheric processes and radiative transfer. The emphasis throughout the nineteenth century and early in the twentieth century focused strongly on long-term geological implications of changes in the carbon dioxide content i.e., as a means to understanding cyclical glacial theory (e.g., Chamberlin in 1899 [47]). The discourse is believed to be started by French mathematician and physician **Joseph Fourier** in 1824, when he described the basic concepts of planetary energy budget and the greenhouse effect, that's in fact in the core of the climate debate, in his article published in the 'Annales de la Chimie et de Physique' [113]. It should be point out that he never mentioned greenhouses in his writing, but recognised that the atmosphere is opaque to 'dark heat' (infrared radiation), but he was unable to identify which components were responsible. In England, **Tyndall** [346] conducted an analysis of the radiative and absorptive properties of atmospheric gases (primarily water vapour and carbon dioxide - referred to as carbonic acid). By investigating the relationships between absorption, radiation and conduction, Tyndall's study was among the first to attempt to calculate the infrared flux within the atmosphere. Towards the end of the nineteenth century an increasing interest focused upon the atmospheric role of carbon dioxide. **Langley** [186] appreciated the absorptive properties of the atmospheric gases and their beneficial effects on maintaining Earth surface temperatures at their present levels: 'The temperature of the Earth under direct sunshine, even though our atmosphere were present as now, would probably fall to -200°C, if that atmosphere did not possess the quality of selective absorption.'. Langley's works (1884 and 1886), although correct in principle, overestimated the effect (if greenhouse gases were removed, the surface air temperature would be close to -18°C assuming that the planetary albedo retained its current value). In 1895 **Svante Arrhenius** presented a paper to the Royal Swedish Academy of Sciences on 'The influence of carbonic acid [Carbon dioxide] in the air upon the temperature of the ground' [12]. This paper was later communicated to the Philosophical Magazine and published in 1896. He disagreed with Tyndall's conclusion that the absorptive properties of water vapour were such that it made a larger contribution than carbon dioxide. His major achievement was the construction of a quantitative mathematical analysis of the influence of CO2 on the planetary energy budget. Arrhenius forged ahead with developing equations to quantify how widely atmospheric CO2 would have to vary in order to produce changes to both colder and warmer climates sufficient to explain the ice ages. The calculations involved balancing the following quantities: the radiative budget, namely the solar radiation arriving at the Earth's surface, and the subsequent absorption of re-emitted infrared radiation by the atmosphere. His models was set to different parameters: latitudinal sections, mean cloud albedo, snow albedo, ocean albedo and surface relative humidity. The latter factor was assumed constant within the atmosphere, thereby representing the feedback whereby the atmosphere holds more water (with associated absorption of infrared radiation) as it warms. Other feedbacks were not included. Arrhenius investigated six scenarios, in which CO2 was set at 0.67, 1.0, 1.5, 2.0, 2.5, and 3.0 times the level in the atmosphere at that time, respectively. The calculations were 'tedious'[7], taking up to a year of his time. The conclusions he drew were: '[...] If the quantity of carbonic acid decreases from 1 to 0.67, the fall of temperature is nearly the same as the increase of temperature if this quantity augments to 1.5. And to get a new increase of this order of magnitude (3°.4), it will be necessary to alter the quantity of carbonic acid till it reaches a value nearly midway between 2 and 2.5.[...]'[8]. Although he does not provide a precise formula, Arrhenius's measurements and calculations provide him with an important result, which is still relevant today: 'Thus if the quantity of carbonic acid increased in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression.'[9]. That is to say, a doubling of the concentration of CO2 would produce a global warming of about 4-6°C in the earth's mean temperature. This is very close to the range of between 2.5°and 4.5°C projected in the most recent IPCC report. Arrhenius had, after all, investigated the effects of both decreasing and increasing CO2 on radiative balance. As yet, however, neither he nor his contemporaries had any intimation of the potential detrimental effects of CO2 on climate. In his book 'Worlds in the Making' 1908, Arrhenius made the first claim that human industrial activities might significantly affect climate. He wrote there that:

> *The actual percentage of carbonic acid [CO2] in the air is so insignificant that the annual combustion of coal, which has now (1904) [1908 was the publication date] risen to about 900 million tons and is rapidly increasing, carries about one-seven-hundredth part of its percentage of carbon dioxide to the atmosphere. Although the sea, by absorbing carbonic acid, acts as a regulator of huge capacity, which takes up about five-sixths of the produced carbonic acid, we may yet recognise that the slight percentage of carbonic acid in the atmosphere may by the advances of industry*

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[7] The exact statement is: '...Should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them' (ibidem, p. 267). It is remarkable that Arrhenius' laborious analysis gave thermal results close to those later obtained by hundreds of hours of calculations carried out with powerful digital computers.

[8] ibidem, pag. 265.

[9] ibidem, pag. 267.

> *be changed to a noticeable degree in the course of a few centuries.*[10]

He also sounds an optimistic note on this question, countering the 'lamentations'[11, p. 63] which he says were often heard 'that the coal stored up in the earth is wasted by the present generation without any thought for the future' [11, p. 63], stating that: 'By the influence of the increasing percentage of carbonic acid in the atmosphere, we may hope to enjoy ages with more equable and better climates, especially as regards the colder regions of the earth; ages when the earth will bring forth much more abundant crops than at present, for the benefit of rapidly propagating mankind.' [11, p. 63]. In similar fashion, the Swedish meteorologist **Nils Ekholm** remarked that: 'it seems possible that Man will be able efficaciously to regulate the future climate of the earth and consequently prevent the arrival of a new Ice Age'[87]. Between 1897-99 **T.C. Chamberlin** presented a series of three papers detailing the geological implications of carbon dioxide theory. In 1897 he reviewed the current hypotheses of climatic change [259] and in 1898 [48] and 1899 [47] postulated the effects that limestone-forming periods (e.g., Carboniferous, Jurassic and Cretaceous) may have had in contributing to subsequent glacial epochs. A key paper in the history of terrestrial radiation studies is the work of **G.C. Simpson** in 1928 [126]. By attempting to verify earlier calculations of outgoing radiation, Simpson identified the latitudinal variability of long wave radiation emissions (uniform between 50°S and 50°N decreasing at the poles by around 20%). The conclusions questioned the assumption that water vapour is the only constituent of the atmosphere which absorbs and emits long wave radiation, leading to the suggestion that carbon dioxide could appreciably modify the figures of outgoing radiation. This supposition was dealt with further in later works [125]. By the late 1930s the role of atmospheric carbon dioxide had re-emerged. The rise of industrialisation was, in reality, much faster than Arrhenius and Ekholm expected. Society became urbanised and manufacturing continued apace in the early twentieth century as railroads ferried raw materials such as iron and steel to factories where machines now did much of the work. International trade was expanding, fuelled by a growing demand for consumer goods, including new inventions such as the telephone and gasoline powered automobiles. **G. S. Callendar** in 1938 [43] estimated that between 1890 and 1938 around 150 million tons of carbon dioxide had been pumped into the atmosphere from the combustion of fossil fuels, of which about three quarters had remained in the atmosphere[11]. Call-

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[10] [11, p. 54]

[11] From [43] in page 223: 'By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from

endar was by profession a steam engineer and an amateur meteorologist, doing much of his research in his spare time, without access to a computer[148] . Despite ranking as non-specialist, was more than a match for his professional counterparts. Callendar, with his expertise in physics, was fully acquainted with Arrhenius's calculations linking global temperature change to atmospheric CO2. Calculations based on theory were all very well, but Callendar wanted proof. With his interest in meteorology, Callendar set about collect the necessary data. He extracted monthly average temperature records from the World Weather Records, a massive series of volumes published by the Smithsonian Institution[60]. He could estimate global temperature based on 147 stations around the world. Using this information, Callendar calculated a global increase in land temperatures of about 0.3°C between 1880 and the late 1930s. In his own words: '[...] the greater part of the warmth of recent years has occurred in the northern regions ; these, with the exception of the west Pacific stations, all show a decided rising tendency since about 1920.' [43, p. 234]. This increase was, he remarked, consistent with combustion of fossil fuels that had generated about that 150 thousand million tonnes of CO2. Analysis of ice cores has subsequently confirmed Callendar's early CO2 estimates, despite 'small contributions from human activities' [12]: 'New measurements of CO2, CH4 and N2O over the past 2000 years confirm the large increases during the last 200 years and more precisely define variability during the LPIH [Late Pre Industrial Holocene].', and it has been shown that his calculations of Earth temperature agree remarkably well with modern estimates for the same period[148]. In order to formally establish the physical link between warming and CO2, Callendar sought to apply his expertise in physics to calculate the Earth's heat balance from first principles. He undertook calculations for different levels of CO2 in the atmosphere, from which he distilled the results in to a single graph (Figure 5a).

Based on the results, Callendar suggested that about half of the warming from 1880 - 1935 was due to changes in CO2. Moreover, he calculated temperature increase to the end of the twentieth century, although the resulting figure of 0.16 °C was considerably too low given that the actual warming was about 0.6°C. The cause of the discrepancy was not, however, because of fundamental deficiencies in Callendar's equations. Rather, he had used estimates of atmospheric CO2 increase that were much too conservative. Furthermore, he considered only CO2 and water vapour climate-forcing mechanism, whereas other greenhouse gases, including methane, nitrous oxide, and

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the best available data that approximately three quarters of this has remained in the atmosphere.'

[12] as reported in [206]

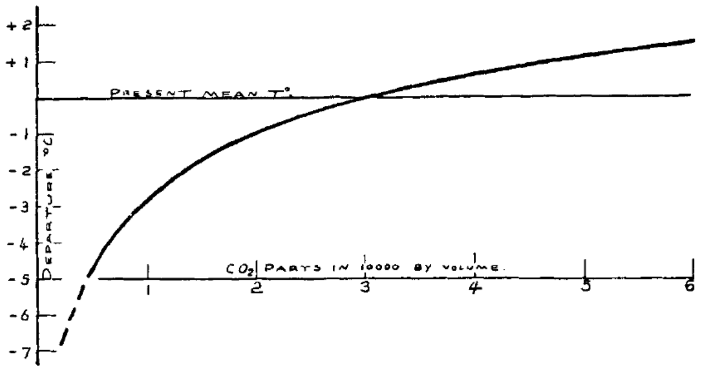

Figure 1.3: Change of surface temperature with atmospheric carbon dioxide (H,O vapour pressure. 7.5 mm Hg.)

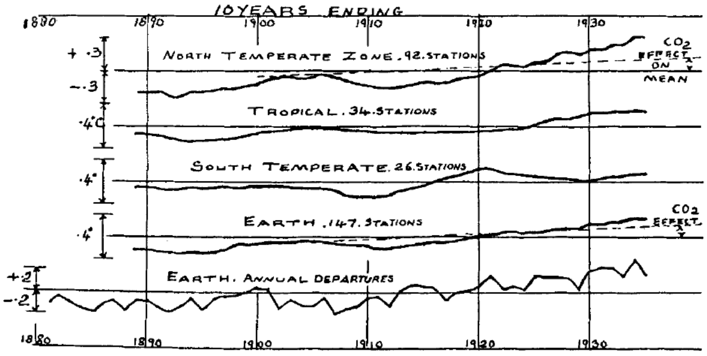

Figure 1.4: Temperature variations of the zones and of the earth. Ten-year moving departures from the mean. 1901-1930.

chlorofluorocarbons, play a significant role. Aerosols (particulates), released during the burning of fossil fuels, exert a radiative influence on climate, but opposite in sign, because they cause cooling by direct reflection of sunlight and by modification of the optical properties of clouds[51]. A subsequent work of Callendar [42] in 1949 reiterated the role of human climate forcing, suggesting that the increase in atmospheric carbon dioxide may account for the observed slight rise in average northern latitude temperature during the first four decades of the twentieth century:

> *It is only during the present century that man has exerted his influence on a sufficient scale to disturb nature's slow-moving carbon-balance, but now his demand for heat and power has led to the transfer of large quantities of ' fossil' carbon from the rocks to the air.*[13]

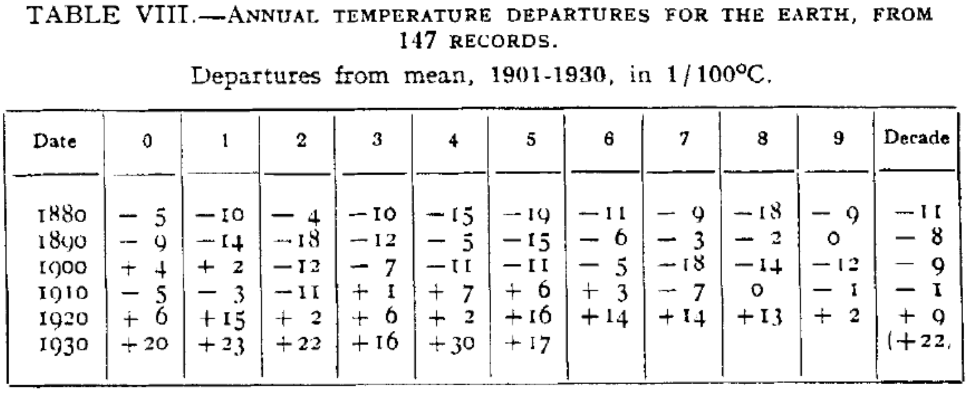

TABLE VIII.—ANNUAL TEMPERATURE DEPARTURES FOR THE EARTH, FROM 147 RECORDS.

Departures from mean, 1901-1930, in 1/100°C.

Date	0	1	2	3	4	5	6	7	8	9	Decade
1880	− 5	−10	− 4	−10	−15	−19	−11	− 9	−18	− 9	−11
1890	− 9	−14	−18	−12	− 5	−15	− 6	− 3	− 2	0	− 8
1900	+ 4	+ 2	−12	− 7	−11	−11	− 5	−18	−14	−12	− 9
1910	− 5	− 3	−11	+ 1	+ 7	+ 6	+ 3	− 7	0	− 1	− 1
1920	+ 6	+15	+ 2	+ 6	+ 2	+16	+14	+14	+13	+ 2	+ 9
1930	+20	+23	+22	+16	+30	+17					(+22,

Figure 1.5: Annual temperature departures from the whole Earth

Like Arrhenius, Callendar did not foresee the potential detrimental impacts of climate warming. Rather, he emphasised the societal benefits that might accrue from increasing temperature: crop production would be enhanced, especially at northerly latitudes, and the return of another deadly ice age would be delayed indefinitely.

> *In conclusion it may be said that the combustion of fossil fuel, whether it be peat from the surface or oil from 10,000 feet below, is likely to prove beneficial to mankind in several ways, besides the provision of heat and power. For instance the above mentioned small increases of mean temperature would be important at the northern margin of cultivation, and the growth of favourably situated plants is directly proportional to the carbon dioxide pressure*[14]

Despite the above considerations, Callendar's re-examination of the hypotheses of Arrhenius[12] and Chamberlin[47] in the context of human activities, represents the transition from a theory of glacial climate change through to the human influence on atmospheric carbon dioxide levels, and its subsequent role as a climate-forcing mechanism. During the 1950s the development of the greenhouse theory took on new dimensions. Research moved towards calculating the temperature increase given an atmospheric doubling of carbon dioxide. In 1955, **G. Plass**, of the Aeronautical Division of the Ford Motor Company, was responsible for the development of surface energy balance approaches to climate sensitivity that yielded the first modern estimates of global surface temperature response to increased Carbon Dioxide:

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[13] in [42] at p. 312.

[14] in Callendar [43] at p. 236.

> *The most recent calculations of the infra-red flux in the region of the 15 micron CO2 band show that the average surface temperature of the earth increases 3.6°C if the CO2 concentration in the atmospheric is doubled and decreases 3.8°C if the CO2 amount is halved, provided that no other factors change which influence the radiation balance. Variations in CO2 amount of this magnitude must have occurred during geological history; the resulting temperature changes were sufficiently large to influence the climate.*[15]

In 1957 **R. Revelle** and **H. E. Suesse** emphasized the significance of the rise in atmospheric CO2[269]:

> *Thus human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and Oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years.*[16]

> *Equilibrium is approached through rock weathering and marine sedimentation. Estimated rates of these processes give a very long time constant of the order of magnitude of I00,000 years. Rapid changes in the amount of carbon dioxide produced by volcanoes, in the state of the biosphere, or as in our case, in the rate of combustion of fossil fuels, may therefore cause considerable departures from average conditions.*[17]

> *The answer to the question whether or not the combustion of coal , petroleum and natural gas has increased the carbon dioxide concentration in the atmosphere depends in part upon the rate at which an excess amount of CO2, in the atmosphere is absorbed by the oceans.*[18]

In 1956, during the **International Geophysical Year** (IGY), Revelle was joined at the Scripps Institution of Oceanography (San Diego, California) by

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[15] in Plass in [249] at p. 40.

[16] in [269] at p. 19.

[17] [269, p. 20]

[18] [269, p. 20]

Charles David Keeling, who was to lead an IGY programme on atmospheric CO2. Keeling thus started a series of measurements at the Mauna Loa volcano in Hawaii, which have shown the progressive year-on-year increase of CO2 in the atmosphere[175].

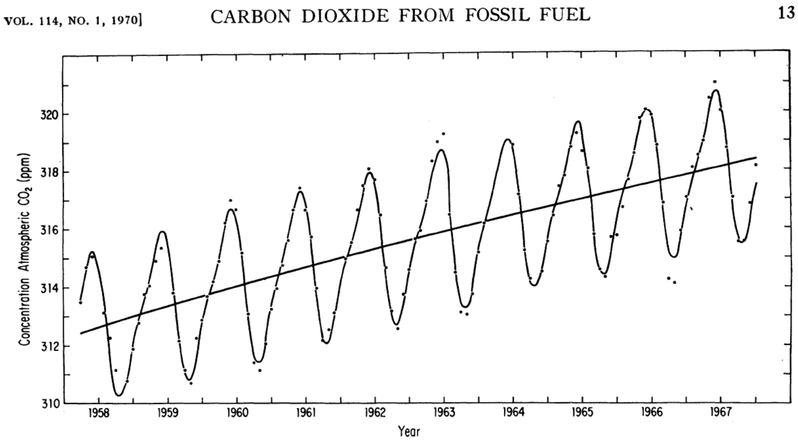

Figure 1.6: Long-term variations in the concentration of atmospheric C02at Mauna Loa Observatory. The dots indicate the observed monthly average concentrations. The oscillating curve is a least squares fit of these averages based on an empirical equation containing 6 and 12 month cyclic terms and a trend function. The slowly rising curve is a plot of the trend function, chosen to contain powers of time up to the third (figure reported from [175]).

The potential societal significance of climatic change was slightly finding its own way. Keeling himself was pondering ‘the fact that the human race was returning to the air a significant part of the carbon that had been slowly extracted by plants and buried in sediments during a half billion years of Earth history.’.[19] Furthermore, he underscored:

> *The rise in CO2 is proceeding so slowly that most of us today will, very likely, live out our lives without perceiving that a problem may exist. But CO2 is just one index of man’s rising activity today. We have rising numbers of college degrees, rising steel production, rising costs of television programming and broadcasting, high rising apartments, rising numbers of marriages, relatively more rapidly rising numbers of divorces, rising employment, and rising unemployment. At the same time we have diminishing natural resources, diminishing distract-free time, diminishing farm land around cities, diminishing virgin lands in the distant*

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[19] in [174, p. 48].

> *country side... . [Viewed over thousands of years] I am struck by the obvious transient nature of the CO2 rise. The rapid changes in all factors I [have just] mentioned, including the rapid rise in world population, are probably also transient; these changes, so familiar to us today, not only were unknown to all but the most recent of our ancestors but will be unknown to all but the most immediate of our descendants.*[20]

In 1963 the **Conservation Foundation** sponsored a meeting on this topic, and its report stated the situation more clearly than any before it: 'A doubling of the atmospheric is calculated to increase the average surface temperature CO2 by 3. 8°C under clear sky conditions and about 2°C under conditions of average cloudiness. (These estimates can be questioned; however, they are unlikely to be wrong by a factor of more 1 than two or three.)' [21] - though the time scale involved is left unspecified. A subsequent statement further remarked the potential anthropogenic climate forcing:

> *The recent systematic atmospheric analyses for CO2 which began during the International Geophysical Year show consistent increases each year for all parts of the earth. The current rate of increase averages 0. 7 ppm per year or about 0. 2 percent. The combustion of fossil fuels at current rates adds the equivalent of 1. 6 ppm of CO2 to the atmosphere each year and must therefore be considered to be contributing to the net increase. However, there may be other large sources of CO2 which are not so easy to distinguish and which are masked by the increase due to the burning of fossil fuels.*[22]

In addition to the above, Revelle in a report, which he prepared in 1965 for the **President's Science Advisory Cormmittee** (PSAC), described the impacts of the atmospheric carbon dioxide as a factor in man's environment. It worth reporting some remarkable passages of the introduction:

> *Only about one two-thousandth of the atmosphere and one ten-thousandth of the ocean are carbon dioxide. Yet to living creatures, these small fractions are of vital importance. Carbon is the basic building block of organic compounds, and land plants obtain all of their carbon from atmospheric carbon dioxide [...] Over the past several billion years, very large quantities of carbon dioxide*

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[20] [174, p.48].

[21] in [76, p. 6]

[22] in [76, p.6]

> *have entered the atmosphere from volcanoes. The total amount was at least forty thousand times the quantity of carbon dioxide now present in the air. Most of it [...] was precipitated on the sea floor as limestone or dolomite. About one-fourth of the total quantity, at least ten thousand times the present atmospheric carbon dioxide, was reduced by plants to organic carbon compounds and became buried as organic matter in the sediments. A small fraction of this organic matter was transformed into the concentrated deposits we call coal, petroleum, oil shales, tar sands, or natural gas. These are the fossil fuels that power the worldwide industrial civilization of our time. Throughout most of the . . . [million or so] years of man's existence on earth, his fuels consisted of wood and other remains of plants which had grown only a few years before they were burned. The effect of this burning on the content of atmospheric carbon dioxide was negligible, because it only slightly speeded up the natural decay processes that continually recycle carbon from the biosphere to the atmosphere. During the last few centuries, however, man has begun to burn fossil fuels that were locked in the sedimentary rocks, [...] and this combustion is measurably increasing the atmospheric carbon dioxide. The present rate of production from fossil fuel combustion is about a hundred times the [rate of natural removal by] weathering of silicate rocks. [...] Within a few short centuries, we are returning to the air a significant part of the carbon that was slowly extracted by plants and buried in the sediments during a years. Not all of this added carbon dioxide will remain in the air. part of it will become dissolved in the ocean, and part will be taken up by the biosphere, chiefly in trees and other terrestrial plants, and in the dead plant litter called humus. The part that remains in the atmosphere may have a significant effect on climate: carbon dioxide is nearly transparent to visible light, but it is a strong absorber and back-radiator of infrared radiation, particularly in the wave lengths from 12 to 18 microns; consequently, an increase of atmospheric carbon dioxide could act, much like the glass in a greenhouse, to raise the temperature of the lower air.*[23]

The PSAC Report dealt with many aspects of air and water pollution, but it is remembered as a first public recognition in a United States government document that climate change could be caused by human activities and that this would have important consequences for the world. The PSAC Report of

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[23] in [268]

1965 had called the attention of the world to the distinct possibility that the Earth could become warmer as a result of human activities, and a handful of scientists on both sides of the Atlantic were beginning to develop a physical theory to explain the behaviour of the complex system that determines climate. The time was ripe then to address the question of global environmental problems and the scope of human activities in a more systematic and quantitative way. The early 1970s also saw sufficient concern about climate modification. Two very unusual conferences played a significant role in making the problem of climate change visible: the **Study of Critical Environmental Problems** (SCEP) [278] in 1970 and the **Study of Man's Impact on the Climate** (SMIC) [364] in 1971. These conferences were initiated and organized by **Carroll Louis Wilson**, professor of management at the Massachusetts Institute of Technology (MIT). The major objective of SCEP, as stated in the Preface of the report by the leading authors, Wilson and Matthews, was 'to raise the level of informed public and scientific discussion and action on global environmental problems'[278]. The conclusion was perhaps the strongest statements ever made at that time:

> *Although we conclude that the probability of direct climate change in this century resulting from CO2 is small, we stress that that long-term potential consequences of CO2 effects on the climate or of social reaction to such threats are so serious that much more must be learned about future trends of climate change. Only through these measures can societies hope to have time to adjust to changes that may ultimately be necessary.*[24]

The SMIC report focused more sharply on the question of climate change, to provide 'an authoritative assessment of the present state of scientific understanding of the possible impacts of man's (sic) activities on the regional and global climate'[364]. It is particularly notable that the following year (1972) witnessed the first **United Nations Conference on the Human Environment** (in Stockholm), and the SMIC Report was used as a major background paper for all participants. One useful outcome of the Conference was the decision to found a new organization devoted to the preservation of the global environment, the **U. N. Environment Programme** (UNEP). The state of knowledge at that point was, however, still considerably undeveloped. The report from SMIC stated bluntly on the question of whether CO2 rises would lead to climatic changes: 'We do not know yet' (quoted in Lunde in [202]). The theory that industrial and agricultural aerosols would lead to a cooling of the atmosphere was also widespread, and no

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[24] [278, p. 12]

agreement could be reached between the participants as to which tendency would be most important. The 1972 Stockholm Conference on the Human Environment represented a major shift in the priority given to climatic issues by international organisations. Climate impacts were 'central concerns' now. This change led to two main developments. First, there was a series of UN-sponsored conferences during the 1970s on climate-related problems. These included the **UN World Food Conference** in 1974, the **UN Water Conference** in 1977, and the **UN Desertification Conference** in 1977. These conferences highlighted various aspects of severe problems associated with different climatic scenarios, and made clear the possible consequences of significant human-induced climate change. Moreover they stressed the importance of action at the national level and provided the framework for the activities of international organizations in the field of water and food resources development and management. During the 1960s and early 1970s there were several extreme climatic events. Five terrible years (1969 - 1974) of drought afflicted the Sahel, in 1962 Soviet Union too. India has experienced different monsoon failures: 1965, 1966, 1972, 1974[25]. Moreover a recent research article, published in 2012 [279], points to the possibility of even more severe changes to monsoon rainfall caused by climatic shifts that may take place later this century and beyond. A hydrological drought peak occurred on July 1976 and covered the majority of temperate Europe, extending from the UK and France in the west to Russia in the east[272]. The Mediterranean region was largely unaffected[26]. These made clear human dependence on climate and provided a rationale for stepping up research into climate in general. The second development, related to the first, was a change in the character of meteorological research. Prior to this, scientific research had been largely into the general understanding of weather. After 1972-3 the research programmes expanded into the field of long-term climatic trends and conditions, rather than short-term weather patterns. A quantitative theory of climate was emerging, primarily as a result of early cooperative research in the United States and the Soviet Union, and computers were increasingly able to handle complex numerical models of the climate system. Substantial cooperative research on potential climate changes began with a **Conference in Stockholm** in July 1974, on the 'physical basis of climate and climate modelling'. This conference, organised by Global Atmospheric Research Programme (GARP), gathered together about seventy

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[25] See: india-drought-bulletin ➡. This passage reports the full count: In the past, India has experienced twenty two large scale droughts in 1891,1896, 1899, 1905, 1911, 1915, 1918, 1920, 1941, 1951, 1965, 1966, 1972, 1974, 1979, 1982, 1986, 1987, 1988, 1999, 2000 and 2002 with increasing frequencies during the periods 1891-1920, 1965-1990 and 1999-2002.

[26] See: www.geo.uio.no ➡.

climate scientists from a wide range of countries. The importance aspect of the conference was aimed at developing a consensus about how best to model the climate system quantitatively, thus providing basis for trend prediction. The foreword of the technical note are firmly grounded:

> *determine the potential of mathematical calculation for predicting and explaining the climate quantitatively. In fact prospects are good that mathematical models will provide an understanding of the basic controls of the climate which will prove essential for the future management of the natural resources of the earth. In addition to the basic programme on climatic research proposed in this document we obviously need to understand the impact of climate on man and his activities better than we do to-day.*[27]

One major milestone was the **International Symposium on Long- Term Climate Fluctuations**, sponsored by the World Meteorological Organization (WMO) and held in Norwich, England, the summer of 1975[28] see 1.7. The importance of this meeting was that it established that industrial aerosols and smoke particles and agricultural slash and burn practices, previously thought to cool the troposphere, do not do this, thus paving the way for CO2 to be the main candidate for affecting temperature.

Another step taken by the WMO was a Technical Note entitled 'Effects of Human Activities on Global Climate', prepared by **Kellogg**[178]. It relied heavily on the SMIC Report, but was able to bring together a great deal of further information that was simply unavailable in 1971.

Also of particular note were three assessments made by the US **National Academy of Sciences** (NAS) in 1975, 1977 and 1979. The 1975 report appeared to serve as a useful summary of the state of opinion at the time. The preface states:

> *The increasing realization that man's activities may be changing the climate, and mounting evidence that the earth's climates have undergone a long series of complex natural changes in the past, have brought new interest and concern to the problem of climatic variation. The importance of the problem has also been underscored by new recognition of the continuing vulnerability of man's economic and social structure to climatic variations. Our response to these concerns is the proposal of a major new program*

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[27] in [127].

[28] World Meteorological Organization Rept. WMO No. 421, Geneva, Switzerland, quoted in Kellogg [177]

> *of research designed to increase our understanding of climatic change and to lay the foundation for its prediction.*[29]

> *The prediction of climate is clearly an enormously complex problem. Although we have no useful skill in predicting weather beyond a few weeks into the future, we have a compelling need to predict the climate for years, decades, and even centuries ahead.*[30]

> *The onset of this climatic decline could be several thousand years in the future, although there is a finite probability that a serious worldwide cooling could befall the earth within the next hundred years.*[31]

On a complementary basis, the 1977 report attempted to 'evaluate the interactions between hydrology, water supply, climate, and climatic change and to highlight areas where deficiencies in knowledge and data make rational water-resource decision-making more difficult than it needs to be.'[32]. The 1979 report was based on a study group which met during the summer of 1979 to determine whether the models being used to calculate global warming had a scientific basis and were sufficiently reliable. Its conclusion stated: 'When it is assumed that the CO2 content of the atmosphere is doubled and statistical thermal equilibrium is achieved, the more realistic of the modeling efforts predict a global surface warming of between 2°C and 3.5°C, with greater increases at high latitudes.'[33]. In addition:

> *The warming will be accompanied by shifts in the geographical distributions of the various climatic elements such as temperature, rainfall, evaporation, and soil moisture. The evidence is that the variations in these anomalies with latitude, longitude, and season will be at least as great as the globally averaged changes themselves, and it would be misleading to predict regional climatic changes on the basis of global or zonal averages alone.*[34]

That same year a much larger international gathering was convened to deal with all aspects of climate variability and change. The occasion was the

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[29] in [13].
[30] in [163].
[31] in [163].
[32] in [163].
[33] in [227].
[34] in [227, p.2].

historic first **World Climate Conference** (WCC), organized and hosted by the WMO in Geneva in February, 1979. Several hundred scientists and dignitaries attended this week-long conference, and the last two days were devoted to meetings of smaller working groups to review the terms of reference of the proposed international World Climate Programme. Its purpose, decided at the twenty-ninth session of the WMO Executive Committee during May-June 1977, was: '(a) To review knowledge of climatic change and variability, due both to natural and anthropogenic causes; and (b) To assess possible future climatic changes and variability and their implications for human activities.' [35]. A Conference Statement was discussed and redrafted several times, and at the final Plenary Session the Chairman, **Robert M. White**, was able to obtain agreement on the following Statement. Two significant points are reported. The first one foresees the potential man-made adverse changes in climate:

> *we can say with some confidence that the burning of fossil fuels, deforestation, and changes of land use have increased the amount of carbon dioxide in the atmosphere by about 15 per cent during the last century and it is at present increasing by about 0.4 per cent per year. It is likely that an increase will continue in the future. Carbon dioxide plays a fundamental role in determining the temperature of the earth's atmosphere, and it appears plausible that an increased amount of carbon dioxide in the atmosphere can contribute to a gradual warming of the lower atmosphere, especially at high latitudes. Patterns of change would be likely to affect the distribution of temperature, rainfall and other meteorological parameters, but the details of the changes are still poorly understood.*[36]

The second one preludes to the possibility that such climate changes could be detectable before the first half of the twenty-first century:

> *It is possible that some effects on a regional and global scale may be detectable before the end of this century and become significant before the middle of the next century. This time scale is similar to that required to redirect, if necessary, the operation of many aspects of the world economy, including agriculture and the production of energy. Since changes in climate may prove to be beneficial in some parts of the world and adverse in others, significant social and technological readjustments may be required.*[37]

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[35] WMO-No.537 referenced in [372]

[36] WMO-No.537 referenced in [372].

Following the Conference, WMO moved swiftly to give effect to the call for a **World Climate Programme** (WCP). **Eighth World Meteorological Congress** (Geneva, April/May 1979) agreed that, as the UN specialized agency for meteorology embracing both weather and climate, WMO should take the lead in promoting studies of climate variability and change and their implications for society and the environment. Congress recognized, however, that climate issues were already becoming highly interdisciplinary and that implementation of the proposed World Climate Programme would require the involvement of many other UN bodies such as UNESCO, FAO, WHO and UNEP, as well as the scientific community through ICSU. The WCP provided the organisational framework within which much climate change research has operated. Possibly more importantly, it organised the **Villach conference** of 1985, which began the process through which global warming became politicised[38]. This conference aimed to examine the state of knowledge on climate and climate change, and to establish some sort of scientific consensus on the degree of responsibility for global warming of each gas, and on a preliminary prediction of warming scenarios. In Lunde's words the conference was 'probably the most important greenhouse event between 1979 and the convening of IPCC in October 1988' [202]. The statement and conclusions of the Villach conference were significantly more confident than that of the First WCC. It stated that the current consensus was that:

> *While some warming of climate now appears inevitable due to past actions, the rate and degree of future warming could be profoundly affected by governmental policies on energy conservation, use of fossil fuels, and the emission of some greenhouse gases.*[39]

> *The most advanced experiments [...] show increases of the global mean equilibrium surface temperature for a doubling of the atmospheric COz concentration, or equivalent, of between 1.5 and 4.5°C.*[40]

> *[...] the understanding of the greenhouse question is sufficiently developed that scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments.*[41]

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[37] WMO-No.537 referenced in [372].

[38] WMO-No.661 referenced in [372].

[39] WMO-No.661 referenced in [372], p. 1.

[40] WMO-No.661 referenced in [372], p. 3.

> *Although quantitative uncertainty in model results persists it is highly probable that increasing concentration of the greenhouse gases will produce significant climatic change.*[42]

The confidence expressed at Villach was based on a significant growth in both the scope and the complexity of climate research during the 1980s. The most important of these developments included much more realistic models of the atmosphere, and the consolidation of the realisation that other anthropogenic gases (CFCs, methane, nitrous oxide, tropospheric ozone) are radiatively important: 'The amounts of some trace gases in the troposphere, notably carbon dioxide (COz), nitrous oxide (NzO), methane (CH4), ozone (O3) and chloro-fluorocarbons (CFC) are increasing. These gases are essentially transparent to incoming short-wave solar radiation but they absorb and emit longwave radiation and are thus able to influence the Earth's climate.'[43]. In 1988 **Ramanathan** [255] provides a good up-to-date view of the greenhouse theory, emphasizing the importance of water vapour as a radiatively active gas as well as a summary of important climate feedback mechanisms i.e., water, ice-albedo, cloud and ocean-atmosphere interactions. As scientific knowledge increased concerning the likelihood of global warming, the types of gas involved and their anthropogenic sources, and about the severity of the possible changes, the activities of the scientists involved in the WCP and in national programmes became inherently more political because of the implications of the responses they envisaged. There was a small rise in public interest in global warming in the early 1980s, stimulated in particular by press coverage in 1984 of reports by **James Hansen** and **Stephen Schneider** (as reported by Mazur in [214]). This then died off until 1988, when global warming exploded on to the political agenda. However, scientists had started to call on politicians to act. During the period 1985-1988, many more scientists also became convinced of the need, not only for some framework convention analogous to that developed for ozone depletion (the **Vienna Convention**), but for strong preventive action on global warming. This helped to consolidate the scientific consensus to policy makers. This process occurred as they became more convinced that the human-enhanced greenhouse effect was responsible for the global warming experienced in the 1980s. For example, **Kenneth Hare**, Chair of the Climatic Board of Canada, and of the Advisory Group on Greenhouse Gases, wrote in 1988:

> *Until a short while ago, my own position was...that the evidence was too equivocal to do more than give a yellow alert to*

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[41] WMO-No.661 referenced in [372], p. 3.

[42] WMO-No.661 referenced in [372], p. 57.

[43] WMO-No.661 referenced in [372], p. 2.

> *governments...I was an announced wait-and-see conservative...It was the paper by Jones et al. [1986] published in Nature that began to sway me to the above position [that temperature rises in the 1980s can reasonably strongly be attributed to ghg concentration increases]...I can and do tell them [governments] that they should base their environmental planning on the assumption that the greenhouse warming will continue and accelerate.*[44]

This process of politicisation started at the Villach Conference. A major part of the conference's report involved detailed description of research's priorities. It made recommendations which emphasised the need for economic, social and technological research into policy options for responding to any potential climate change, as reported in the following passage:

> *Support for the analysis of policy and economic options should be increased by governments and funding agencies. In these assessments the widest possible range of social responses aimed at preventing or adapting to climate change should be identified, analyzed and evaluated. These assessments should be initiated immediately and should employ a variety of available methods. Some of these analyses should be undertaken in a regional context to link available knowledge with economic decision-making and to characterize regional vulnerability and adaptability to climatic change. Candidate regions may include the Amazon Basin, the Indian subcontinent, Europe, the Arctic, the Zambezi Basin, and the North American Great Lakes.*[45]

The last recommendation was that 'UNEP, WMO and ICSU should establish a small task force on greenhouse gases, or take other measures, to initiate, if deemed necessary, consideration of a global convention.'[46]. A shift of emphasis away from solely the need for more research, towards including assertions of the need for political action, had started. WCP also followed up the Villach Conference with two workshops entitled 'Developing Policies for Responding to Climatic Change' held in **Villach** and in **Bellagio**, Italy, in 1987. These workshops came to similar, but stronger, conclusions stating that: 'A prudent response to climate change would consider both limitation and adaptation strategies. In fact, even if a very concerted effort were made now to limit emissions, some adaptation would still be necessary. This is

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[44] In [142].

[45] In WMP-No.661 referenced in [372], p. 3-4.

[46] In WMP-No.661 referenced in [372], para. 5.

because of the climatic changes, forced by GHG-producing human activities during the recent decades, that may already be underway and also by those that would occur before the limitation strategy had become effective.'[47]. They called for: 'Examination by organizations, including the inter governmental mechanism to be constituted by the WMO and UNEP in 1988 , of the need for an agreement on a law of the atmosphere as a global commons or the need to move towards a convention along the lines of that developed for ozone.'[48] ; and for: 'Reexamination of long-term energy strategies with the goals of achieving high end-use efficiency . Intensification of development of non-fossil energy systems.' [49]. Alongside these developments, the **World Commission on Environment and Development** (WCED) presented its report Our Common Future (also known as the 'Brundtland Report'[37] after the Norwegian Prime Minister Gro Harlem Brundtland, who chaired the commission), on 27 April 1987. This was a general report on environmental degradation and how it is related to development issues. The commission had been set up by the UN in 1983[50]. Regarding climate, its report echoed the recommendations of the 1985 Villach Conference, and in particular emphasised the 'urgent' necessity of increasing energy efficiency and shifting the fuel mix towards renewables:

> *The burning of fossil fuels and, to a lesser extent, the loss of vegetative cover, particularly forests, through urban-industrial growth increase the accumulation of CO2 in the atmosphere. [...] They estimated that if present trends continue, the combined concentration of CO2 and other greenhouse gases in the atmosphere would be equivalent to a doubling of CO2 from pre-industrial levels, possibly as early as the 2030s, and could lead to a rise in global mean temperatures 'greater than any in man's history'[51].[...] The very long time lags involved in negotiating international agreement on*

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[47] In [164], p. 19

[48] In [164], p. v

[49] In [164], p. v

[50] The General Assembly, in its resolution 38/161 of 19 December 1983, inter alia, welcomed the establishment of a special commission that should make available a report on environment and the global problematique to the year 2000 and beyond, including proposed strategies for sustainable development. The commission later adopted the name World Commission on Environment and Development. In the same resolution, the Assembly decided that, on matters within the mandate and purview of the United Nations Environment Programme, the report of the special commission should in the first instance be considered by the Governing Council of the Programme, for transmission to the Assembly together with its comments, and for use as basic material in the preparation, for adoption by the Assembly, of the Environmental Perspective to the Year 2000 and Beyond.

[51] In WMP-No.661 referenced in [372], p. 1.

> *complex issues involving all nations have led some experts to conclude that it is already late*[52]*. Given the complexities and uncertainties surrounding the issue, it is urgent that the process start now.[...] While these strategies are being developed, more immediate policy measures can and should be adopted. The most urgent are those required to increase and extend the recent steady gains in energy efficiency and to shift the energy mix more towards renewables. Carbon dioxide output globally could be significantly reduced by energy efficiency measures without any reduction of the tempo of GDP growth. These measures would also serve to abate other emissions and thus reduce acidification and urban-industrial air pollution. Gaseous fuels produce less carbon dioxide per unit of energy output than oil or coal and should be promoted, especially for cooking and other domestic uses.*[53]

Among state decision-makers, however, there was still considerable inertia about the issue, and the idea of a convention or any sort of political agreement on greenhouse gases was not being properly addressed. During 1985- 7 the political leaders have given priority to ozone depletion issue, leading the adoption of the **Vienna Convention** in 1985, and the subsequent **Montreal Protocol** in 1987. The ozone depletion issue was obviously related, as CFCs are both ozone destroyers and greenhouse gases. The political discussion of global warming had developed gradually during the mid-1980s. However, it gained much momentum in 1988. A combination of factors produced this rapid rise. Of particular importance was the US drought in 1988. This drought was reported to be the worst since the dustbowls of the 1930s. The US drought combined with the perception that freak weather patterns were being experienced throughout the world during the 1980s. The hurricanes, Gilbert and Joan, were hugely destructive. Gilbert left a fifth of the people of Jamaica homeless. Joan brought a similar trail of death and devastation [28]. The point of these references to the natural disasters during that period is merely to show that they provided a backdrop for the increased confidence with which scientists made claims about a potential global warming. Faced with the freak weather conditions alluded to above, and the realisation that the 1980s was clearly the hottest decade on record, including the six hottest

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[52] If we fail to do this we run the risk of being overtaken by events, and of having to deal with a global warming for better or for worse when it is already too late to do anything about it or to deal with its impacts, Ibidem, p. 9, supra note 44, and The development of globally agreed policies designed to abate emissions will take many years of international effort to formulate and negotiate, Ibidem, p. 16.

[53] Ibidem, p. 176-177.

years ever recorded. The most clear of these views, and perhaps more importantly, the most widely hyped by the media[214], was given in the statement by **James Hansen**, chief climate scientist at NASA's **Goddard Institute for Space Studies** (GISS), at a hearing of the US Senate's Energy and Natural Resources Committee, on 23 June 1988 [180]. Hansen's most widely reported statement was that 'it is time to stop waffling so much. We should say that the evidence is pretty strong that the greenhouse effect is here'[54]. In his formal statement, while recognising that 'it is not possible to blame a specific heat wave/drought on the greenhouse effect', he emphasised that 'global warming has reached a level such that we can ascribe with a high degree of confidence a cause and effect relationship between the greenhouse effect and the observed warming' [180]. The erratic weather patterns, especially the US drought, the general importance of environmental issues in the mid-to-late 1980s, and Hansen's testimony, combined to cause global warming to emerge rapidly onto the international political agenda. The **Toronto Conference** on **The Changing Atmosphere: Implications for Global Security**, held during 27-30 June 1988 in Toronto, and hosted by the Canadian government as a response to the WCED Report, was where global warming was first dealt with as a major political issue. 'More than 300 scientists and policy makers from forty-eight countries, United Nations organisations, other international bodies and nongovernmental organisations participated in the sessions'[55]. The Toronto Conference was the meeting at which ideas about the sort of international response needed came to be expressed more strongly. Howard Ferguson, the conference's Director, stated in his address that 'action on serious negotiations start now'[56]. Beginning with a dire warning: 'Humanity is conducting an unintended, uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to a global nuclear war.' [57]. the Toronto Conference paralleled the Villach Conference assessment of the degree of likely warming under a business-as-usual scenario, and the possible impacts that could result from this warming. However, it also innovated in making detailed recommendations for action.

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[54] Excerpt of 'Greenhouse Effect and Global Climate Change' the June 23, 1988 Hearing Before the Committee on Energy and Natural Resources of the United States Senate. See babel.hathitrust.org ➡

[55] In WMP-No.710 referenced in [372], p. 45.

[56] See The Conference Statement at 292, and is reprinted in 5 AM. U. J. INT'L L. & POL'Y 515 (1990).

[57] Ibidem, p. 46, continuing: '[...]The Earth is atmosphere is being changed at an unprecedented rate by pollutants resulting from human activities, inefficient and wasteful: fossil fuel use and the effects of rapid population growth in many regions. These changes represent a major threat to international security and are already having harmful consequences over many parts of the globe'.

It called upon governments ‘to work with urgency towards an Action Plan for the Protection of the Atmosphere. This should include an international framework convention...The Conference also called upon governments to establish a World Atmosphere Fund financed in part by a levy on the fossil fuel consumption of industrialised countries...’[58]. The conference outlined an ambitious claim with respect to reducing CO2 emissions. It stated that governments and industry should ‘reduce CO2 emissions by approximately 20 per cent of 1988 levels by the year 2005 as an initial global goal’ [59]. This was the first international conference to call for such radical action. Following the Toronto Conference, global warming moved rapidly up the international agenda[215]. In 1988, shortly before the Toronto Conference, governments took the first step to address the climate change issue by requesting the **World Meteorological Organization** (WMO) and the **U.N. Environment Programme** (UNEP) to establish the **IPCC**[60].The IPCC’s mandate was to ‘provide internationally coordinated assessments of the magnitude, timing and potential environmental and socio-economic impact of climate change and realistic response strategies.’[347].

> *The Council believed that the establishment of a more broadly representative mechanism should be considered in view of the complexity and importance of the issue. The Council therefore requested the Secretary-General, in co-ordination with the Executive Director of UNEP, to explore and, after appropriate consultation with members of the Executive Council, to establish an ad hoc intergovernmental mechanism to carry out internationally co-ordinated scientific assessments of the magnitude, timing and potential impact of climate change. The mechanism developed should avail itself of balanced scientific expertise and provide for participation by governments and organizations.*[61]

> *The Council paid particular attention to establishing an intergovernmental mechanism to carry out internationally co-ordinated scientific assessments of the magnitude, timing and potential impact of climate change. The Council noted the relevant decisions of the forty-second session of the UN General Assembly and of*

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[58] Ibidem, p. 47.

[59] Ibidem, p. 53.

[60] See WMO No.682 [266], UNEP Report [265],WMO No. 707 [264] and for general discussions of the IPCC, see [110]

[61] In [266], p.7.

> *the UNEP Governing Council. The Council welcomed the initiatives of the Secretary-General in establishing the Intergovernmental Panel on Climate Change (IPCC) and noted with appreciation the co-operation and positive response of the Executive Director of UNEP in this matter. It further noted with satisfaction the responses from the governments received to date to the letter from the Secretary-General seeking the views of governments as to participation in the activities of the panel. The Council considered it necessary to proceed urgently with the establishment of the panel and requested the Secretary-General to approach Member countries to obtain as soon as possible their response to his letter.*[62]

> *Urges the Executive Director to ensure that the United Nations Environment Programme, working in close co-operation with the World Meteorological Organization and the International Council of Scientific Unions, in particular, the Special Committee on Global Change of the International Council of Scientific Unions maintains an active, influential role within the World Climate Proqramme through the fulfilment of its central responsibility for climate impact studies and by ensuring that the world climate research programme includes studies on the causes and effects of atmospheric changes, taking account of social and economic aspects.*[63]

The IPCC was established to perform the fullest assessment of the state of current scientific knowledge on climate and potential impacts of global warming, and to examine potential response options. WMO and UNEP outlined its purpose as follows: '(i) Assessing the scientific information that is related to the various components of the climate change issue, such as emissions of major greenhouse gases and modification of the Earth's radiation balance resulting therefrom, and that needed to enable the environmental and socio-economic consequences of climate change to be evaluated; (ii) Formulating realistic response strategies for the management of the climate change issue.' [64]. At its first meeting in November 1988, the IPCC elected Professor Bert Bolin of Sweden, a highly respected climatologist, as chairman and established three working groups: the first on **science** (chaired by the United

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[62] In WMO No.707 [264], p. 14.

[63] UNEP report in [265], p. 75.

[64] See [367], p. 4. This document summarized the same definition as in [264] in p.14.

Kingdom), the second on **impacts** (chaired by the Soviet Union), and the third on **response strategies** (chaired by the United States). The opening of the report states: '(i) Assessment of available scientific information on climate change; (ii) Assessment of environmental and socio-economic impacts of climate change; (iii) Formulation of response strategies.'[65]. The IPCC also adopted an expedited work schedule to allow preparation of its **First Assessment Report** by October 1990, in time for the forty-fifth session of the **U.N. General Assembly** and the eleventh **World Meteorological Congress**. In May and June 1990, the IPCC working groups finalized their **First Assessment Reports**, and, in August, the IPCC plenary met in Sundsvall, Sweden to approve the reports and adopt an overview statement. The report predicted that: 'under the IPCC Business-as-Usual (Scenario A) emissions of greenhouse gases, a rate of increase of global mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0 2°C to 0 5°C per decade), this is greater than that seen over the past 10,000 years This will result in a likely increase in global mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century The rise will not be steady because of the influence of other factors'[66]. In other words, an average rate of 0.3°C per decade is unprecedented in human history and this could lead to erratic weather patterns where 'episodes of high temperatures will most likely become more frequent in the future, and cold episodes less frequent'[67]. The sea level will be affected by such warming scenario: '[...] Over the same period global sea level has increased by 10-20cm. These increases have not been smooth with time, nor uniform over the globe' [68]; and in addition: '[...] These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface' [69]. The report quickly gained acceptance as an authoritative scientific statement on the climate change problem. The IPCC meeting in Sundsvall was followed in November 1990 by the **Second World Climate Conference** (SWCC)[165] in Geneva, perhaps the biggest governmental meeting focusing on environmental issues prior to UNCED. The Conference's main objectives were to review the UNEP/WMO World Climate Programme (WCP), to recommend policy actions and to endorse the IPCC's conclusions: 'reflect[ing] the international consensus of scientific understanding of climate change'. The SWCC was an important step towards a global climate treaty. The UN General Assembly was urged to establish

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[65] ibidem p. 4.

[66] [61] at xi.

[67] Ibidem at xii.

[68] Ibidem at xii.

[69] Ibidem at xi.

formal negotiations towards a Framework Convention on Climate Change. The General Assembly discussed this issue on 21 December 1990, and established the **Intergovernmental Negotiating Committee** for a Framework Convention on Climate Change (INC), in **Resolution 45/212** [253], entitled 'Protection of global climate for present and future generations' [347]. The committee was charged with the task of negotiating a Framework Convention and any associated protocols designed to counter climate change. Two main points of the above mentioned resolution states:

> *Recalling its resolutions 43/53 of 6 December 1988 and 44/207 of 22 December 1989, in which it recognized that climate change is a common concern of mankind, and urging Governments and, as appropriate, intergovernmental and non-governmental organizations and scientific institutions, to collaborate in a concerted effort with the aim of preparing, as a matter of urgency, a framework convention on climate change, and other related instruments, containing appropriate commitments for action to combat climate change and its adverse effects, taking into account the most up-to-date, sound scientific knowledge and any existing uncertainties, as well as the particular needs and development priorities of developing countries.*[70]

> *Decides to establish a single intergovernmental negotiating process under the auspices of the General Assembly, supported by the United Nations Environment Programme and the World Meteorological Organization, for the preparation by an Intergovernmental Negotiating Committee of an effective framework convention on climate change, containing appropriate commitments, and any related instruments as might be agreed upon, taking into account*

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[70] See [253]: '[...] Reaffirms that, owing to its universal character, the United Nations system, through the General Assembly, is the appropriate forum for concerted political action on global environmental problems'; '[...] Urges Governments, intergovernmental and non-governmental organizations and scientific institutions to collaborate in efforts to prepare, as a matter of urgency, a framework convention on climate and associated protocols containing concrete commitments in the light of priorities that may be authoritatively identified on the basis of sound scientific knowledge, and taking into account the specific development needs of developing countries' in [252]; '[...] Convinced that climate change affects humanity as a whole and should be confronted within a global framework so as to take into account the vital interests of all mankind [...] Requested [...] to initiate action leading, as soon as possible, to a comprehensive review and recommendations with respect to: [...] (e) Elements for inclusion in a possible future international convention on climate' in [347].

> *proposals that may be submitted by States participating in the negotiating process, the work of the Intergovernmental Panel on Climate Change and the results achieved at international meetings on the subject, including the Second World Climate Conference.*[71]

Between February 1991 and May 1992, the INC held five sessions. Under the terms of the U.N. General Assembly resolution establishing the INC, each negotiating session could last only two weeks[72] and the INC was to complete its work in time for the Convention to be signed at the **United Nations Conference on Environment and Development** (UNCED) on 5 June 1992[73]. Real negotiations, however, began only in the final months before UNCED. Given the public visibility of the UNCED process, most delegations wished to have a convention to sign in Rio. This global conference, held on the 20th anniversary of the first international Conference on the Human Environment[34] brought together policy makers, diplomats, scientists, media personnel and non-governmental organization (NGO) representatives from 179 countries in a massive effort to reconcile the impact of human socio-economic activities on the environment and vice versa. This continuum of conferences represented a remarkable achievement for the United Nations system. Through the conference process the entire international community has come together to agree on shared values, on shared goals and on strategies to achieve them. This effort showed one of the United Nations system's greatest strengths: the ability to move from consciousness-raising to agenda-setting to agreement on action by Member States to follow-up on conference commitments and to effective assistance for the countries that need help in realizing their commitments.

In Rio, Governments (108 represented by heads of State or Government) adopted three major agreements aimed at changing the traditional approach to development: **Agenda 21** - a comprehensive programme of action for global action in all areas of sustainable development. It addresses :

> *the pressing problems of today and also aims at preparing the world for the challenges of the next century. It reflects a global*

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[71] In [253].

[72] '[...] Decides that the maximum duration of each of the negotiating sessions should be two weeks' in [252].

[73] The G.A. Res. 45/212 [253], recalled the G.A. Res. 44/228 of 22 December 1989 on the United Nations Conference on Environment and Development: '[...]Decides to convene the United Nations Conference on Environment and Development, which shall be of two weeks' duration and shall have the highest possible level of participation, to coincide with World Environment Day, on 5 June 1992'.

> *consensus and political commitment at the highest level on development and environment cooperation. Its successful implementation is first and foremost the responsibility of Governments. National strategies, plans, policies and processes are crucial in achieving this International cooperation should support and supplement such national efforts. In this context, the United Nations system has a key role to play. Other international, regional and subregional organizations are also called upon to contribute to this effort. The broadest public participation and the active involvement of the non-governmental organizations and other groups should also be encouraged.*[74]

The Rio Declaration on Environment and Development - a series of principles defining the rights and responsibilities of States in order to work 'towards international agreements which respect the interests of all and protect the integrity of the global environmental and developmental system, [r]ecognizing the integral and interdependent nature of the Earth'[75]. **The Statement of Forest Principles** - a set of principles to underlie the sustainable management of forests worldwide. However, it was nonbinding statement, directed at '[t]he implementation of national policies and programmes aimed at forest management, conservation and sustainable development, particularly in developing countries, should be supported by international financial and technical cooperation, including through the private sector, where appropriate.'[76]. In addition, two legally binding Conventions aimed at preventing global climate change and the eradication of the diversity of biological species were opened for signature at the Summit, giving high profile to these efforts: The **United Nations Framework Convention on Climate Change** (UNFCCC) and The **Convention on Biological Diversity** (CBD). The objective of the UNFCCC is:

> *to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*[77]

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[74] In [348]

[75] In [270]

[76] See A/CONF.151/26 (Vol. III) [267] at undocs.org ➦.

> *Acknowledging that change in the Earth's climate and its adverse effects are a common concern of humankind.*[78]

The objectives of the CBD, 'to be pursued in accordance with its relevant provisions', are:

> *the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer of relevant technologies, taking into account all rights over those resources and to technologies, and by appropriate funding.*[79]

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[77] In [351].
[78] In [351].
[79] In [66].

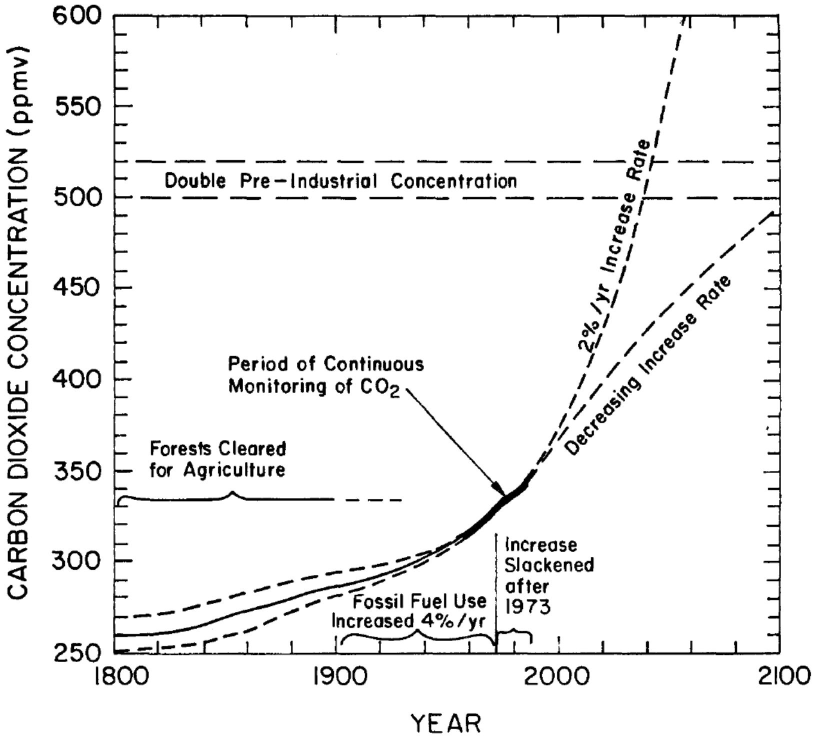

Figure 1.7: Past and future changes in atmospheric carbon dioxide concentration, measured in parts per million by volume (ppmv). Some increase probably occurred in the 19th Century due to extensive clearing of forests and the conversion of biomass to carbon dioxide (a process still going on), though there were few direct measurements in that period. During most of this Century fossil fuel burning and the consequent production of carbon dioxide increased at a rate of 4% yr -1 , but in 1973 there was the OPEC oil embargo and a worldwide recession resulting in a definite slackening of the rate of increase (see Clark, 1982). A good guess is that future consumption of fossil fuels will lie somewhere between a continuing 2% yr -1 of increase ('high') and a linearly decreasing rate of change such that 50 yr from now we will return to the present level of consumption ('low'). For the high case the concentration of carbon dioxide will be double that of the pre-Industrial Revolution level before the middle of the next Century; for the low case it may be about 100 yr later (Source: [177]).

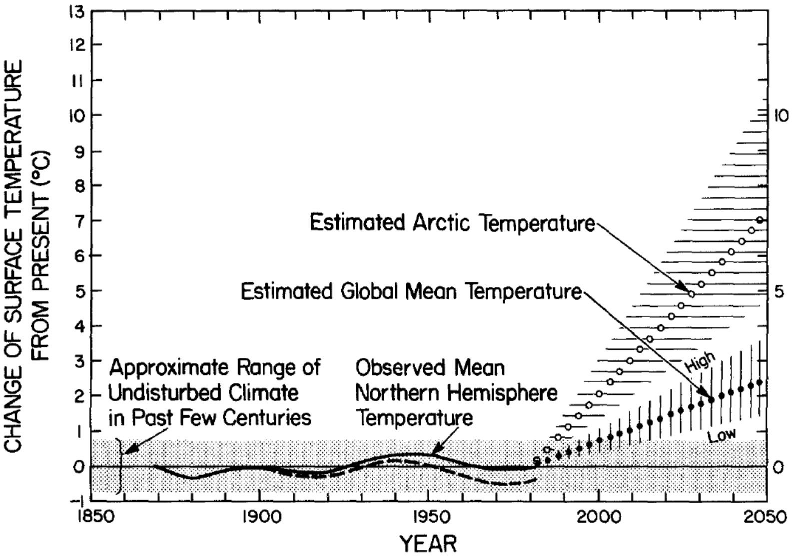

Figure 1.8: Estimates of past and future temperature variations. The future changes of global mean surface temperature are based on a 3°C warming for a doubling of carbon dioxide concentration, and the possible range between a high and a low scenario is the same as in Figure 1.7. Changes in the Arctic are expected to be about three times larger than the average. The shaded area shows the range within which the earth's temperature has remained for the past 1,000 years or more. The dashed line is the hypothetical global temperature record that might have occurred if there had been no increase in carbon dioxide or other infrared absorbing gases. The rate of global temperature change shown here will be slowed by the thermal inertia of the o ceans and hastened by the contributions of other trace gases to the greenhouse effect (Source: [177]).

Chapter 2

Anthropogenic Energy System

2.1 Overview

Energy consumption worldwide grew by **2.9%** in 2018 (as in 2.1), nearly twice the average rate of growth since 2012, driven by a modest global economy, globally led by developing countries, as well as higher heating and cooling needs in some parts of the world[1] (see 2.3). https

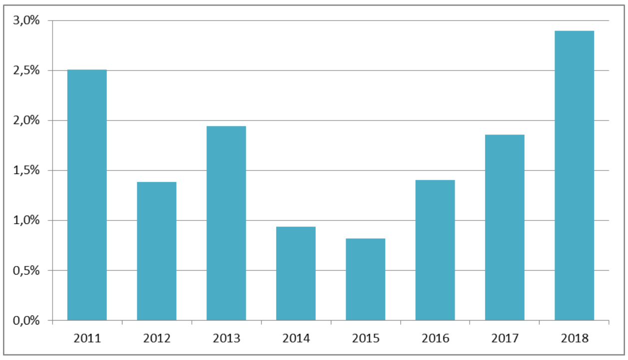

Figure 2.1: Global primary energy demand rose by 1.9% in 2017, the largest annual increase since 2010 and well above those in 2015 and 2016. Most of the increase came from emerging economies, where demand increased by 2.7%, or 9.2 exajoules (EJ) compared with 0.7% (1.5 EJ) in advanced economies (IEA WEO, 2018).

It seems that much of the surprising strength in energy consumption in 2018 may be related to weather effects. In particular, there was an unusually large number of both hot and cold days last year, which led to higher energy consumption as the demand for cooling and heating services increased[2]. Demand for all fuels increased, led by **natural gas**, even as **solar and wind**

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[1] See: climate.nasa.gov... .

[2] See: bp.com....

posted double digit growth. Higher **electricity demand** was responsible for over half of the growth in energy needs. **Energy efficiency** saw a significant improvement. Globally, efficiency gains since 2000 prevented **12%** more energy use than would have otherwise been the case in 2017. Energy efficiency is a major driver for uncoupling energy consumption from economic development (see 2.2)[3].

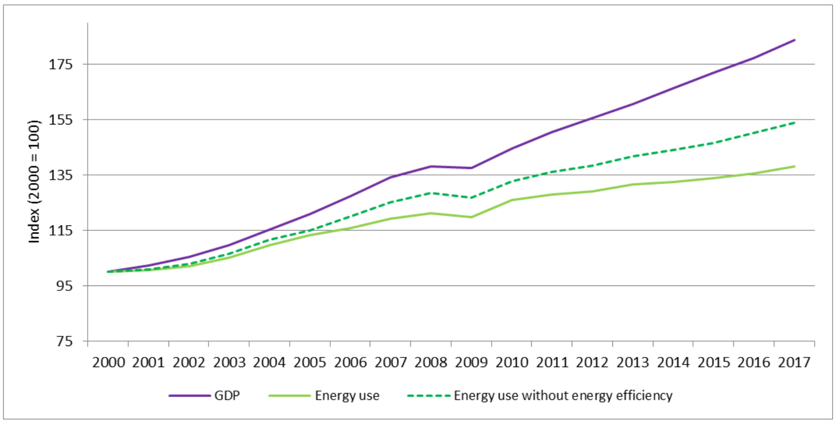

Figure 2.2: The importance of energy efficiency improvements to reducing the impact of rising economic activity on final energy use has been steady since 2000.

Higher energy demand was propelled by a global economy that expanded by **3.6%** in 2018, a higher pace than the average annual growth of **3.5%** seen since 2010 (see 2.3[4]). **China**, the **United States**, and **India** together accounted for nearly **70%** of the rise in energy demand (see 2.4)[5].

The **United States** had the largest increase in oil and gas demand worldwide. Gas consumption jumped **10%** from the previous year, the fastest increase since the beginning of IEA records in 1971. The annual increase in US demand last year was equivalent to the United Kingdom's current gas consumption. After three years of decline, energy demand in the **United States** rebounded in 2018, growing by **3.7%**, or 80 Mtoe, nearly one-quarter of global growth. A hotter-than-average summer and colder-than-average winter were responsible for around half of the increase in gas demand in the United States, as gas needs grew both for electricity generation and for heating.

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[3] See: www.iea.org/efficiency... . Efficiency can enable economic growth, reduce emissions and improve energy security. The right efficiency policies could enable the world to achieve more than 40% of the emissions cuts needed to reach its climate goals without new technology.

[4] See: www.imf.org...

[5] See: bp.com....

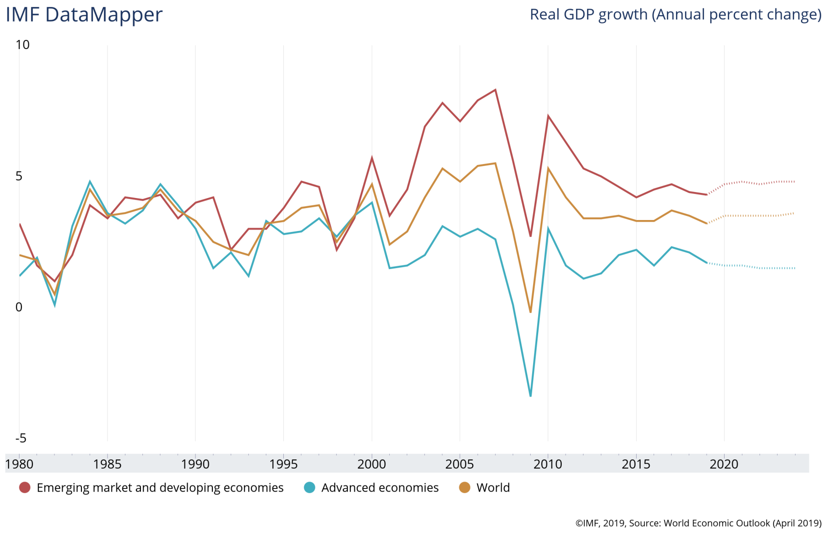

Figure 2.3: Global growth remains subdued. Global growth is forecast at 3.2% in 2019, picking up to 3.5% in 2020 (0.1 percentage point lower than in the April WEO projections for both years). GDP releases so far this year, together with generally softening inflation, point to weaker-than-anticipated global activity.

Weather conditions last year were also responsible for almost a **fifth of the increase** in global energy demand as average winter and summer temperatures in some regions approached or exceeded historical records. Cold snaps drove demand for heating and, more significantly, hotter summer temperatures pushed up demand for cooling. **India** saw primary energy demand increase **4%** or over **35 Mtoe**, accounting for **11%** of global growth, the third-largest share. Growth in India was led by coal (for power generation) and oil (for transport), the first and second biggest contributors to energy demand growth, respectively. Energy demand in **Europe** in 2018 followed a different path. Despite an economic expansion of **1.8%**, demand increased by only **0.2%**. An increase in energy efficiency in Germany resulted in a **2.2%** drop in energy demand, with oil demand decreasing by more than **6%**. Demand in France and the United Kingdom increased moderately.

2.2 World energy markets by fuel type

The biggest gains came from **natural gas**, which emerged as the fuel of choice last year, accounting for nearly **45%** of the increase in total energy demand. Demand for all fuels rose, with **fossil fuels** meeting nearly **70%** of

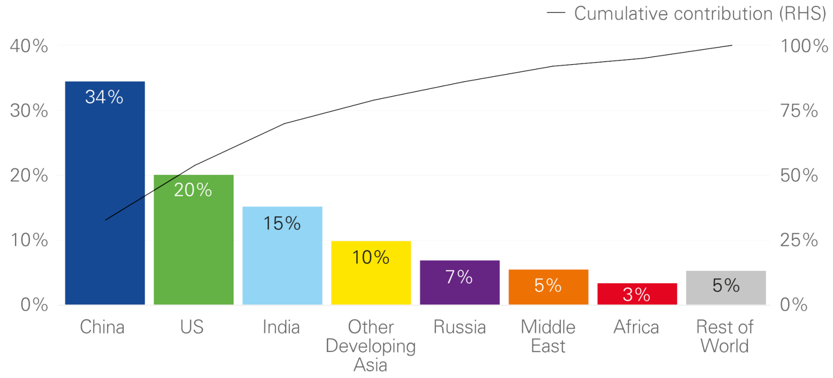

Figure 2.4: China, the US and India together accounted for more than two thirds of the global increase in energy demand, with US consumption expanding at its fastest rate for 30 years. The growth for all fuels increased but growth was particularly strong in the case of gas (168 mtoe accounting for 43% of the global increase). All fuels grew faster than their 10-year averages, apart from renewables, although renewable still accounted for the second largest increment to energy growth (71 mtoe, 18% of the global increase). (See bp.com...)

the growth for the second year running[6]. Renewables grew at double-digit pace, but still not fast enough to meet the increase in demand for electricity around the world (see 2.5).

Natural gas remains a key fuel in the electric power sector and in the industrial sector. In the power sector, natural gas is an attractive choice for new generating plants given its moderate capital cost and attractive pricing in many regions as well as the relatively high fuel efficiency. The global **coal** demand declined in 2015 and 2016. In 2017 and 2018, it rebounded, but air quality and climate policies, coal divestment campaigns, phase-out announcements, declining costs of renewables and abundant supplies of natural gas are all putting pressure on coal. As a result, coal's contribution to the global energy mix is forecast to decline slightly from **27%** in 2017 to **25%** by 2023[7]. According to IEA analysis, global coal demand is growing, but is still below "peak" levels seen in 2014[8]. World use of **petroleum and other liquid fuels** grows from **90** million barrels per day (mb/d) in 2012 to **100 mb/d** in 2020 and to **121 mb/d** in 2040. Most of the growth in liquid fuels consumption is in the transportation and industrial sectors. In the transportation sector, in particular, liquid fuels continue to supply most of the energy consumed. Although advances in nonliquids-based transportation

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[6] Change year-on-year.

[7] See: www.iea.org....

[8] See: www.carbonbrief.org....

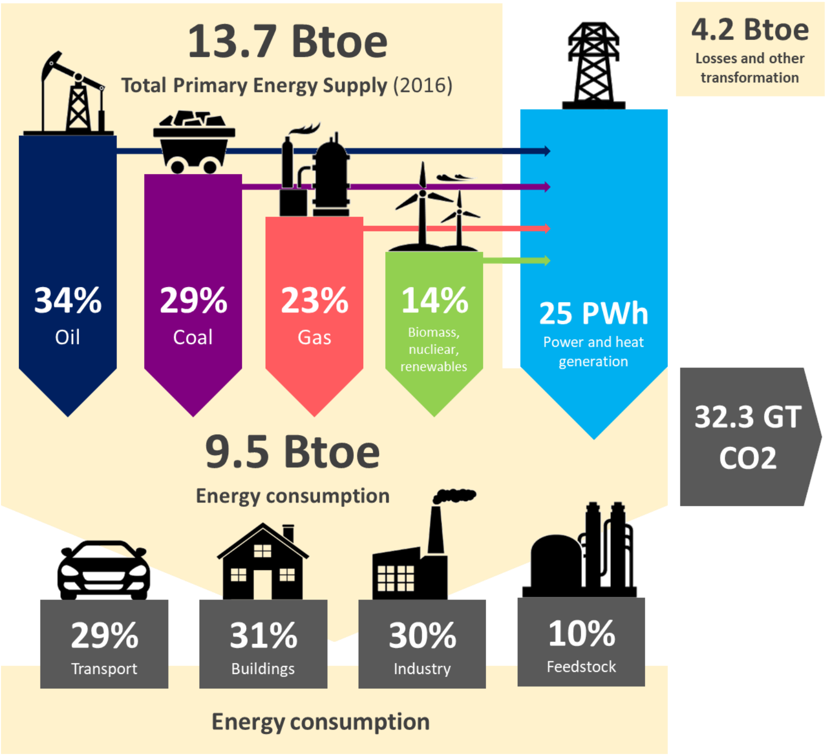

Figure 2.5: Current energy needs are met primarily by oil, gas and coal, with consumer preferences driving demand.

technologies are on the way, they are not enough to offset the rising demand for transportation services worldwide. Additionally, the **Organization of the Petroleum Exporting Countries** (OPEC) will invest in incremental production capacity to maintain a **39%-43%** share of total world liquids production through 2040[9], consistent with their share over the past 15 years. Increasing volumes of crude oil and lease condensate from OPEC producers contribute **13.2 mb/d** to the total increase in world liquids production, and crude oil and lease condensate supplies from non-OPEC countries add another **10.2 mb/d**. World net **electricity generation** increases by **69%** from **21.6 PWh** in 2012 to **25.8 PWh** in 2020 and to **36.5 PWh** in 2040, according to US Energy Information Administration and IEA[10]. The electric power sector remains among the most dynamic areas of growth among all energy markets. Electricity is the **world's fastest-growing form of end-use energy consumption**, as it has been for many decades. There are specific

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[9] See: www.iea.org....

[10] Energy losses associated with electricity generation and transmission are not included in the consumption numbers.

reasons to single out electricity. The increasing digitalization of the global economy is interlocked with electrification, making the need for electricity for daily living more essential than ever. Electricity is increasingly the "**fuel**"[11] of choice for meeting the energy needs of households and companies resulting in rapidly rising electricity demand. Since 2000, global electricity demand has grown **two-thirds** faster than total final consumption, mostly stemming from growth in China and India (averagely all non-OECD countries). This trend looks set to continue.

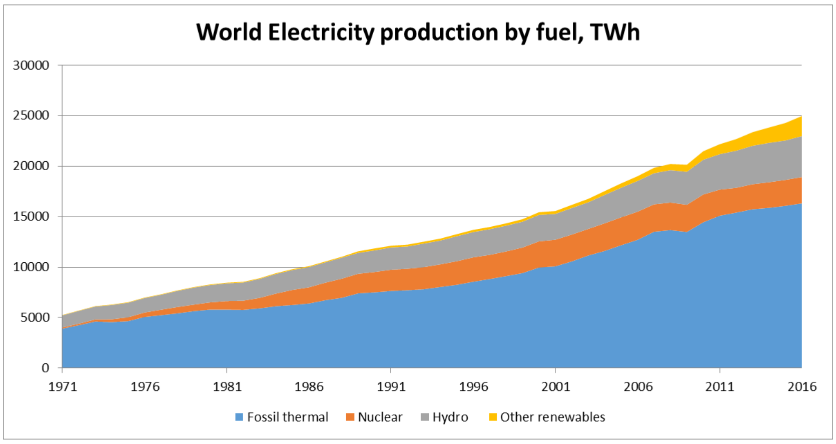

Figure 2.6: Annual temperature departures from the whole Earth.

The global electricity supply is also being transformed by the rise of **variable renewable sources** of generation such as wind and solar PV. This puts electricity at the forefront of the clean-energy transitions, providing access to the nearly 1 billion currently deprived[12]www.forbes.com..., helping cut air pollution and meet climate goals. However, these changes will require a new approach to how power systems are designed and how they operate, otherwise, rising electrification could result in less secure energy systems, underscoring the urgent need for policy action in this critical sector. Economic growth is an important factor in electricity demand growth. Although world gross domestic product (GDP) growth slows in comparison with the past two decades, electricity demand continues to increase, especially among the

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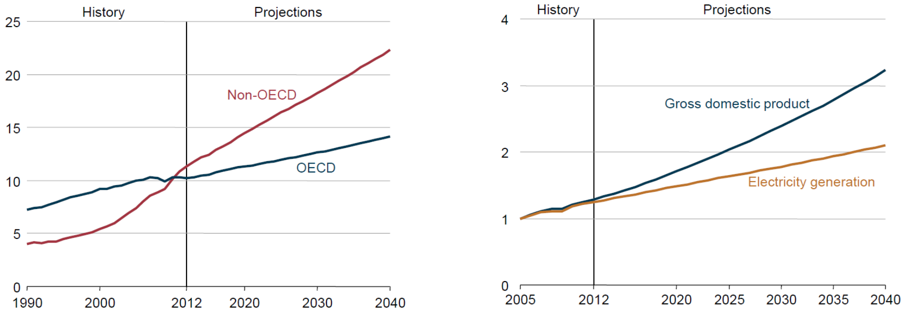
[11] Electricity is a carrier of energy rather than a fuel, but on particular circumstances it is referred to as a "fuel" in this special focus insofar as it competes with other fuels to provide energy services.

[12] According to IEA, India completed the electrification of all villages in early 2018, and plans to achieve universal access to electricity by the early 2020s. However despite significant steps forward in Kenya, Ethiopia, Tanzania and Nigeria, 600 million people remain without access to electricity in sub-Saharan Africa (see: www.iea.org... and www.worldbank.org... and www.forbes.com...).

emerging **non-Organization for Economic Cooperation and Development** (non-OECD) economies. In 2012, electricity generation in non-OECD countries represented slightly more than one-half of world electricity demand. With continued strong economic growth, the non-OECD share of world electricity generation increases to **61%** in 2040, as total non-OECD electricity generation nearly doubles, from **11.3 PWh** in 2012 to **22.3 PWh** in 2040 (2.7a). In general, the projected growth of electricity demand in **OECD countries**, where electricity markets are well grounded and electricity consumption patterns are mature, is slower than in the non-OECD countries. OECD GDP increases by **2.4%/year**, less than half the **4.7%/year** GDP growth projected for non-OECD countries (see previous 2.3). Different scenario analysis studies reflect the expectation that economic activity will continue to drive electricity demand growth; however, the rate of growth in electricity consumption continues to become smaller compared to the rate of growth in GDP. From 2005 to 2012, world GDP increased by **3.7%/year**, while world net electricity generation rose by **3.2%/year**. In many parts of the world, policy actions aimed at improving efficiency will help to decouple economic growth rates and electricity demand growth rates more in the future (2.7b). According to EIA forecast, world GDP grows by **3.3%/year**, and world net electricity generation grows by **1.9%/year**, from 2012 to 2040. The **69%** increase in world electricity generation through 2040 is far below what it would be if economic growth and electricity demand growth maintained the same relationship they had in the recent past.



(a) OECD and non-OECD net electricity generation, 1990-2040 (trillion kilowatthours).

(b) Growth in world electricity generation and GDP, 2005-40 (index, 2005 = 1).

Figure 2.7: OECD and non-oecd net electricity generation and growth in world electrcity generation and GDP (see EIA, IEO 2016).

Many countries, particularly among the developed OECD nations are pursuing policies and regulations intended to increase the pressure on generating companies to reduce greenhouse gas emissions from electric power plants by decreasing the use of fossil fuels. As a result, the role of coal as a dominant fuel for electric power plants is expected to be reduced. It is noteworthy to mention **China**'s target of 15% renewable electricity by 2020, the **European Union**'s 2030 **Energy Framework objectives**, and **India**'s megawatts-to-gigawatts renewable energy commitment. Additionally, the U.S. Environmental Protection Agency replaced the Obama-era **Clean Power Plan** on June'19 with **Affordable Clean Energy** (ACE)[13] that focuses on efficiency improvements at generating stations. The new rules' scheme calls for efficiency improvements at generating stations and directs states to take the initiative on how they choose to regulate power plant emissions. However, a broad and diverse group including political leaders, business representatives, and public health advocates have come out in strong opposition to such new set of rules[14]. On a global scale, policymakers have proposed a range of programs that place particular emphasis on the countries' **Intended Nationally Determined Contributions** (INDCs) for addressing CO2 emissions reductions as part of the 21st Conference of Parties (COP21) meetings held in Paris from November 30 to December 11, 2015. On the efficacy of this INDCs is still a matter of debate between scientists and policymakers. New and unforeseeable government policies or legislation, aimed at limiting o reducing greenhouse gas or other power-sector emissions, could substantially steer the trajectories of fossil and nonfossil consumption. Current studies claim the coal share of total generation will decline from **40%** in 2012 to **29%** in 2040, even as world coal-fired generation increases by **25%** through 2040. At the same time, the shares of total generation for both renewable energy sources and natural gas expand: from **22%** in 2012 to **29%** in 2040 for renewables and from **22%** in 2012 to **28%** in 2040 for natural gas (2.8). Furthermore, Western Europe is accelerating its coal exit. Specific action on climate change and to phase out coal-fired power generation are all impacting coal demand. Along with the expansion of renewables, these policy efforts will eventually push coal out of the Western European power mix. By contrast, most countries in Eastern Europe have not announced phase-out policies and a handful of new coal power plants are under construction in **Poland**, **Greece** and in the **Balkans**. Some countries in Eastern Europe are among the few places in the world where lignite remains the fundament of the electricity system[15].

As a result of higher energy consumption, global energy-related CO2

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[13] See www.epa.gov....

[14] Trigger a debate on the ACE is beyond the scope of this thesis. I suggested the interested reader to check references for further details.

[15] See www.iea.org....

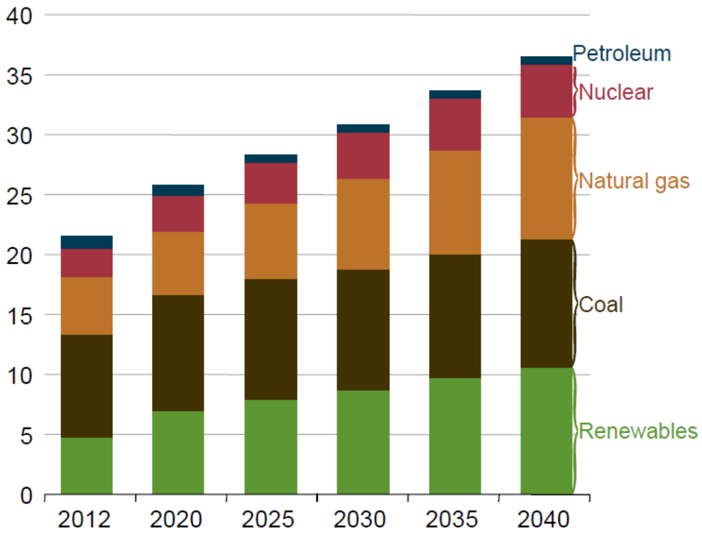

Figure 2.8: Renewables account for a rising share of the world's total electricity supply, and they are the fastest growing source of electricity generation (see EIA, IEO 2016).

emissions increased to **33.1 Gt CO2**, up **1.7%**. Coal-fired power generation continues to be the single largest emitter, accounting for **30%** of all energy-related carbon dioxide emissions[16] (see 2.9).

Much of the growth in emissions is attributed to developing nations outside the OECD, many of which continue to rely heavily on fossil fuels to meet the **fast-paced growth** of energy demand (see 2.10). In particular, the data compiled by BP suggest that in 2018, global energy demand and carbon emissions from energy use grew at their fastest rate since 2010/11, moving even further away from the accelerated transition envisaged by the Paris climate goals.

According to EIA projections, **non-OECD emissions** in 2040 total **29.4 Gt CO2**, or about **51%** higher than the 2012 level. In comparison, **OECD emissions** total **13.8 Gt CO2** in 2040, or about **8%** higher than the 2012 level (see 2.11).

2.3 World energy transformation

Since the early 1970s the mix of fuels has been relatively static with hydrocarbons contributing a steady **80%**. The remainder of the energy mix includes approximately **10%** biomass (mostly dung and wood), **6%** nuclear, **3%** hy-

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[16] See www.snam.it.

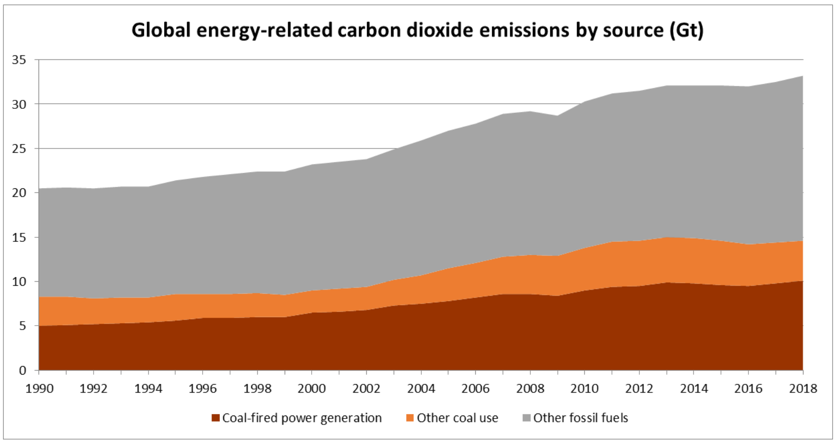

Figure 2.9: Driven by higher energy demand in 2018, global energy-related CO2 emissions rose 1.7% to a historic high of 33.1 Gt CO2. While emissions from all fossil fuels increased, the power sector accounted for nearly two-thirds of emissions growth. Coal use in power alone surpassed 10 Gt CO2, mostly in Asia. China, India, and the United States accounted for 85% of the net increase in emissions, while emissions declined for Germany, Japan, Mexico, France and the United Kingdom (See Global Energy & CO2 Status Report 2019).

dropower and around **1-2%** of the "new renewables" (solar photovoltaic and wind). Conversely, the final energy consumption has doubled since then. Yet as we look at the continued growth of new renewables in combination with emerging technological possibilities and the environmental pressures of the 21st century, we see a new phase of transition. The dynamics of change in the next 50 years will be much more apparent than they have been in the past decades. There will be not only growth, as prosperity and the benefits of modern living continue to become more widespread, but also transformation in economic structures and transition in the technologies applied in the energy system. However, because of the convenience of oil and gas and the cheapness of coal, the shift will not happen by itself.

To achieve net-zero emissions requires the widespread transformation of the **energy system**, including not only the volume and proportion of different **primary energies** consumed (oil, gas, coal, solar, wind, nuclear, etc.) and the **energy carriers** they produce (electricity, liquid fuels, etc.), but also how energy is used in homes, offices, transport systems and industries. How quickly and how far society can decarbonise depends on whether and how much historic patterns of energy and material demand can be changed. These structural transformations will occur at different paces and in different locations and will be determined both by political and economic local circumstance and by the technical potential for change in key sectors. The direct, energy-related CO2 emissions from **transport** account for around **24%** of

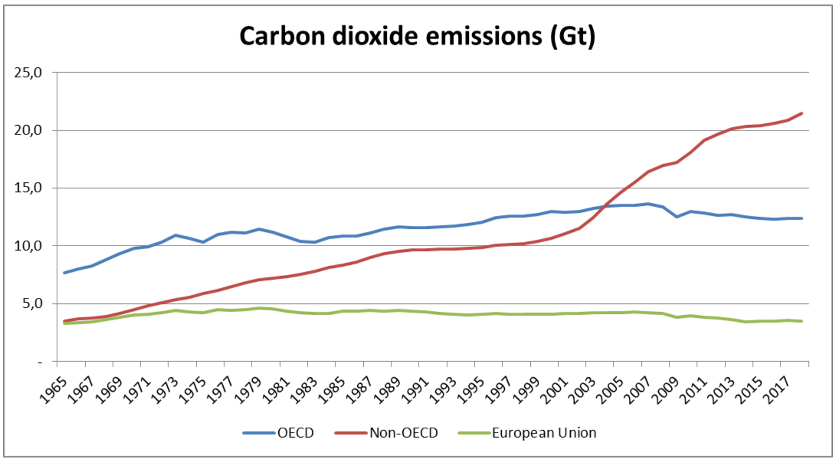

Figure 2.10: Carbon emissions grew by 2.0%, the fastest growth for seven years, according to BP statistics.

global emissions of CO2 (according to BP statistics). The growing and more prosperous global population of a net-zero world will need far greater levels of transport both for personal mobility and for the trade and transport of goods. Energy-service demands for transport are likely to grow three to four times larger than they are today, even assuming significant energy efficiency improvements and a far greater proportion of the global population living closer together in highly compact cities (where they will travel fewer passenger kilometres). At the moment, the **global transport sector**, with the exception of rail, is almost entirely reliant in liquid hydrocarbons, including petrol, diesel and bunker fuel for shipping. The potential to decarbonise varies across different transport subsectors. **Passenger road transport** will be the easiest to electrify, with battery and fuel cell electric vehicles potentially reaching **80%** of the global passenger car fleet over coming decades. EVs are particularly suited for short- and medium-distance travel in urban environments and densely populated regions, where recharging points can be easily concentrated to minimise the risk of batteries running out of power mid-journey. Unlike passenger **road transport**, the movement of **heavy freight** over longer distances in ships and trucks requires **more energy-dense fuels**. Here, alongside growing use of batteries for shorter freight needs, such as inside cities, the use of **hydrogen** (which emits no CO2) and **liquefied natural gas** (LNG) - both energy-dense liquid fuels - will complement and eventually displace a proportion of conventional fuels over time. And for the longest journeys by air and sea, where the size and weight of batteries will probably remain prohibitive for the foreseeable future, liquid hydrocarbons and biofuels are likely to dominate for a long time to come.

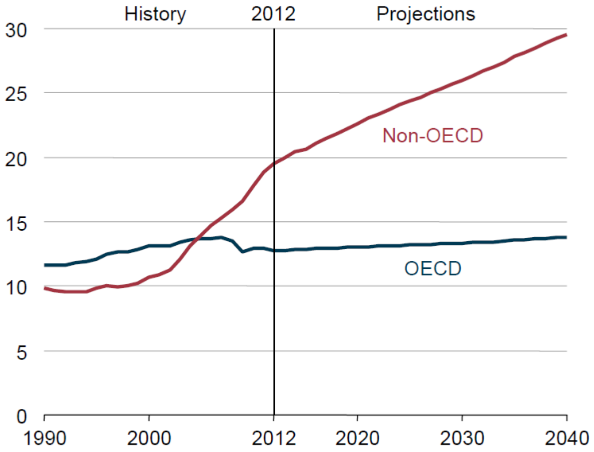

Figure 2.11: According to EIA studies, non-OECD emissions in 2040 total 29.4 GT, or about 51% higher than the 2012 level. In comparison, OECD emissions total 13.8 GT in 2040, or about 8% higher than the 2012 level (see EIA, IEO 2016).

Today, **less than 1%** of the global vehicle fleet is electric. For light-duty use, that figure will rise significantly in coming years as the price and range of battery-electric and hydrogen-fuel-cell-electric vehicles improve over time. The **evolution of battery technology** is one of the most important variables that will shape the eventual pace of electrification. Beyond the natural time cycle required for cars to be replaced with newer models, there are few hurdles to the take-up of advanced batteries as breakthroughs occur beyond ensuring sufficient supply of key resources, such as lithium. Eventually, advanced batteries may even allow some **hybridisation of air transport**. In the longer term, the growth of vehicles with batteries may one day provide one of the solutions to the intermittency of renewable energy sources: smart IT technology and algorithms could enable an individual car owner to trade the power storage capacity of a car battery sitting in a garage to help balance the power grid. The **growth of hydrogen** as a transport fuel will depend not only on technological progress, but also on institutional capability to build-out the necessary infrastructure and pipeline systems. If the mechanisms are mastered and **hydrogen roll-out** is achieved globally, hydrogen might take over a significant share of the hydrocarbon needs. Predict with complete confidence technical advances as far out into the future as the middle of this century and beyond. But it is apparent that the **decarbonisation of transport** - which today relies overwhelmingly on hydrocarbon fuels - is composed of a series of different tasks for different transport modalities, each with its own specific technical constraints. After the **train**, the easiest mode of transport to tackle is the **private car**. Solutions for **freight**,

shipping and **aviation** are still hard-to-decarbonize sectors.

2.4 World transport sector energy consumption

This section discusses delivered energy consumption[17] in the transportation sector. World delivered energy consumption in the transportation sector increases at an annual average rate of **1.4%**. Virtually all (**94%**) of the growth in transportation energy use occurs in the developing, **non-OECD economies**. Steady economic growth leads to rising standards of living that result in demand for personal travel and freight transport to meet growing consumer demand for goods in non-OECD nations. Conversely in **OECD nations**, the combination of well-established consuming patterns, comparatively slow economic and population growth rates, and vehicle efficiency improvements, leads to an average increase in total transportation energy use of only **0.2%/year** from 2012 to 2040. Worldwide, **liquid fuels** remain the dominant source of transportation energy consumption, although their share of total transportation energy is likely to decline from **96%** in 2012 to **88%** in 2040, according to EIA projection. IEA reports different trends. Liquid fuels declines to around **85%** by 2040, down from **94%** currently (2017). World **liquid fuels** consumption grows by **36 quadrillion Btu**, with **diesel** (including biodiesel) showing the largest gain (**13 quadrillion Btu**), **jet fuel** consumption increasing by **10 quadrillion Btu**, and **motor gasoline** (including ethanol blends) increasing by **9 quadrillion Btu** (2.12). **Motor gasoline** remains the largest transportation fuel, but its share of total transportation energy consumption declines from **39%** in 2012 to **33%** in 2040. The share of **natural gas** as a transportation fuel grows from **3%** in 2012 to **11%** in 2040. As a result of favourable fuel economics, a strong increase is projected for the natural gas share of total energy use by **large trucks**, from **1%** in 2012 to **15%** in 2040. In addition, **50%** of **bus** energy consumption is projected to be natural gas in 2040, as well as **17%** of **freight rail**, **7%** of **light-duty vehicles**, and **6%** of **domestic marine vessels**. **Electricity** remains a minor fuel for the world's transportation energy use, although its importance in passenger rail transportation remains high. The electricity share of total light-duty vehicle energy consumption grows to **1%** in 2040, as new plug-in electric vehicles increasingly penetrate the total light-duty stock.

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[17] Energy use includes the energy consumed in moving people and goods by road, rail, air, water, and pipeline.

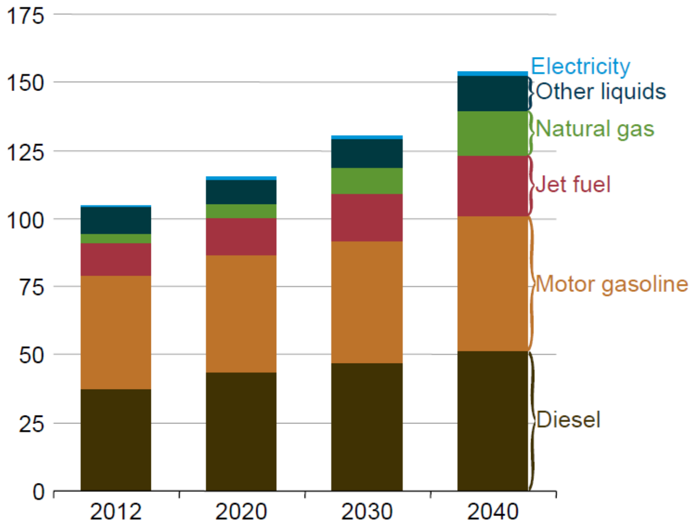

Figure 2.12: Worldwide, liquid fuels remain the dominant source of transportation energy consumption, although their share of total transportation energy declines somewhat over the projection period, from 96% in 2012 to 88% in 2040.

Despite the large number of policy measures and initiatives applied in the transport sector, the reduction in CO2 is relatively small. Demand for transport services grows strongly, but gains in energy efficiency limit increases in energy used. More than **half of this consumption** stems from the use of petrol in cars and light and medium-duty trucks which can be gradually electrified overtime. The remainder is concentrated in modes of transport which are harder to electrify such as heavy-duty trucks, aviation, and marine.

2.4.1 Final energy consumption by mode of transport (EU region)

In 2016, energy consumption in transport in the **EU-**[18] was **28%**, about **3.7 exajoules** (EJ, 10_18 Joules) higher than in 1990 (2.13)[19]. For the **EEA-33**[20], the figure was **34%**. In the **EU-13**[21], most of this growth oc-

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[18] The EU-28 is the abbreviation of European Union (EU) which consists a group of 28 countries (Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, United Kingdom) that operates as an economic and political block.

[19] See: www.eea.europa.eu....

[20] EU-28 together with Iceland, Liechtenstein, Norway, Switzerland and Turkey.

[21] New EU member states (EU-13). Since 2004 there have been 13 new countries added to the European Union - Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary,

curred in road and maritime transport. However, in the **EU-15**[22] the growth occurred mainly in air transport, although the largest absolute increase in energy consumption occurred in road transport. Split of energy consumption between old and new EU Member States. In 2016, transport in the EEA-33 countries consumed approximately **18.65 EJ** of energy. The original EU-15 Member States consumed the vast majority of the energy (**80%**), with just **12%** consumed by the EU-13 Member States. The final **8%** was used in the remaining EEA[23] member countries. On average, each person in the EEA countries used 2.0 tonnes of oil equivalent to meet their energy needs in 2016.

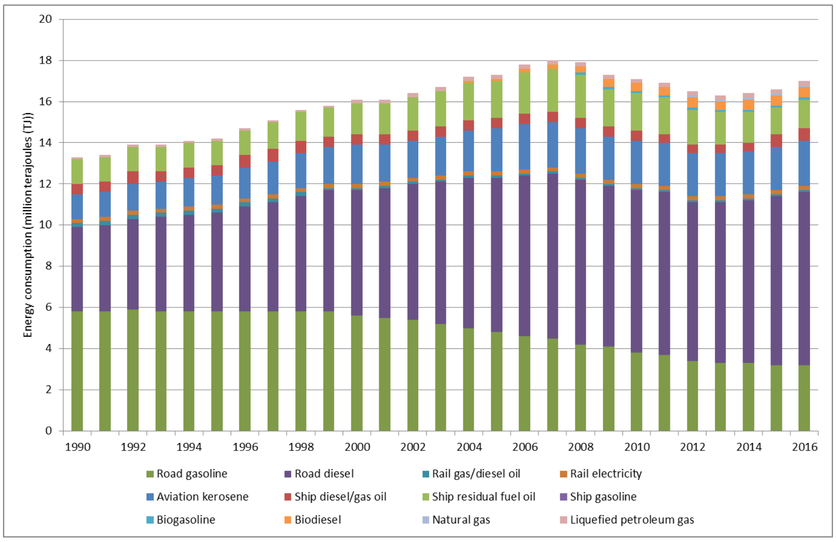


Figure 2.13: Oil derived fuels cover all fuels excluding biodiesel, biogas, biogasoline, electrical energy, natural gas and solid biofuels. In 2016, oil derived fuels accounted for 95% of all fuels consumed. At 3% of total energy consumption, biodiesel was the largest source of non-oil derived fuels, while rail electricity was second at 1%. The '70% reduction from 2008 oil consumption' is an EU-28 goal that relates to an impact assessment that accompanied the European Commission's Transport White Paper (EC, 2011a), which in turn suggested that a 70% reduction (from 2008 levels) in oil consumption in transport should be achieved by 2050.

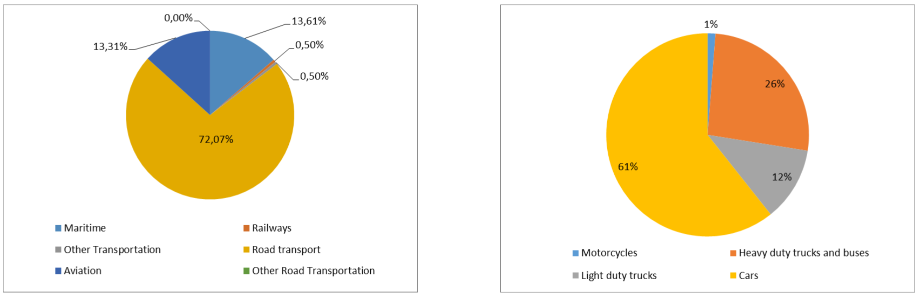
Latvia, Lithuania, Malta, Poland, Romania, Slovakia and Slovenia.

[22] The EU-15 comprised the following 15 countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.

[23] Countries that belong to the EEA include Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

2.4.2 GHG emissions from transport

Since 2014, greenhouse gas emissions from the EU-28 transport sector (including international aviation but excluding international shipping) have been increasing. In comparison with 2015, emissions in 2016 had increased by almost **3%**, mainly on account of higher emissions from road transport, followed by aviation. In 2016, transport (including aviation and shipping) contributed **27%** of total greenhouse gas emissions in the EU-28[24]. EEA estimates show that emissions from transport (including aviation) further increased by **1.5%** in 2017. In 2016, **road transport** was responsible for almost **72%** of total greenhouse gas emissions from transport[25]. Of these emissions, **44%** were contributed by **passenger cars**, while **19%** came from **heavy-duty vehicles and buses**.



(a) (b)

Figure 2.14: (a) Share of transport greenhouse gas emissions. (b) Share of transport mode greenhouse gas emissions, relative to transport sector emissions.

As a result of a significant rise in passenger-kilometer and tonne-kilometer demand, greenhouse gas emissions from international aviation more than doubled from 1990 levels (**+114 %**), followed by increases in international shipping (**+33%**) and road transportation (**+22%**) emissions. In comparison with 2015, EU greenhouse gas emissions from international shipping increased by **4%** in 2016, returning to 2002 levels. However, they will need to further decrease by one-third by 2050 in order to meet the EU reduction target of a **40%** reduction in emissions from 2005 levels. However, emissions from transport (including international aviation but excluding international shipping) were still more than **26%** above 1990 levels in 2016. Emissions will, therefore, need to fall by two-thirds by 2050 in order to meet the **60%** greenhouse gas emission reduction target of the 2011 Transport White Paper.

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[24] This figure drops to 20% if international shipping is excluded from the overall value

[25] including international aviation and international shipping.

2.4.3 Policy context and targets

There are no specific greenhouse gas emission reduction targets foreseen for the transport sector under the Kyoto Protocol. However, there are several European policies and strategies (see below) that aim to reduce greenhouse gas emissions from transport. From 1 January 2012, air transport has been included in the **EU Emissions Trading System**. However, in order to allow time for negotiations on a global, market-based measure that can be applied to aviation emissions, only emissions from flights within the European Economic Area currently fall under the EU system. The EU's overall goal, set out in the 2011 **White Paper for Transport**, is to reduce greenhouse gas emissions from transport (including international aviation but excluding international shipping) by 2050 to a level that is **60%** below that of 1990. This includes the intermediate goal of reducing greenhouse gas emissions from transport by **20%**, compared with 2008 levels, by 2030 (**+8%** compared with 1990 levels)[26]. Similarly, emissions from international shipping are to be reduced by **40%** from 2005 levels by 2050. As the transport sector is not included in the Emissions Trading Scheme, it is the responsibility of Member States to reduce transport emissions through national policies in order to reach their national **Effort Sharing** targets (which cover sectors such as transport, buildings, agriculture, waste, etc.). These Effort Sharing targets are equivalent to a **10%** reduction against 2005 levels by 2020 and a **30%** reduction by 2030. While the EU as a whole remains on track to meet its 2020 targets to reduce greenhouse gas emissions and increase renewable energy use, recent increasing trends in energy consumption need to be reversed in order to meet the 2020 targets. Renewed efforts will also be necessary to meet the 2030 climate and energy targets. The uptake of renewable energy as part of the EU's energy mix resulted in a **17.4%** share of renewables in gross final energy consumption in 2017, according to preliminary EEA data. This indicates that the EU remains on track to reach its target of a renewables share of **20%** by 2020. However, the pace of increasing renewables use was only up marginally from **17.0%** in 2016. There has also been insufficient progress towards the **10%** target for renewables in the transport sector by 2020. With 2020 approaching, the trajectories needed to meet the national targets are becoming steeper. Increased energy consumption and persisting market barriers are hindering the uptake of renewables in several Member States. Preliminary EEA data for 2017 show that 20 Member States were on track to reach their individual targets on renewable

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[26] These overall transport targets are monitored annually and are in line with the economy-wide targets of a 20% reduction in total greenhouse gas emissions by 2020 from 1990 levels and a 40% reduction target by 2030.

energy by 2020 - a decline from 2016, when 25 countries were on track. In many countries, the slowing of progress is due to increases in total energy consumption, which caused the share of renewables in energy consumption to fall. Over the past decade, energy consumption generally decreased at a pace that could ensure the achievement of the EU's 2020 targets on energy efficiency. However, in 2015, energy consumption in the EU began to increase, and the EEA's preliminary estimates for 2017 indicate that both primary energy consumption and final energy consumption now lie above the indicative trajectory towards 2020. Notably, in 2016, growing demands for energy in the transport sector reached **33%** of final energy consumption in the EU. The continued growth in energy consumption, particularly in transport but also in other sectors, makes achieving the 2020 target increasingly uncertain. Preliminary EEA data from 2017 show that 13 Member States are expected to have increased their primary energy consumption to levels above the trajectories to their 2020 targets. That is an increase of three countries from 2016. Member States will need to increase their efforts to bring the EU back on track and reverse the trend of increasing energy consumption, in particular in the transport sector.

2.4.4 Relevant measures to support low-carbon mobility

There are a range of other relevant policies and measures that support moves at the EU level towards low-emission mobility. The proposed revision of the **Clean Vehicle Directive**[28] will better promote the use of public procurement to incentivise the creation of markets for innovative and low-emitting vehicles. Action is also being taken to support electric and hydrogen-fuelled vehicles. The **European Green Vehicles Initiative** (EGVI)[29] is a contractual Public Private Partnership launched in 2013 with an estimated budget of EUR 1.5 billion[30]. The expected outcome is to improve transport system efficiency, develop alternative powertrains and improve batteries.

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[28] See: ec.europa.eu/transport/modes/road/news... and europa.eu/rapid....

[29] See: egvi.eu/who-we-are.... The European Green Vehicles Initiative is a contractual Public Private Partnership (cPPP) dedicated to delivering green vehicles and mobility system solutions of the future which match the major societal, environmental and economic challenges. Launch in 2013, as part of the Smart, Green and Integrated Transport challenge of Horizon 2020, EGVI has succeeded to the European Green Cars Initiative (2009-2013).

[30] The Horizon 2020 contribution is around EUR 750 million and the remaining amount from industrial partners.

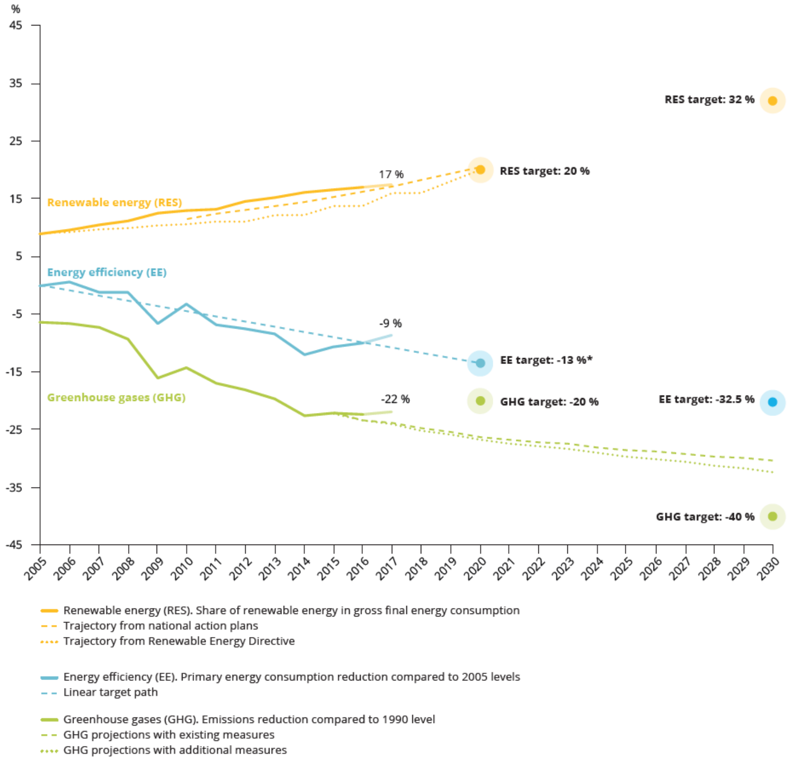

Figure 2.15: *The energy efficiency targets for 2020 and 2030 [27].

2.4.5 Fuel Cell and Hydrogen Research and Demonstration projects

Hydrogen and fuel cell technologies were identified amongst the new energy technologies needed to achieve a **60%** to **80%** reduction in greenhouse gases by 2050, in the **European Strategic Energy Technology Plan**[31] presented along with the **Energy Policy Package**[32] in January 2008[33]. It was revised in 2015 to effectively line up with the EU's Energy Union research

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[31] The European Strategic Energy Technology Plan (SET Plan) aims to accelerate the development and deployment of low-carbon technologies. It seeks to improve new technologies and bring down costs by coordinating national research efforts and helping to finance projects.

[32] On 9 March 2007, the EU Heads of State have agreed on a comprehensive package of measures to establish a new integrated climate change and energy policy to combat climate change and boost the EU's energy security and competitiveness as proposed in the Commissions' Communications of 10 January 2007 Limiting Global Climate Change to 2°Celsius: The way ahead for 2020 and beyond [316] and 'An Energy Policy For Europe'. Further references in: www.europarl.europa.eu...

[33] See: ec.europa.eu/transport... and europa.eu/rapid....

and innovation priorities[34]. On hydrogen for transport, the **Decision No 1982/2006/EC**[35] of the European Parliament and of the Council of 18 December 2006, concerning the **Seventh Framework Programme** of the European Community for research, technological development and demonstration activities (2007-2013), identified key issues and priorities for accelerating deployment of a wide range of applications (from portable to stationary and transport):

> *Integrated action to provide a strong technological foundation for competitive EU fuel cell and hydrogen industries, for stationary, portable and transport applications. The Hydrogen and Fuel Cells European Technology Platform contributes to this activity by proposing an integrated research and deployment strategy.*[36]

This led to the formation of a Public Private Partnership - the "**Fuel Cells and Hydrogen Joint Undertaking**" (FCHJU) - between the European Commission, industry and the research community. Formally set up by a **Council Decision No 521/2008**[37], it is responsible for implementing the **Fuel Cells** and **Hydrogen Joint Technology Initiative** (FCH JTI), the political initiative proposing this public-private partnership in fuel cell and hydrogen technologies. Work is being encouraged at local level through initiatives through a succession of **hydrogen bus** demonstration projects: **CUTE** (2001-2006), **HyFLEET:CUTE** (2006-2009), **ECTOS** (2001 - 2007), **CHIC** (2010-2016), **HIGH V.LO City** (2012 - 2019), **HYTRANSIT** (2013 - 2018) , **3MOTION** (2015 - 2020) and **JIVE** (2017-2020). The deployment of clean public transport systems in European Regions has to be accompanied by a related life cycle based sustainability assessment. Consideration of the entire life cycle for energy resources and technologies is essential to obtain correct information on energy consumption and greenhouse gas emissions during various life cycle stages, to determine the environmental advantage over conventional technologies and to develop future scenario for better sustainability. The above will be the topic of the next chapter.

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[34] See: ec.europa.eu/commission....

[35] In [324]: Decision No 1982/2006/EC of the European Parliament and of the Council of 18 December 2006 concerning the Seventh Framework Programme of the European Community for research, technological development and demonstration activities (2007-2013). Statements by the Commission, eur-lex.europa.eu....

[36] In [324], p. 19.

[37] In [322]: Council Regulation (EC) No 521/2008 of 30 May 2008 setting up the Fuel Cells and Hydrogen Joint Undertaking with EEA relevance and Council Regulation (EU) No 559/2014 of 6 May 2014 establishing the Fuel Cells and Hydrogen 2 Joint Undertaking Text with EEA relevance.

Chapter 3

Life Cycle Sustainability Assessment methodology

> *The magnitude of the challenges to science posed by sustainability concerns in the twenty-first century may well be as great as the challenges posed by food, health, and security concerns in the twentieth. It is past time to start thinking about developing the institutional capacity to fund and promote sustainability science in terms that are commensurate with the magnitude of the task ahead.*[1]

> *What is wrong with this model? Simply put, humanity can have neither an economy nor social well-being without the environment. Thus, the environment is not and cannot be a leg of the sustainable development stool. It is the floor upon which the stool, or any sustainable development model, must stand. It is the foundation of any economy and social well-being that humanity is fortunate enough to achieve.*[2]

> *Society must cease to look upon "progress" as something desirable. "Eternal Progress" is a nonsensical myth. What must be implemented is not a "steadily expanding economy", but a zero-growth economy, a stable economy. Economic growth is not only unnecessary but ruinous.*[3]

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[1] Clark, W.C. (2001), A Transition Toward Sustainability, Ecology Law Quarterly, vol. 27, no. 4, pp. 1021-1075 [57].

[2] Neil K Dawe et al. 'The faulty three-legged-stool model of sustainable development'. In: *Conservation biology* 17.5 (2003), pp. 1458–1460 [77].

[3] Solzhenitsyn, A.I., 1974. Letter to Soviet leaders. London: Index on Censorship.

3.1 The emergence of Sustainability Science

Climate change rose to the top of the political agenda more than forty years ago during **Stockholm Conference**[4] (1972), where the United Nations agreed on the urgent need to respond to the problem of environmental deterioration. Principle 24 of the **Stockholm Declaration** encouraged governments to negotiate and conclude treaties in the environmental field:

> *International matters concerning the protection and improvement of the environment should be handled in a cooperative spirit by all countries, big and small, on an equal footing. Cooperation through multilateral or bilateral arrangements or other appropriate means is essential to effectively control, prevent, reduce and eliminate adverse environmental effects resulting from activities conducted in all spheres, in such a way that due account is taken of the sovereignty and interests of all States.*[5]

Later, the publication of the **World Conservation Strategy**[160] in 1980 marked a shift from the traditional focus on cure toward a concern for the wider pressures affecting the natural environment and it confirmed a growing belief that the assimilation of aims of both **conservation** and **development** was the key to a sustainable society.

> *The Strategy is intended to stimulate a more focussed approach to living resource conservation and to provide policy guidance on how this can be carried out. It concentrates on the main problems directly affecting the achievement of conservation's objectives; and on how to deal with them through conservation. In particular, the Strategy identifies the action needed both to improve conservation efficiency and to integrate conservation and development.*[6]

> *Conservation and development have so seldom been combined that they often appear-and are sometimes represented as being-incompatible.*[7]

It first enunciated, but not clearly defined, the concept of **sustainable development**, which was later expanded by the **World Commission on**

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[4] At the United Nations Conference on the Human Environment held at Stockholm, the international community adopted the Stockholm Declaration on the Human Environment, U.N. Doc. A/CONF.48/14/Rev.1 (1972) in [349]

[5] Stockholm Conference [349], at Art. II, princ. 24.

[6] World Conservation Strategy: Living Resource Conservation for Sustainable Development [160].

[7] Ibidem.

Environment and Development (WCED), the Brundtland Commission, in 1987 [37].

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*[8]

Moreover, It developed guiding principles for sustainable development, as it is generally understood today, that were incorporated in the **Agenda 21 action plan** that emerged from the **United Nations on Environment and Development** (UNCED) in 1992, and declared it as the guiding principle for the 21st Century [348].

> ***Sustainable development*** *must be achieved at every level of society. Peoples' organizations, women's groups and non-governmental organizations are important sources of innovation and action at the local level and have a strong interest and proven ability to promote sustainable livelihoods. Governments, in cooperation with appropriate international and non-governmental organizations, should support a community-driven approach to sustainability.*[9]

> *Human beings are at the centre of concerns for* ***sustainable development****. They are entitled to a healthy and productive life in harmony with nature.*[10]

> *In order to achieve* ***sustainable development****, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it.*[11]

From the efforts to address these tensions, research and applications program has begun to emerge, leading to a research agenda called **sustainability science**[12] as appears in the report **Our Common Journey** (OCJ) written by the National Academy of Sciences [69]. The term was coined by (Clark, 2001) in his seminal paper "**A Transition toward Sustainability**". As an emerging field of science, it has an active solution-oriented research agenda,

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[8] Ibidem.

[9] In [348].

[10] Ibidem.

[11] Ibidem.

[12] National Research Council 1999. Our Common Journey: A Transition Toward Sustainability in [69].

a theoretical perspective in coupled socio-environment systems, with the aim of understanding the fundamental character of interactions between nature and society and of encouraging those interactions along more sustainable trajectories. The OCJ report explored the following definition of a sustainability transition:

> *For a successful **transition to sustainability**, the world must provide the energy, materials, and information to feed, house, nurture, educate, and employ many more people than are alive today- while preserving the basic life support systems of the planet and reducing hunger and poverty*[13]

. At institutional level, during the **World Summit on Sustainable Development** (WSSD) [14] in 2002[152], global commitment to sustainable development was further strengthened. Unlike its predecessor, it was primarily concerned with implementation rather than with new treaties and targets.

> *Identify specific activities, tools, policies, measures and monitoring and assessment mechanisms, including, where appropriate, **life-cycle analysis** and national indicators for measuring progress, bearing in mind that standards applied by some countries may be inappropriate and of unwarranted economic and social cost to other countries, in particular developing countries.*[15]
>
> *Develop production and consumption policies to improve the products and services provided, while reducing environmental and health impacts, using, where appropriate, science-based approaches, such as **life-cycle analysis**.*[16]

In 2012, Sala et al. [275], in their review paper, defined sustainable science as:

> *solution-oriented discipline that studies the complex relationship between nature and humankind, conciliating the scientific and social reference paradigms which are mutually influenced- and covering multi temporal and spatial scales. The discipline implies a holistic approach, able to capitalize and integrate sectorial knowledge as well as a variety of epistemic and normative stances and methodologies towards solutions' definition.*[17]

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[13] Ibidem.

[14] held in Johannesburg, South Africa, 26 August - 4 September 2002, was a ten-year review of the 1992 UN Conference on Environment and Development (UNCED).

[15] In [152].

[16] Ibidem.

This definition implies that ontological, epistemological and methodological aspects are interlinked and are necessary to define the scientific backbone of the new discipline. In order to provide a synthesis and to operationalize sustainability, I charted in Figure 3.1 a conceptual framework and relevant terminology adapted from Sala et al.[275], showing the hierarchical differences among each terms.

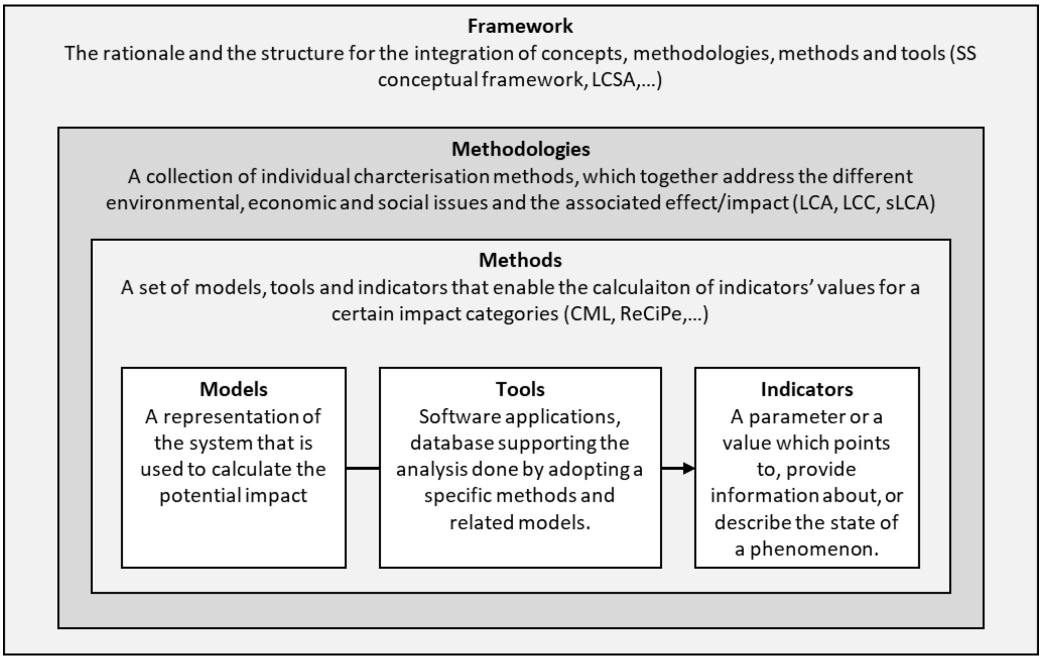

Figure 3.1: The terms are reported highlighting the hierarchical relationship between them. The framework definition is the key level for setting the rationale and the structure for the further integration of single methodologies, methods, models, tools and indicators (adopted from Sala et al.[275]).

This chapter focusses only on methodology and related methods which together link science with actions. Such putting into action is substantiated in **calculating the environmental impacts** of providing goods and services (generally termed "**products**") to society, with the aim of acquiring a better insight into complex problems of sustainability. I distilled out the underpinnings of the above calculations, extrapolating the necessary preconditions that form the building blocks of the sustainability methodology. The starting point is to apply the **life cycle metaphor** to product/service realization. The life cycle perspective, borrowed from biology, means that all processes requires to perform the function of the product are considered. In this view, a producers can be held responsible for their products **from cradle to grave** and therefore, should develop products, which have improved performance in all stages of the product life cycle as shown in Figure 3.2.

The next step is to implement the **computational structure** that is able to quantify all environmental impacts of a product during its entire life cycle. It numerically defines the relationships of the individual subsystems to each other in the delivery of the final product. These numerical relationships become the source of "**proportionality factors**", which are quantitative relationships that reflect the relative contributions of the subsystems to the total system, in terms of environmental burdens. The next section introduces the ISO-standard LCA method, including the description of the required steps to carry out a LCA study. The following and last sections is about the well-to-wheel (WTW) analysis used to compare alternative transportation mode, taking into consideration only the fuel provision pathway (i.e. the production stage is not considered). The comparison between LCA and WTW is reported to complete the picture.

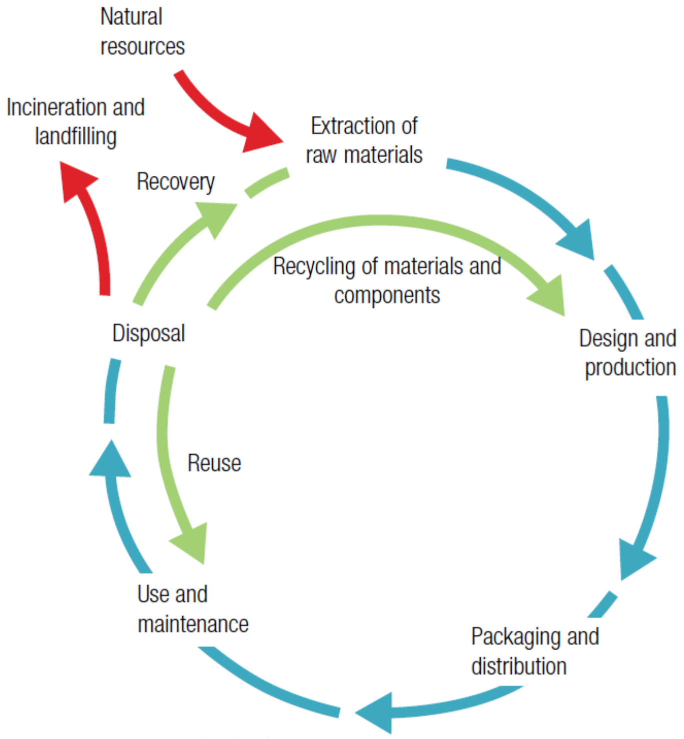

Figure 3.2: Life cycle thinking also means taking account of the environmental, social and economic impacts of a product over its entire life cycle (from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling) and value chain, from cradle to grave. Source: [263].

3.2 The concept of environmental indicator

The multi-dimensional concept of sustainable development may refer to a potentially large number of programmes and initiatives. The main drawback of such a concept is that it requires an ungainly amount of mostly physical data for its assessment. Such information does not carry the same suggestive power as aggregate monetary indicators. Also, physical data sets of levels of activities do not reflect the relative importance of these activities as do monetary indicators: such indicators are weighted by the price system that, in its turn, reveals individual preferences according to existing supply and demand patterns. On the other hand, the controversiality of valuation in monetary terms arises as the question of externality and non-marketability comes to the fore. According to Sen [282] the 'The GNP captures only those means of well-being that happen to be transacted in the market, and this leaves out benefits and costs that do not have a price-tag attached to them'. However, there are compromises between the desire to supply nutshell information to policy makers and the need for transparency in data measurement and interpretation. Such transparency is only possible, if the original concerns that triggered data collection can be readily linked unequivocally to the data and indictors actually compiled.Bartelmus [17] suggested four main categories of data/indicator systems or frameworks that could address the integration of environmental and economic concerns in planning and policy making.

3.2.1 Accounting systems of environmental-economic performance

National accounts provide the most widely used indicators for the assessment of economic performance, trends of economic growth and of the economic counterpart of social welfare. However, two major drawbacks of national accounting have raised doubts about the usefulness of national accounts data for the measurement of long-term sustainable economic growth and socio-economic development. As argued by Sen [282], the question of the distribution of that GNP among the population is left out the balance: 'It is, of course, possible for a country to have an expansion of GNP per head, while its distribution becomes more unequal, possibly even the poorest groups going down absolutely in terms of their own real incomes'[282].
In 1993, the United Nations Statistics Division (UNSTAD) elaborated a universally adopted System of National Accounts (SNA) to provide a rigorous framework for economic statistics and indicators. However, conventional accounts neglected the role of natural capital in economic growth which is a key concern in the current sustainability discussion. The proposed System of

integrated Environmental and Economic Accounting (SEEA) addresess this omission by incorporating alternative or adjusted valuations of non-marketed environmental processes and impacts into the national accounts.

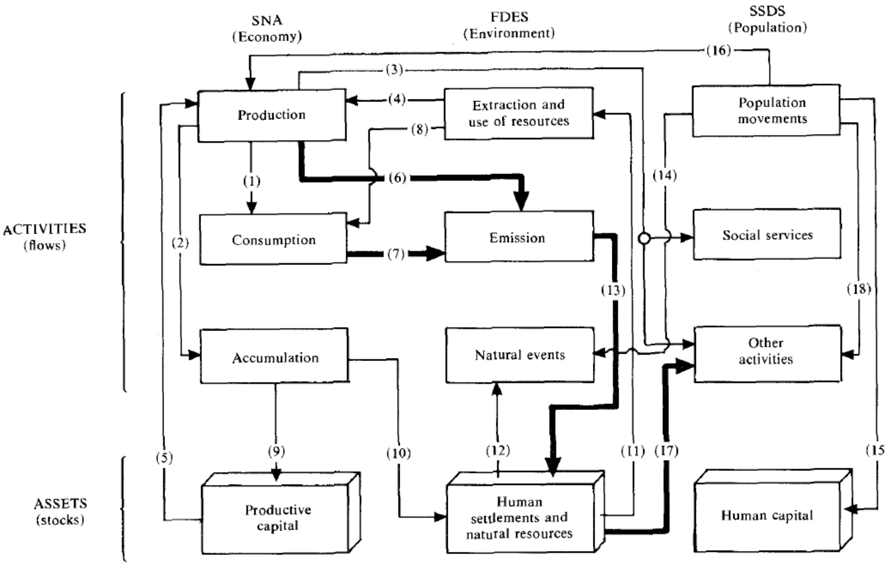

Figure 3.3: A new accounting system for environment for the evaluation of economic and natural assets [16].

Bartelmus summarises the three main dimensions (see Figure 3.3).

- Contingent valuation of potential damage resulting from depletion and degradation.
- Maintenance costing of environmental depletion and degradation; and
- Market valuation of economic natural assets and their changes describing the state (stock) and trend (flows);

Integrated 'green' accounts provide the appropriate framework for indicators that assess the availability and consumption or use of different types of produced and natural capital, in physical and monetary unit.

3.2.2 Frameworks for environmental statistics

National accounts are rigorously defined systems of economic statistics. The system character is expressed in accounting identities and balance sheets, derived from macroeconomic theory and use of a common numéraire, the price, for adding up commodities and services.

Environment statistics are multi-disciplinary in character, their sources are dispersed, and a variety of methods are applied in their compilation. More importantly, no general theory for connecting stocks, flows and structural changes of the population or the environment is available, a natural numéraire is lacking and, though some statistical standards exist, they are far from being commonly applied.

Frameworks, therefore, have been developed for listing statistical topics in a sequence of activities, impacts and (social) responses rather than formulate causal relationships among those topics. For the above reasons, the United Nations [115] **Framework for the Development of Environment Statistics** (FDES) takes a board integrative view incorporating social, demographic and economic statistics that are related to environmental concerns. No attempt is made, therefore, to base integrated accounting on a complete model of the environment. The contents of the FDES are termed 'statistical topics'. They describe those aspects of general environmental concerns which can, at least theoretically, be undergone to statistical assessment. The determination of statistical topics under each information category constitutes an important step towards the identification of relevant statistical variables for each topic. The information categories under which the statistical topics are presented in FDES, shows the definitional characteristics of both the information categories and their respective statistical topics.

3.2.3 Ad-hoc nomenclatures and lists of environmental indicators

The 1992 Earth Summit recognized the important role that indicators can play in helping countries to make informed decisions concerning sustainable development. This recognition is articulated in Chapter 40 of Agenda 21 which calls on countries at the national level, as well as international, governmental and non-governmental organizations: '[to] develop the concept of indicators of sustainable development in order to identify such indicators' [348]. Therefore, the definition of such indicators could provide a solid basis for decision-making at all levels. Moreover, Agenda 21 specifically calls for the harmonization of efforts to develop sustainable development indicators at the national, regional and global levels, including the 'incorporation of a suitable set of these indicators in common, regularly updated, and widely accessible reports and databases' [348]. In response to this call, the **Com-**

mission on Sustainable Development (CSD)[18] approved in 1995, the **Programme of Work on Indicators of Sustainable Development** and called upon the organizations of the UN system, intergovernmental and non-governmental organizations with the coordination of its Secretariat to implement the key elements of the work programme. The main objective of the CSD Work Programme was to make indicators of sustainable development accessible to decision-makers at the national level, by defining them, elucidating their methodologies and providing training and other capacity building activities. At the same time, it was foreseen that indicators as used in national policies could be used in the national reports to the Commission and other intergovernmental bodies. The first version was finalised in 1996 with the suggestion of 134 indicators [350] and put to a field test. The Nineteenth Special Session of the General Assembly held in 1997 [251] for the five-years review of UNCED affirmed the importance of the work programme on indicators of sustainable development (as contained in para. 111 and 133.b of the Programme for the Further Implementation of Agenda 21) in coming up with a practical and agreed set of indicators that are suited to country-specific conditions and can be used in monitoring progress towards sustainable development at the national level. The following step has been to conceive a list of ‘representative’ indicators for each of the above-mentioned topics.

3.2.4 Policy framework: Agenda 21

A policy framework usually focuses on agreed concerns and priorities, and programmes addressing those concerns. However, the relevance of data organized within such a framework cannot be taken for granted. Lifting the political statements to an organized data collection requires a definitional effort as emerged in a UN report on the development of statistical concept of human settlements [64]. The FDES was further revisited to present the related environmental concerns in terms of statistical topics, variable and indicators. The CSD used a similar approach to properly arrange programmes and activities of the UNCED’s Agenda 21 in an organizing framework. The CSD recognised the need to group those programmes into more manageable ‘clusters’, as reported during the first session of the CSD held in June 1993 [63]. The clusters, considered as basis for a ‘multi-year thematic programme work’ [63], are:

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[18] The General Assembly, in its resolution 47/191 of 22 December 1992, requested the Economic and Social Council to establish a high-level Commission on Sustainable Development to ensure effective follow-up to the Conference on Environment and Development (1992).

- Toxic chemicals and hazardous wastes (chapters 19, 20 and 22);
- Atmosphere, oceans and all kinds of seas (chapters 9 and 17);
- Land, desertification, forests and biodiversity (chapters 10-15);
- Roles of major groups (chapters 23-32); Health, human settlements and fresh water (chapters 6, 7, 18 and 21);
- Decision-making structures (chapters 8 and 38-40);
- Education, science, transfer of environmentally sound technologies, co-operation and capacity-building (chapters 16 and 34-37);
- Financial resources and mechanisms (chapter 33);
- Critical elements of sustainability (chapters 2-5);

Still, Agenda 21 continues to provide a viable policy framework for achieving sustainable development worldwide and, therefore, plays a key role in any international effort to develop, compile and disseminate environmental and/or sustainable development indicators. One way adopted to capture most of the above-descripted approaches and listings of environmental and sustainable development indicators has been to match the concerns of potential 'data users' as reflected in Agenda 21 with the framework for environmental 'data production'[19], the FDES, endorsed by the international statistical community [291][20]. The result was a framework for indicators for sustainable development (FISD) which fosters the systematic transition from global policy concerns to more operational topics and, hence, via FDES, to statistical variables. Two elements interacted to provide the foundation for FISD: the political stance of the Agenda 21, which embodies a comprehensive blueprint for sustainable development[21] , and the endorsement of FDES as statistical methodology for a comprehensive data collection, processing and dissemination. The established framework has permitted the monitoring of changes in

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[19] The two quoted terms data users and data producers are reported in [64] to underscore the interdisciplinary character of environment statistics and the variety of actors involved in process, which call for a comparative analysis of data availability and the co-ordination of data collection, processing and dissemination.

[20] The Statistical Commission, at its twenty-third session in 1985, welcomed the publication of the FDES and requested the UNSTAT to promote its application (see paras 83 and 86).

[21] The sustainable development, according to UN, is seen as a unifying umbrella concept under which a broad spectrum of United Nations activities in the economic, social and environmental/natural resources fields related to a common over-arching goal.

the state of the environment and of the causes of depletion and degradation (namely, pressures), and policy responses to those changes. The reporting scheme paved the way for successive initiatives aimed at the standardisation of assessment methodologies, applying the principles of sustainable development at an operational level, thus reconciling the economic, social and environmental needs.
Figure 3.4 summarizes the above-described approaches showing the building blocks and related information interfaces. More importantly, the model incorporates four main information categories: the impacts-and-effects column reflects the measurement aspect of indicators, presenting the results of an economic activity and its impacts or state; the activities/events column relates to the causes (or pressures) of depletion and degradation, mainly from production, consumption and natural disasters; the responses column identifies the responses of resource management, pollution monitoring and control, or macro-polices of SD; the inventories/stock correlates the capacities of the economy and nature in terms of produced capital and natural assets.

In April 2001, the Ninth Session of the CSD approved the report 'Indicators of Sustainable Development: Guidelines and Methodologies' [80] that has been prepared as the culmination of the CSD Work Programme on Indicators of Sustainable Development initiative (1995-2000). It provides a detailed description of key sustainable development themes and sub-themes and the CSD approach to the development of indicators of sustainable development for use in decision-making processes at the national level. Reference is made to some or all of the following topics:

- climate change.
- natural disasters;
- production, consumption patterns/technologies;
- activities of economic sectors;
- ecosystems. Acidification, eutrophication, biodiversity;
- quality of environmental media (air, water, land): pollution and wastes;
- renewable and non-renewable resources;
- human needs (health, food, housing, education, other socio-cultural needs and aspirations);
- population;

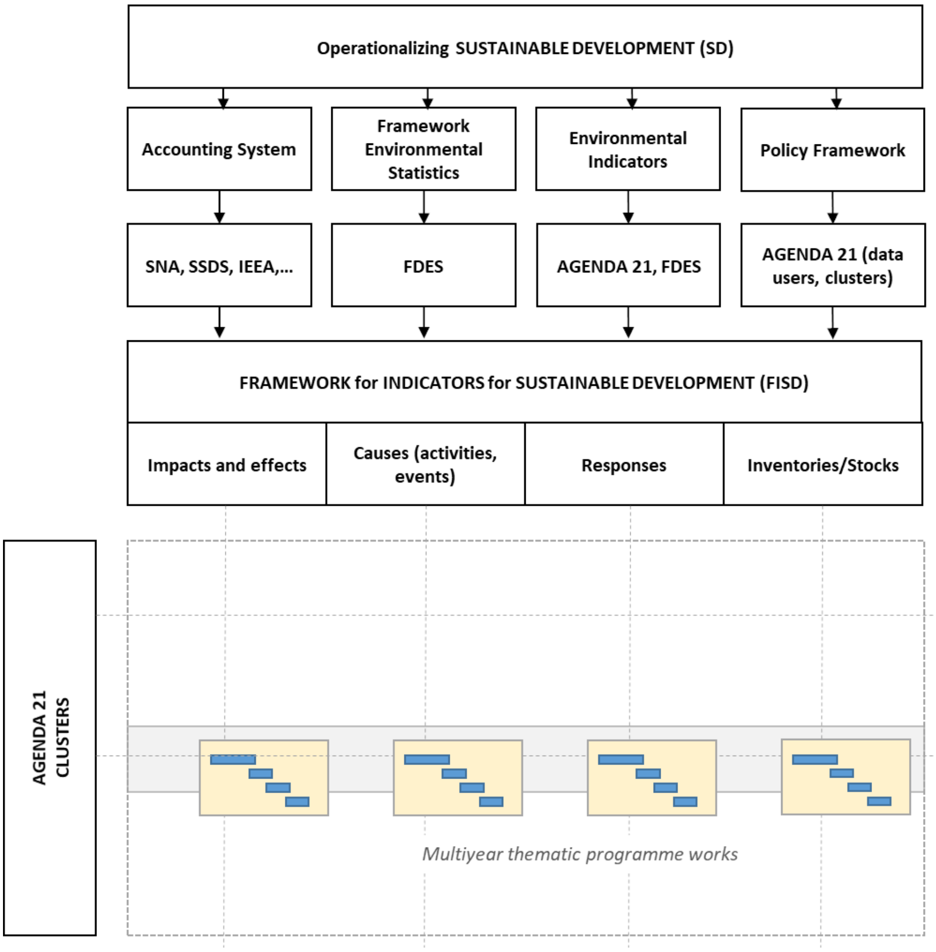

Figure 3.4: Framework for indicators for sustainable development and multi-years themaric programme works.

The conceptual separation into driving force, state, and response indicators was removed in the final version [80].

3.3 Measuring the state of the environment

Operationalizing sustainable development means to provide measures of nature's and society's long-term ability to survive and prosper together, as well as to guide planning and policy making in the transition to sustainable livelihoods [31]. Daly [75] has suggested four preliminary operational principles of sustainability, with emphasis on natural resources' constraints and consumption patterns. However, the environmental considerations, especially those associated with human health, dominate the current political and scientific discourse[22]. The measure of the state of the environment is, therefore, necessary: 1) to determine the present and future **states of ecosystems**, 2) to establish empirical limits of variation in natural resources, 3) to diagnose abnormal conditions and identify issues in time to develop effective mitigation and, 4) to identify potential agents of abnormal change. The foundation underlying these objectives is the concept of **ecological integrity** that can facilitate and structure the **monitoring** efforts.

3.3.1 Ecological integrity

The concept of **ecological integrity** was introduced by Aldo Leopold [190] who stated that 'A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends otherwise' (p.224-225). Decades later, the term has been incorporated in several legal documents, such as the US Clean Water Act (CWA)[23] in 1972 and the Parks Canada Act[24] in 1988. The United Nations, during the Stockholm Conference of 1972, recognized that 'natural ecosystems, must be safeguarded for the benefit of present and future generations' [349]. Since the late 1990s, on the wave of the Rio Declaration (1992), practical and measurable approaches to ecological integrity spurred significant academic debates. In that, Principle no. 7 of the Declaration avows: 'States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem' [270]. The corpus of EU nature conservation law is quite neatly confined to the 1979 Wild Birds and 1992 Habitats Directives. it pursues an 'enclave' strategy, requiring the active designation of areas enjoying special nature conservation status, within which special rules of environmental protection are to apply. The key means of legal pro-

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[22] Environmental degradation is undermining the achievement of development goals and contributes to a growing gap between rich and poor countries. The Earth planet is getting warmer and that warming is primarily due to human emissions of carbon dioxide and other greenhouse gases. Serious and irreversible impacts on human and natural systems will be devastating at a planetary scale. The Europena Commission stated: 'Even if all emissions from human activities would suddenly stop, the climate would continue to change. However, continued unabated, anthropogenic pollution and greenhouse gas emissions will further increase global warming, ocean acidification, desertification and changing climate patterns' link ➡.

[23] The preamble asserts: The objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters.

[24] In the document the concept of ecological integrity was formalized as follows: ecological integrity means, with respect to a park, a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes" link.

tection is that of preventing national competent authorities from permitting plans or projects which might adversely affect sites of high ecological value designated under the 1979 and 1992 Directives. To this end, Article 6(3) of the habitats Directive is the key provision, requiring that an 'appropriate assessment' must be carried out in respect of any plan or project which might significantly affect such a site [217].

> *Maintaining and enhancing the integrity and resilience of the environment and ecosystems is critical for the long-term effectiveness of climate mitigation and adaptation*[25]

[55]. With an increasing demand for natural resources in a world of rapid biodiversity loss and environmental changes [45], [114], including the recent COVID-19 pandemic outbreak, **ecological integrity** upraises to a holistic concept and framework that encompasses several interwoven dimensions. First of all, **ecological integrity** recognizes the concept of **ecosystem** (i.e. ecological system) as the basic unit of enquiry. Tansley, in his seminal paper published in 1935 [297], regarded the **ecosystem** as including 'not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome-the habitat factors in the widest sense' [297]. The study of **ecosystems** requires understanding relationships between structure[26] and function[27] within the system as recalled by Odum [235]. Additionally, the above definition embodies a measurable suite of ecological conditions relevant to a collection of organisms [70], [276], including inorganic 'factors' [297], [296]. In other words, **ecosystems** are not randomly placed on Earth [283] nor isolated [297] but are open systems with significant linkages to neighbouring systems (via energy transfers and nutrient flows mediated by physical, chemical, and biological processes) [258]. **Ecological integrity** focuses on conserving native biodiversity (i.e.

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[26] Odum [235] articulated the the comcept of Structure:'(1)The composition of the biological community including species, numbers, biomass ,life history and distribution in space of population ; (2) the quantity and distribution of the abiotic (non-living) materials such as nutrients, water,' etc.; (3)the range, or gradient, of conditions of existence .such as temperature, light, etc. Dividing ecological structure into these three division is, of course, arbitrary but I believe convenient, for actual study of both aquatic and terrestrial situations'.

[27] Function is articulated as follows [235]: '(1)The rate of biological energy flow through the ecosystem, that is, the rates of production and the rates of respiration of the populations and the community; (2) the rate o material or nutrient cycling, that is, the biogeochemical cycles; (3) biological or ecological regulation including both regulation of organisms by environment, (as, for example, in photoperiodism) and regulation of environment by organisms (as, for example,'in nitrogen' fixation by 'microorganisms)'.

biological diversity[28]) that can be formally defined as 'the variety and variability among living organisms and the ecological complexes in which they occur' [65]. Additionally, because 'these items are organized at many [biological] levels", biodiversity "encompasses different ecosystems, species, genes, and their relative abundance' [65]. Other insightful analyses confirm that biodiversity can be monitored at multiple levels of organization (i.e. genes, species, and ecosystems), and at multiple spatial and temporal scales: 'Big questions require answers from several scales' [232]. Besides, [262] argue that: '[t]he breadth of the concept reflects the interrelatedness of genes, species, and ecosystems', therefore, 'altering the make-up of any level of this hierarchy can change the others', and 'these linkages must be taken into account in management policies' [262].

The hierarchical organizations are useful tool for understanding **pattern of ecosystems**. Reid et al. [262] proposed a model of three distinct hierarchies (namely, taxonomic, genetic, and ecological) that are linked at the species-genome-population levels, but not at any other levels. Klijn et al. [182] presented a hierarchical paradigm of ecosystems ranked in spheres. This framework enables ecosystem classification and mapping at different spatial scales on behalf of environmental policy. Klijn [181] proposed three hierarchies that are relevant with special reference to ecology: system levels, organizational levels, and scale levels. According to the authors the three hierarchies should be regarded as three axes in a conceptual space to frame an individual ecosystem in a domain of analysis. The above-described approaches deal with the definition, recognition, and representation of ecosystems over time, space, and environmental gradients. More importantly, ecosystems lack crisply defined boundaries, thus making the modelling attempt quite arbitrary and aimed at study. Levy argued that the 'scientific worker' [191] tends to separate 'matter occupying space and time" '[191], treating the objects as'"independent and isolated entities is a public affair' [191] or, put differently, 'isolated practically from the rest of the system, and definitely and completely isolated in time from their earlier history that involves the stages leading up to the present situation'[29]. Thus, ecosystems form a continuum

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[28] It is worth to clarify the difference between the two terms - integrity and diversity - in the current ecological context. Whereas diversity is collective property of system elements, integrity is synthetic property of the system [7]. Besides, diversity can be expressed simply as the number of kind of items. On the other hand, integrity refers to the conditions under which a biota can be maintained by its natural and biogeographic processes. Such processes occur at organizational levels above and below its own level [232]. Therefore, the concept of integrity should account for the influence of processes at multiple organizational levels and multiple spatiotemporal scales, as argued in the subsequent passages.

[29] He continues: 'Science, like common sense, sets out in the first instance to search for systems that can be imagined as isolated from their setting in the universe without

that extends to encompass all of the biosphere. The boundaries are drawn at a specific superorganism level, exhibiting the kinds of characteristics that are purposive of analysis. Two distinct trends are apparent: one treats ecosystems as composed of well-defined, discrete, integrated units which can be variously considered in terms hierarchical organization, whereas the other holds that ecosystems change continuously and are not differentiated, except arbitrarily, into sociological entities. Arthur O. Levejoy argued that: '[t]here are not many differences in mental habit more significant than that between the habit of thinking in discrete, well-defined class-concepts and that of thinking in terms of continuity, of infinitely delicate shadings- off of everything into something else, of the overlapping of essences, so that the whole notion of species comes to seem an artifice of thought not truly applicable to the fluency, the so to say universal overlapping of the real world' [200]. The terms continuous, continuity, and continuum referring to ecosystems have a long history and have been used in diverse context. [200] refers to the principle of continuity derived from Plato and successively defined by Aristotle in his work 'The Categories'[30]. McIntosh [216] conceptualized the general idea of continuity as 'implying an uninterrupted series of elements passing into one another, asserting that no sharp transitions are obvious between communities and that species composition changes gradually from place to place or time to time' [216][31]. Moreover, he quoted a formal definition from [71]: '[a]n adjectival noun referring to the situation where the stands of a community or large vegetational unit are not segregated into discrete and objectively discernible units but rather form a continuously varying series'. Vannote et al. [353] applied such principle to stream ecosystems, recognizing that '[m]any communities can be thought of a continua consisting of mosaics of integrading population aggregates' [353] (see Figure 3.5).

Bjornerud [22] argued that '[for] this reason there is no single appropriate scale at which to investigate the biosphere. Organisms at all scales contribute to the maintenance of the whole, in ways appropriate to their positions in the hierarchy' [22]. **Ecological integrity** comprises the supporting processes, namely gene flow, disturbances, and nutrient cycling [232]. These processes

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appreciably disturbing their structure and the process they present and [t]he isolation is only tentative in thought, and is conducted for purposes of discussion in the first instance, and for convenience in detailed examination' [191].

[30] He argues: 'That all quantities - lines, surfaces, solids, motions, and in general time and space - must be continuous, not discrete, Aristotle maintained' [200].

[31] He also reports the terms vegetational continuum, that is plainly described as 'a gradient of communities in which species are distributed in a continuously shifting series of combinations and proportions in a definite sequence or pattern' [216].

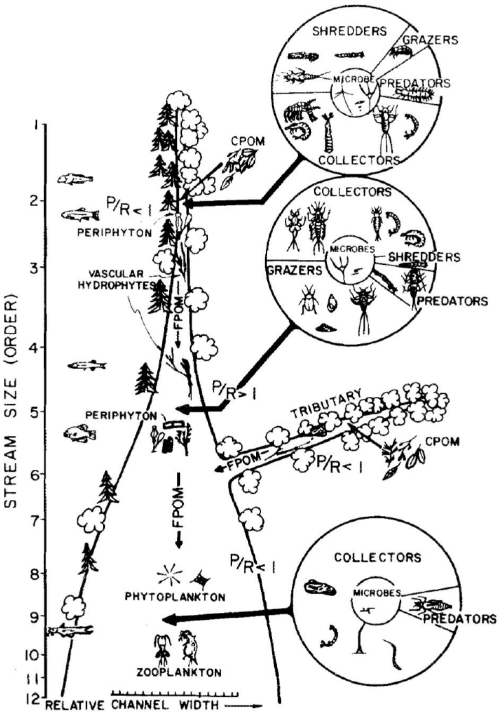

Figure 3.5: River Continuum Concept provides a framework for integrating predictable and observable biological features of lotic systems. From headwaters to mouth, the physical variables within a river system present a continuous gradient of physical conditions. This gradient should elicit a series of responses within the constituent populations resulting in a continuum of biotic adjustments and consistent patterns of loading, transport, utilization, and storage of organic matter along the length of a river. Implications of the concept in the areas of structure, function, and stability of riverine ecosystems can be drawn.

are measured as rates (i.e. amount of change per unit of time) as reported in [170]. Tracing the flow of matter and energy through the processing compartments (producers, herbivores, carnivores, detritus, and detritivores) can be used to construct a model of the systems. The adverse effects are, thus, inferred from changes in processing rates of various compartments, irrespective of the identities of the resident species [41]. These processes responses have been thoroughly reviewed by [234], who presented four categories of trends expected in stressed ecosystems, namely: energetics, nutrient cycling, community structure, and general system-level trends. Structural and processing changes are tightly coupled and, hence, their importance have to be balanced. In one case, many spices share very similar functions, and this collectively guarantees significant functional redundancy for the involved ecosystems. On the other case, functional capacity could be impaired without lost of species. Thus, the functional measurements would provide an earlier warning of major changes in the ecosystem community than would structural measurements [41]. The assessment of both functional and structural properties could provide decision-makers with a quantitative picture of the mode and tempo of change in ecosystems (further details are provided in [235]). In sum, **ecological integrity** encompasses element **composition** (measured as the number of items) and **process** performance (measured as rates) examined over **multiple levels of organization** [7]. The above-described characteristics of **ecological integrity** may be reflected in a recent oft-cited definition [242]:

> *[T]he ability of an **ecological system** to support and maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region. An ecological system or species has integrity or is viable when its dominant ecological characteristics (e.g., elements of composition, structure, function, and ecological processes) occur within their natural ranges of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human disruptions*[32]

The above definition echoes the concept of **integrity objective** elucidated in [172] as 'the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region' [172]. A similar definition was also given by [40]: '[b]iological integrity may be defined as the maintenance of the community structure and function characteristic of a particular locale or deemed satisfactory to society' [40]. Frey [116], referring to water, defined integrity as 'the capability of supporting and maintaining a balance, integrated, adaptive community of organisms having a composition and diversity comparable to that of the natural habitats of the region'. Therefore, the summation of chemical, physical and biological integrity can correspond to **ecological integrity**, as argued by Karr et al. [172]. Similarly, Rapport [258] advocates the concept of **ecosystem health**, drawing the conclusion that there are no strictly objective criteria for judging health and recognizing that a healthy system must embody certain basic features, both structural and functional, to manifest **ecosystem integrity** [257]. [44] underscored the difficulties of applying the concept of health to ecosystems, arguing that a compilation of observations on systems states in itself does not guarantee the comprehension of way the systems actually works (i.e. fallacy of induction). He, alternatively, suggested that the optimal state, in terms of neo-Darwin fitness, could be applied to ecosystems. A system possessing **integrity** can withstand, and recover from, most perturbations imposed by environmental processes, as well as major disruptions imposed by man[33]. That is, **ecological integrity** promotes resilience (namely, the capacity to 'absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks', [356]). The measures of **ecological integrity** can, in this view, represent an important source of information to foster an effective environmental and nature management. However, the selection of the gauging points poses a significant challenge to scientists engaged in the design of a diagnostic monitoring program.

3.3.2 Environmental monitoring

The concept of **monitoring** was introduced for the first time[34] during the Stockholm Conference of 1972 [349]. It appears in the **Framework for environmental action** and in the subsequent Recommendations. The function of monitoring is defined as follows. 'to gather certain data on specific environmental variables and to evaluate such data in order to determine and predict important environmental conditions and trends' [349]. However, a literature survey shows that one of the first systematic examination of the monitoring concept was undertaken by the Study of Critical Environmental Problems (SCEP) in 1970. The term was informally defined as: 'systematic observations of parameters related to a specific problem, designed to provide information on the characteristics of the problem and their changes with time' (cited Harvey in [145]). SCEP identified two distinct functions of monitoring. The first is concerned with biota monitoring and measurements to provide essential data for research seeking to explain the workings of the environmental system. The second is concerned with monitoring in the sense of recognizing significant trends in the pattern of variation over space and time, as input to environmental management. This distinction puts forward the conceptual precursors of descriptive and regulatory monitoring, respectively. This early work, which was incorporated in the establishment of the Global Environmental Monitoring System (GEMS)[35], has been reviews by Martin

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[33] It must be clearly said that ecosystems have become severely affected as a result of stress imposed directly, or indirectly, from human activity. The capacity of recovery from anthropogenic disturbances is meant to the extent such perturbations do not tip the ecosystem, thus making this capacity ineffective in the intent.

[34] Harvey [145] revealed that before the Stockholm Conference of 1972 the term monitoring is conspicuous only by its absence.

[35] The Global Environment Monitoring System (GEMS) grew out of the 1972 Stockholm Conference on the Environment. At that world conference, governments requested the establishment of a global monitoring program that could determine the status and trends of key environmental issues. It was in 1975, following the instruction of the UN Conference

et al. [213]. As part of the preparation for the Stockholm Conference, an intergovernmental working group on monitoring (IWGM) was convened in late 1971 , which furnished another early definition of environmental monitoring: 'system of continued observation, measurement and evaluation for defined purposes' (cited in [213]). However, [213] claimed that such definition draws no distinction between descriptive monitoring and regulatory monitoring, nor does it make clear what is meant by 'evaluation'. In the light of the Stockholm Conference, the authors reviewed the concept of evaluation that is now taken to refer a two-stage process: the first is the validation of data ("provide the basis for identification of the knowledge needed" [349]); the second is the interpretation of data ('to determine and predict important environmental conditions and trends' [349]). The concept of **environmental monitoring** has undergone considerable development over the last decades. The evolution of the terminology, related to monitoring, has been prevalently steered by the implementation of programmes coordinate by the United Nations (UN). With reference to the objectives of GEMS, these encompass both the descriptive and regulatory senses. Harvey [145] argues that the very essence of monitoring is that it is action-oriented: 'it is designed to tell how well regulations are working and how far standards are being met' [156]. Moreover,Harvey [145] proposed to avoid similar terms like **survey**[36] and **surveillance**[37] and stick to the term monitoring, used in an all-encompassing way. Additionally, Harvey concludes that due to the complex nature of environmental management, monitoring is, thus, essential to make good environmental decisions. Meijers [221] summarised the above positions into the following definition:

> *Monitoring is the process of repetitive observing, for defined purposes on one or more elements of the environment according to prearranged schedules in space and time and using comparable methodologies for environmental sensing and data collection*

. Often-used modifiers are attached to monitoring to convey a different connotation: biological, ecological, environmental. As clarified by [221], **biological monitoring** has a public health objective. Strictly speaking [155], it measures the **exposure** to chemical agents in various biological media in

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on the Human Environment, that UNEP moved into the field of environmental monitoring by establishing at its Nairobi Headquarters a Programme Activity Centre for GEMS.

[36] Holdgate defines survey as a programme of measurement that defines a pattern of variation of a parameter in space.

[37] Holdgate defines surveillance as the repeated measurement of a variable in order that a trend may be detected. It means that a survey is carried out to give a picture of the environment at one time and it may be deliberately repeated after an interval to provide useful surveillance of trends.

order to detect early adverse effects (biological monitoring of effect).

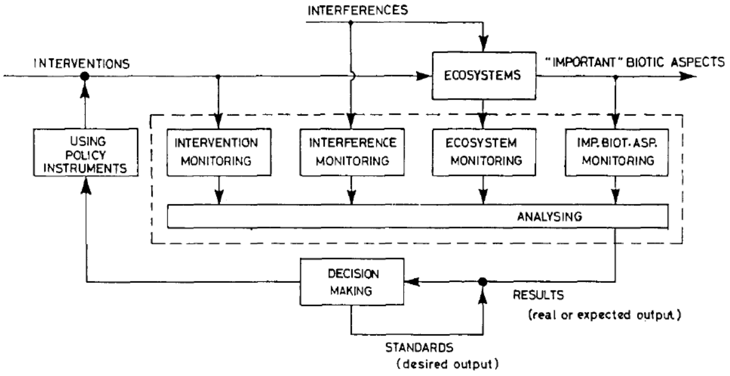

Figure 3.6: Integrated environmental monitoring programmes (i.e. the activities within the dashed line) are essential to improve environmental policy ([300].

The **environmental monitoring** primarily deals with recoding of changes in the environment due to human activities. These changes could involve biotic or abiotic processes, underscoring ecological process-response relations. On the other hand, **ecological monitoring** is more focussed on the recording of changes in ecosystems to determine trends that could be potentially harmful to human health.
With the basic terminology given above, **environmental monitoring** can be characterized as a scientific endeavour which attempts to organize and evaluate ecosystems (and complexes of ecosystems) for the purposes of contributing to a more effective and efficient environmental policy (see Figure 3.6).

3.3.3 Environmental indicators

The general problem of all environmental decision processes is the enormous complexity of the investigated ecosystems. The representation of the most important features of ecosystem ensembles is a prerequisite to elaborate a satisfactory projection. One method to reach such a practicable model is based on the utilization of **indicators** [223]. However, this approach is far from being without concerns. Kay, discussing **ecological integrity**, writes: 'Ecosystems are not static. Their organisation is often changing, both in the short-term and in an evolutionary sense. Furthermore any loss in organisation is often gradual. Thus it is not possible to identify a single organisational state of the system that corresponds to integrity. Instead there is a range of states for which the ecosystem is considered to have integrity' (cited in [144]). The anthropologist Rabinow highlighted further that: 'Nature reflects the accumulation of countless accidents, not some hidden harmony. Things might have turned out quite differently. Ecosystems are ever changing, dissolving, transforming, recombining in new forms'[38]. Additionally, Munn emphasizes that ecosystems are characterized by essentially stochastic processes and by dominant nonlinear mechanisms [285]. This means that ecosystems are sensitive to initial conditions (i.e. small differences in the values of variables at the outset can lead to widely diverging results) and lacks direct proportionality between cause and effect[39]. Therefore, ecosystems manifests correlation, that implies association, but not a cause-effect relation. Because of this, the use of correlation to infer causation is risky, especially as nonlinear dynamics are ubiquitous [294]. For example, Temple et al. [299] examined the variation in bird populations, as indicator of environmental changes brought about by anthropogenic disturbance. He argued:

> *[t]he effects of environmental changes on bird populations are more often influenced by one or more intermediate factors, or the* ***population changes are caused by any one or more of many interacting effects****. The existence of* ***intermediate stages*** *in the* ***cause-and-effect*** *link not only complicates our attempts to understand what is going on, but also acts to produce time lags in the appearance of the effects.*[40]
>
> *In such cases, the environmental change that causes a population change at some later time may be identified if the situation has been monitored for a sufficiently long period, with attention to* ***delays in cause-and-effect relationships****. In other situations,* ***identifying the important causal link among a large number of possibilities may be quite difficult****.*[41]

Despite the above-mentioned difficulties, several pilot projects on environmental monitoring have been undertaken under the GEMS [225]. This collective effort of the world community paved the way for the acquisition of the information needed to investigate environmental processes, and thus to understand and manage the environment and to prevent its degradation [137]. The UNEP promoted an integrated approach to environmental monitoring, as recalled in the following passage (reported in [225]):

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[38] See www.nytimes.com ....

[39] See link for a definition

> *The* ***repeated measurement of a range of related environmental variables*** *or* ***indicators*** *in the living and non-living compartments of the environment, and the investigation of the transfer of substances or energy from one environmental compartment to another. Monitoring becomes* ***truly integrated when*** *the measurements of different variables or of the same* ***variables*** *in different compartments are* ***coordinated in time and space to provide a comprehensive picture of the system under study****. The variables might include chemical substances (e.g., pollutants), geophysical processes (e.g., wind, ocean currents), biological processes (e.g., primary productivity) or other variables as may affect man, his natural resources and the climate*[42]

. An **integrate approach** is, thus, essential, in which **indicators** are some of the main building blocks in monitoring system design. The term 'indicator' traces back to the Latin verb 'indicare', meaning to disclose or point out, to announce or make publicly known, or to estimate or put a price on [139]. Indicators communicate information about progress toward social goals such as sustainable development. But their purpose can be simpler too: the hands on a clock, for example, indicate the time; the warning light on an electronic appliance indicates that the device is switched on [139]. The phrase 'environmental indicator' comprises two components: the term 'indicator' and the term 'environment'. Hammond et al. define an indicator as 'something that provides a clue to a matter of larger significance or makes perceptible a trend or phenomenon that is not immediately detectable. [...] Thus an indicator's significance extends beyond what is actually measured to a larger phenomena of interest'. **Indicators** can, thus, be used to capture complex phenomena in a simplified form. By highlighting key statistics or measurements out of large data sets, indicators facilitate communication, interpretation, and decision-making [229]. Such **environmental indicators** are used to compare a specific area with regions believed to represent undisturbed ecosystems. Standard indicators and baseline values are required in order to operationalise ecological integrity and formulate quantitative prescriptions that can be used in court. According to [210], this necessitates a very pragmatic research practice. That is, **empirical observations through quantitative indicators** appear as the only means to have access to objective reality and truth (see Figure 3.7). Research methods involve the collection of quantitative data to "build up" ecological indicators, as discussed in [210]. Clark et al. in [58] reviewed the design criteria for integrated monitoring, recognizing the centrality of reliable knowledge for effective social responses to environmental problems[43]. The authors point out that a monitoring programme is required to meet more than one set of objective and consequently the design of a monitoring system entails a very large selection of variables from which to choose a manageable subset. Therefore, they suggested to make careful choice, selecting the variables which significantly represent the net effect of several processes. These reductions have to accompanied by quality assurance procedures and regular intercomparisons of monitoring and analytical methods, aimed at guaranteeing reliable pictures of the state of the variables concerned. Furthermore, Karr, on the integrity of running waters, states: 'As technology advanced, chemical and **physical indicators** became the primary regulatory tool to protect water resources' [168] and '[w]hen combined, these metrics characterize the biotic integrity in much the same way that a battery of medical tests are indicators of individual health' [168]. However, he warns that 'good health, human, economic, or ecosystem, is not a simple function of those metrics' [168].

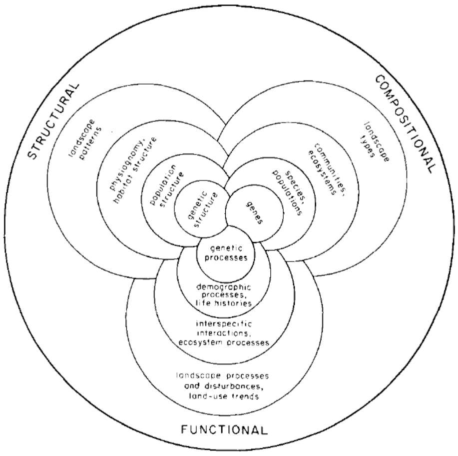

Figure 3.7: Compositional, structural, and functional biodiversity, shown as interconnected spheres, each encompassing multiple levels of organization. This conceptual framework may facilitate selection of indicators that represent the many aspects of biodiversity that warrant attention in environmental monitoring and assessment programs [232].

In [169], Karr argues that an indicator should be used only when the objectives are set appropriately in order to rate the indicator metric accordingly[44]. Karr et al. in [171] proposed five major activities that are necessary to develop effective multimetric indexes. Moreover, the authors

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[43] A sound example of the application of the integrated monitoring is reported in [30] for a network of stations to monitor the pine forests of Poland.

[44] The author reports many individual studies that demonstrate correlations, and in

distinguished between the measurement endpoint (i.e. what is measured) and the assessment points (the ecological goods and services society seeks to protect), leading to the foundation of sustainability assessment, which provides a means to compare environment state with the conditions expected in the absence of humans. In conclusion, the priorities can be summarized as follows: (1) discover the relevant properties of ecosystems associated with loss of integrity, (2) design appropriate indicators, and (3) identify levels of those indicators that can define integrity or lack thereof [210]. It requires improving the **analytical soundness and measurability of indicators**, especially by overcoming conceptual and data deficiencies, and providing a better interpretation of indicator trends[45]. Environmental indicators serve many purposes and take many forms. To be effective, however, they need to be carefully designed and subject to rigorous quality control. In many ways, indicator development can be likened to an engineering process, in that indicators must be designed to meet the user's needs, taking account of the limits and constraints of the available materials and technology (data, models, knowledge, etc.).

3.3.4 Towards standardization

Increasing needs to provide decision support and advances in scientific knowledge in the area of life cycle assessment (LCA) led to a multi-year effort to provide global guidance on environmental life cycle impact assessment (LCIA) indicators under the auspices of the UNEP-SETAC Life Cycle Initiative. As part of this effort, a specific task force focuses on improving and harmonizing LCIA cross-cutting issues as aspects spanning over several or all impact categories including spatiotemporal aspects, reference states, normalization and weighting, and uncertainties. Findings of the cross-cutting issues task force are presented along with an update of the existing UNEP-SETAC LCIA emission-to-damage framework (see Figure 3.8).

3.4 Life Cycle Assessment: a standardised approach

On the following subsections the methodology of the LCA will be addressed, in a generic approach. The main steps of a LCA are briefly described, namely:

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some case cause-effect relationships, between degradation and some biological indicator (see [112] and [298]).

[45] OECD Environmental Indicators for Agriculture – Methods and Results (Link)

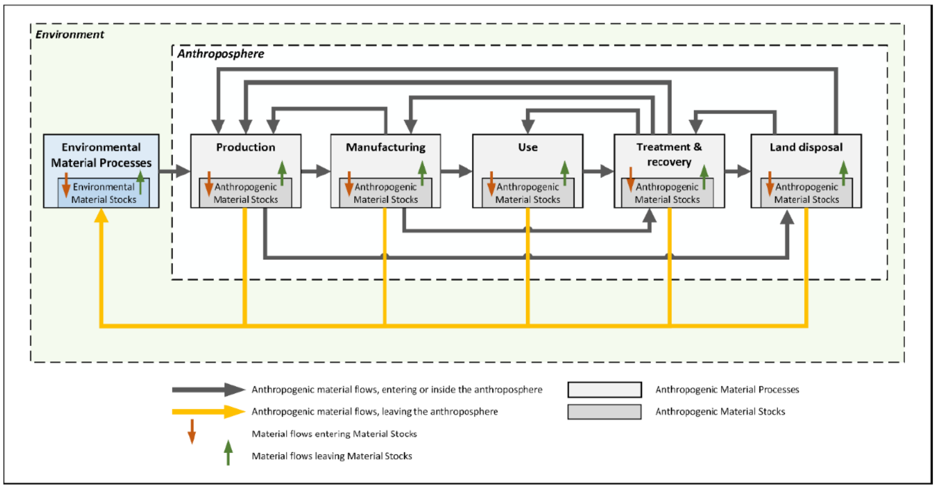

Figure 3.8: General Anthropogenic Material System , which encompasses Anthropogenic Material Processes (light grey boxes), Anthropogenic Material Stocks (dark grey boxes), Anthropogenic Material Flows (arrows) and system boundaries (dashed lines) [287].

Goal Definition & Scope, Life Cycle Inventory, Life Cycle Impact Assessment and Life Cycle Interpretation (see Figure 3.10). Life Cycle Assessment (LCA) is an analytical tool to assist making environmentally relevant decisions concerning product systems. The scope of LCA encompasses development, production, use, disposal and recycling of products for specific applications. LCA is an established, internationally-accepted method that is defined in two ISO standards (14040[90] and 14044[91]). The ISO 14040 defines LCA as follows:

> *LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle.*[46]

The core of the LCA methodology is thinking in product systems and accounting for several environmental goals simultaneously. This methodology helps to keep decision-makers aware of potential shift of burdens that may occur when applying particular individual solutions. The following paragraphs briefly describe the methodology. In LCA, the entire life cycle of the product in question is described. This description includes the extraction of resources, the production of materials and intermediates from the resources, the assembly of the product from the materials, the use of the product, and the end of life (see Figure 3.9).

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[46] In [90].

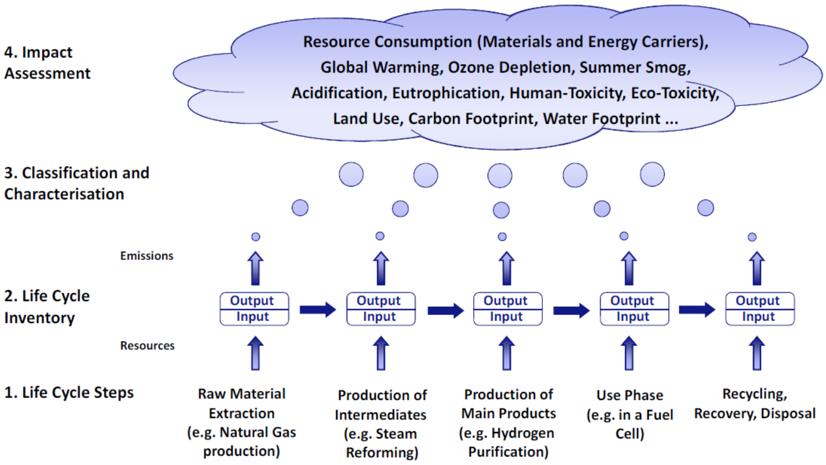

Figure 3.9: Overview of the LCA methodology.

The compilation of all relevant processes (connected by material and energy flows) across the life cycle of the product and relevant processes from other contributing products is referred to as the product system. The purpose of building the product system is to identify the intended benefit from the product to be delivered. Performing a LCA is divided into several steps. Most of them are done sequentially, but there are also iterative parts where the previous steps have to be reconsidered. These steps are: Goal definition, Scope definition, Inventory analysis, Impact assessment, Interpretation.

Figure 3.10 illustrates a simplified overview of LCA methodology derived from the ISO standard 14040 [90]. The main phases (goal definition, scope definition, inventory analysis, impact assessment and interpretation) are shown. The interpretation interacts with all the phases. Moreover in Figure 3.10 the iterative character of a LCA is shown. Once the goal of the work is defined, the initial scope settings are derived, which define the requirements of the subsequent work. However, if during the Life Cycle Inventory phase of data collection and during the subsequent impact assessment and interpretation more information becomes available, the initial scope could be refined and sometimes also could be revised accordingly.

3.4.1 Goal Definition and Scope

The very first step is to clearly state goal and scope. According to ISO 14044 they are defined as follows:

> *The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study, the intended*

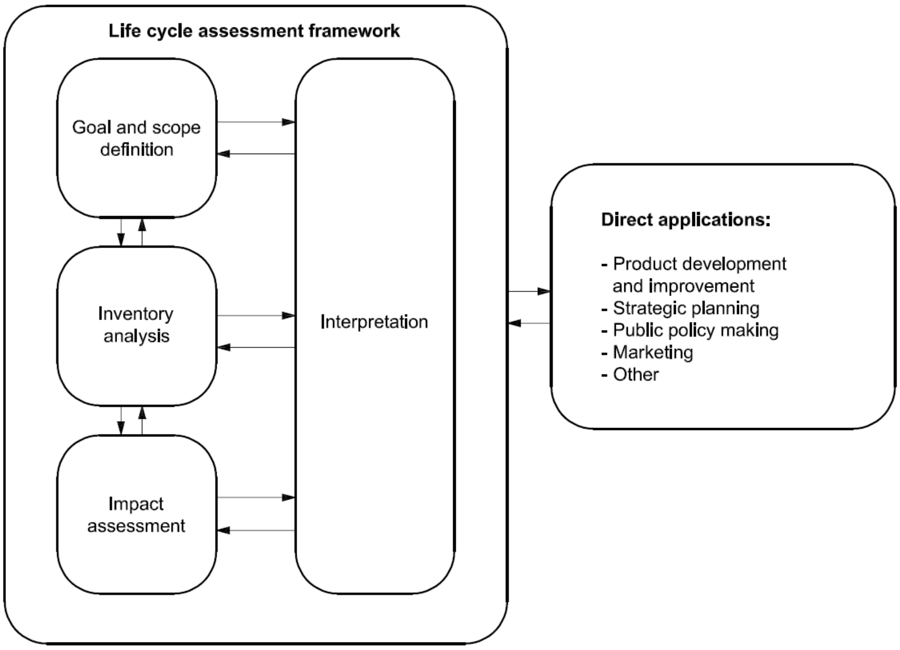

Figure 3.10: Phases and applications of the Life Cycle Assessment (based on ISO 14040 in [90].

> *audience (i.e. to whom the results of the study are intended to be communicated) and whether the results are intended to be used in comparative assertions intended to be disclosed to the public*[47]

> *The scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied.*[48]

During the **goal** definition several aspects have to be defined: Intended application(s), method, assumptions and impact limitations, reasons for carrying out the study and decision-context(s), target audience(s), a statement whether the results are intended to be used in comparative studies which will be made public and the commissioner(s) of the study. Subsequently, in the **scope** phase the following technical aspects are defined: The function, functional unit and the reference flow, Life Cycle Inventory modelling (multifunctionality), system boundary and cut-off criteria, Life Cycle Impact Assessment methods and categories, type, quality and sources of required data and information, data quality requirements, Comparisons between systems, Critical review needs, The intended reporting.

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[47] In [91] Section 4.2.2

[48] In [91] Section 4.2.3.2

3.4.2 Life Cycle Inventory

The **Life Cycle Inventory** (LCI) constitutes the core of the LCA, and it is usually the most time-consuming phase of the whole study. According to ISO 14044, it 'catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment'.

In the LCI phase, data is collected as a result of a process of quantifying inputs and outputs of the system under analysis. Such data may regard energy, raw materials and other physical inputs; products, co-products and wastes; releases to air, water and soil; and other environmental aspects (see Figure 3.11).

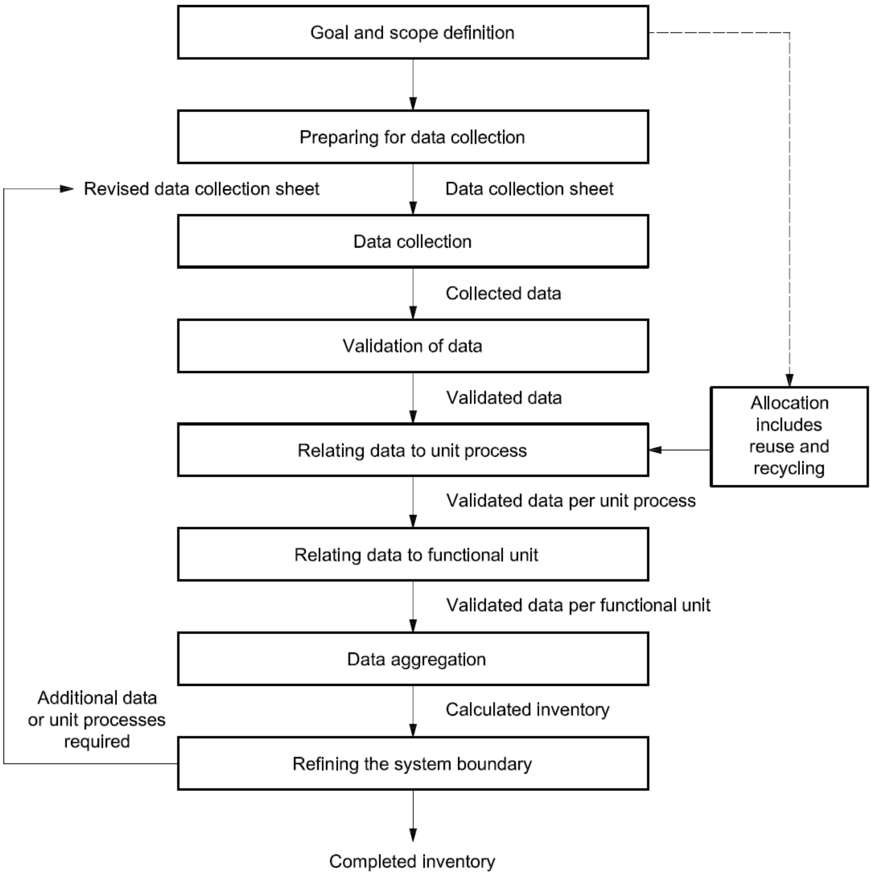

Figure 3.11: Simplified procedures for inventory analysis (source: [91]).

A model of the product system is conceived to represent the interaction of the product system with the environment. The model is commonly programmed in a dedicated LCA software tool and covers each step of the life cycle from the raw material extraction through to the product's end of life in a series of interconnected steps called processes. Interaction with the environment is represented as elementary flows crossing the system boundary, e.g. resources taken from nature and introduced into the product system or emissions arising from combustion, physical, thermal or chemical conversion processes which are vented into the environment. The elementary flows which make up the interaction of a product system with the environment are compiled. Up to this point, the focus has been on the product system. In the next step it shifts towards the environment.

3.4.3 Life Cycle Impact Assessment

The **Life Cycle Impact Assessment** (LCIA) consists in the assessment of the results obtained in the LCI (quantified inputs and outputs) to understand their environmental burden, taking into account resource depletion, human health and environmental impacts. The elements of the LCIA phase are represented in Figure 3.13. Thus, the purpose of the LCIA is to connect a product or process to the correspondent consequences in terms of potential environmental impacts, through a systematic procedure as illustrated in Figure 3.12.

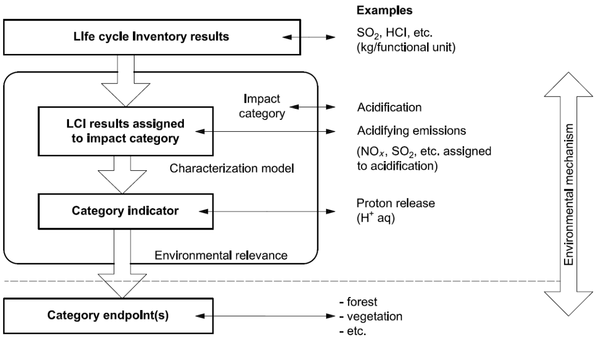

Figure 3.12: The category indicator can be chosen anywhere along the environmental mechanism between the LCI results and the category endpoint(s) (source: [91]).

Each flow from the LCI is grouped into one or more categories. Within each category, the flows are aggregated using equivalence factors called characterisation factors. These factors are based on the physical and chemical properties of the impact-causing substances, as well as on the fate of the flows once they leave the product system towards the environment. The aggregated value is called a **potential impact** and is most commonly given in kg equivalent of a certain reference substance for the respective category.

For example, the unit of the impact **Global Warming Potential** (GWP) is kg carbon dioxide equivalent (kg CO2-eq.). Methane (CH4) has a 25 (IPCC 2007) times greater impact on global warming than carbon dioxide (CO2) over a 100 years span in relation to greenhouse gas impacts. So it is characterised with a factor of 25 when aggregating GWP.

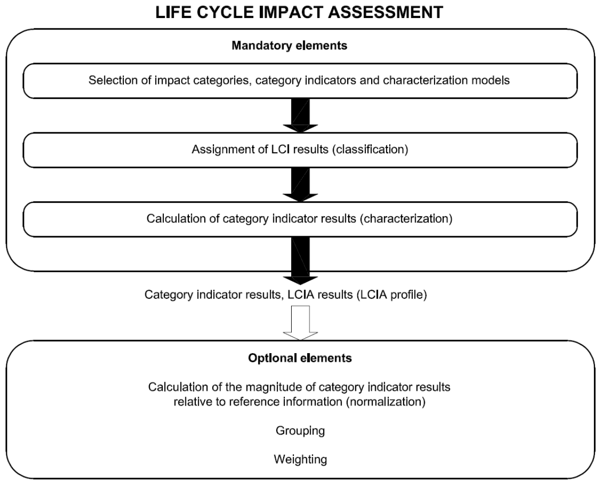

Figure 3.13: this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The LCIA phase also provides information for the life cycle interpretation phase (source: [91]).

3.4.4 Interpretation

Robust conclusions and recommendations relating to the goal and scope of the study are developed in the last phase. The results of the other phases are considered collectively and analysed in terms of the accuracy achieved and the completeness and precision of the data and the assumptions that were used. Grouping and weighting, i.e. aggregation of all the environmental impacts into one single environmental value so as to tell which option is 'best' when comparing product systems, is often requested. However, it is important to note that the aggregation of independent impact categories requires normative decisions. ISO 14044 specifies in section 4.1 that 'It should be recognized that there is no scientific basis for reducing LCA results to a single overall score or number'[91]. Grouping and weighting is based on subjective assessments rather than scientific findings and is therefore generally not recommended and not allowed for comparisons of different products, services or processes. For comparisons, always a complete set of indicators has to be used, e.g. it is not permitted to use Carbon Footprint alone for comparative studies. Most reports cover multiple impact categories, which allow trade-offs between different environmental impacts to be recognised and considered. Decision-makers can use LCA to gain a sound information basis as a foundation for decisions. The strength of the methodology lies in the two core aspects mentioned at the beginning of this text: thinking in product systems and accounting for all relevant impact categories. This ensures that shifts of environmental burdens between life cycle stages (or between impact categories) are recorded and decision makers can modify their processes to optimise the holistic environmental benefits. The ability for multi-dimensional evaluation of system solutions is especially crucial when particular technology efficiencies have been maximised and substantial improvements can only be achieved through such system solutions.

3.5 The changing nature of LCA

Over the years, LCA approach has undergone to a review process, aimed at broadening the object of analysis and the scope of indicator (comprising of performance indicators for all three - or at least two - pillars of sustainable development) [134].

Therefore, LCA approach has developed over decades coming from product-oriented model, used to evaluate environmental impacts, to a bigger framework that elaborates on a wider environmental, economic, and social scale [341], [248], [218], [260].

However, such integrative approach is not without concerns. According to Bento et al. [19], Plevin et al. [250],[207], and Ekvall et al. [89], some LCA studies could give misleading results. The reasons lay in the occurrence of interdisciplinarity, the presence of complex systems, and the prospective environmental evaluation of changes [342], [19] (namely, ‘teleological features’, as stated by Tillman). Gutowski [136] illustrates how human behaviour can alter the expected environmental outcomes suggested by LCA. Additionally, Sterman [292] recognises that **all models are wrong**[49] and humility about the limitations of current knowledge. For example, Searchinger et al. [281] reported that prior studies have found that substituting biofuels for gasoline could reduce greenhouse gases because biofuels sequester carbon through the growth of the feedstock. On the contrary, these analyses have failed to

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[49] However, the above statement echoes what Box et al. [27] said about time-series and forecasting (or one may say, ‘consequential’) problems: ‘all models are approximations. Essentially, all models are wrong, but some are useful.’ at p. 414. Such citation is also recalled in Suh et al. [295].

count the soil carbon emissions from land use change (LUC) and uncertainty analysis to replace the grain (or cropland) diverted to biofuels. Such result raised concerns about large biofuel mandates and highlights the value of using waste products. Agostini et al. [3] underscore the above flaws. Ahlgren et al. [4] identified uncertainty related to the quantification of the GHG emissions due to Indirect LUC (ILUC). Furthermore, Broch et al. [36] highlighted that ILUC modelling approaches are varied and could produce different results.

In the present section two main LCA directions are considered: the characteristics of retrospective and prospective LCA models and Well to Wheel approach.

3.5.1 Attributional and Consequential LCA

The approaches to calculate environmental impacts can be subdivided into two types: attributional LCA (ACLA) and consequential LCA (CLCA). Mainstream LCA has relied on attributional (also called descriptive or accounting) approach, which (most often) means that the LCA considers the immediate physical flows (emissions and resource use) occurring at the location of the life cycle processes. ACLA approach typically implies that the LCA maps the average impact of the studied product system per delivered functional unit. On the other hand, a CLCA (also called change-oriented) approach seeks to map the change of physical flows occurring in response to possible decisions. This can also be described as the consequences of a change in production output, i.e. what the environmental consequence would be if more or less functional units were provided or if recycling materials is taken into consideration. A consequential approach entails inclusion of effects not necessarily physically connected to the product system, but occurring due to, for example, market mechanisms (e.g. virgin material vs scrap metal prices).

The distinction between two types of LCA was suggested in the beginning of the 1990s [88]. It was established toward the end of the decade [341] to resolve debates on what type of input data to use in LCAs and on how to deal with the allocation problems that occur when, for example, a process produces more than one type of product ([250], [295], [84]).

Several different definitions of attributional and consequential LCA have been suggested [88], [370]. Finnveden et al. provided the most cited scientific paper on LCA [109]:

- **Attributional LCA**: LCA aiming to describe the environmentally relevant physical flows to and from a life cycle and its subsystems,
- **Consequential LCA**: LCA aiming to describe how environmentally relevant flows will change in response to possible decisions.

The distinction between the two approaches is quite straightforward. Attributional approaches assume the surrounding world static, i.e. other technical systems are not influenced by the studied product system, whereas consequential approach assumes the surrounding world is dynamic, i.e. there are indirect (secondary) effects occurring in other technical systems as a consequence of the studied product system. Additionally, while ALCAs are generally based on **stoichiometric relationships** between inputs and outputs, and the results may be produced with known levels of accuracy and precision, CLCAs are highly dependent upon economic models representing relationships between demand for inputs, prices elasticities, supply, and markets effects of co-products.
Weidema [357] illustrated the above-mentioned conceptual distinction in Figure 3.14.

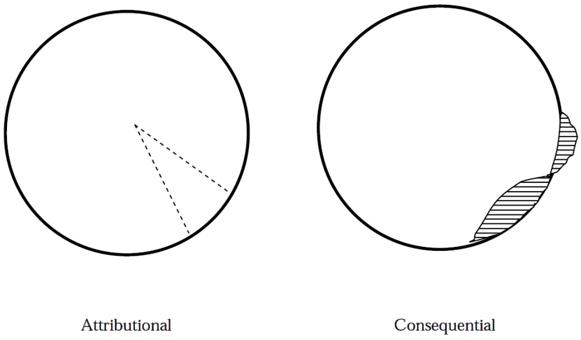

Figure 3.14: The conceptual difference between attributional and consequential LCA. The circles represent the total global environmental exchanges. In the left circle, attributional LCA seeks to cut out the piece with dotted lines that belongs to a specific human activity, e.g. car driving. In the right circle, consequential LCA seeks to capture the change in environmental exchanges that occur as a consequence of adding or removing a specific human activity [357].

3.5.2 Well-To-Wheels analysis

The estimates of the energy use and GHG emissions in the production of a fuel and its use in a vehicle, refer to the so-called "**Well-To-Wheels**" (WTW) analysis. The term fuel is related to an **energy carrier** produced by a single or several resources as the source of primary energy (Edwards et al., 2014). The WTW assessment integrates two stages. The first one, **Well-to-Tank** (WTT), includes energy generation, delivery pathway, and energy storage. The second one, **Tank-to-Wheel** (TTW), comprises energy utilization for traction power during vehicle operation (Nordelöf et al., 2014). Figure 3.15 illustrates the steps necessary to turn a resource into a fuel and bring that fuel to a vehicle. At the regulatory level, **Well-To-Wheels** (WTW) analysis is the preferred methodology used to assess GHG and energy savings in the transport sector. Such methodology is recalled, for example, by the European Union (EU) in the **Fuel Quality Directive** (Directive 2015/652/EC [319]) and in **Renewable Energy Directive** (Directive 2009/28/EC [329]). In the United States the Environmental Protection Agency (EPA) based their regulatory actions on the WTW approach [93][50].

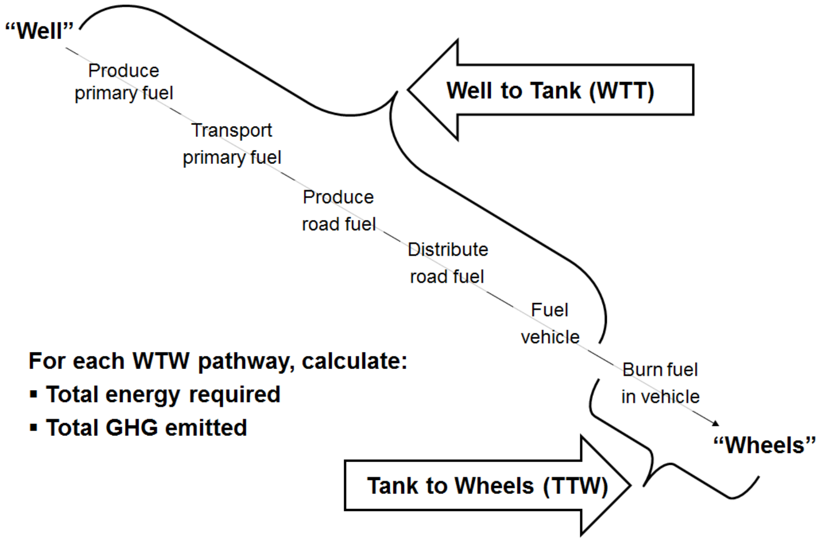

Figure 3.15: Graphic representation of Well-to-Wheels Analysis (from: ec.europa.eu/jrc...).

The WTW study could be considered one type of LCA of vehicles, which focuses exclusively on the life cycle of the energy carrier used to propel the

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[50] Regulatory Impact Analysis: Renewable Fuel Standard Program, Chapter 6 - Lifecycle Impacts on Fossil Energy and Greenhouse Gases, Environmental Protection Agency (EPA) of the United States, EPA420-R-07-004. It is noteworthy to report the following at p. 219: 'For transportation fuels, lifecycle modeling considers all steps in the production of the fuel. This includes production of the fuel feedstock, transportation of the fuel feedstock to a processing facility, fuel processing, and distribution of the fuel to the retail outlet. If the analysis considers only the finished product, it is sometimes called a 'well-to-pump' analysis; if the fuel combustion emissions are included, it can be called a 'well-to-wheel' analysis. While both approaches have advantages, in this work I have considered 'well-to-wheel' impacts. However, I am not addressing the issues of vehicle technology and energy efficiency, since I am making the assumption that the vehicle issues will not be affected by the presence of renewable fuels (i.e., efficiency of combusting one Btu of renewable fuel is equal to the efficiency of combusting one Btu of conventional fuel).'

vehicle, such as fuel (liquid or pressurized), or electricity. Within this scope, WTW focuses on the most energy and pollution-intensive links (Colella et al., 2005). Such narrowed feature makes the WTW particularly suitable to policy making support, even if it can give figures different to those obtained from a rigorous LCA in accordance with the ISO 14040 standard series (ISO 2006). However, the concept of LCA, including also the WTW, as a decision-support tool, suggests that the value of LCA lies in the effective integration of information it provides, within a broader, more holistic process. Edwards et al. in [86] argue that LCA is an overarching methodology that accounts for all the environmental impacts of an industrial process or a product lifecycle. This could include not only energy and GHG emissions from fuel pathways, but also the consumption of all the materials needed for the production process, manufacturing of the plants and of the vehicles, and the end-of-life disposal of such systems, considering recycling options as pointed out in Edwards et al.[86]. Consequently, much wider data sets are required and calculations tend to be more complex, less transparent and comparability might be more limited. These issues are more evident in a new technology development or a demonstration project where system boundaries are still to be clearly defined, and data describing LCA variables can be lacking or not completely shared among stakeholders. In addition, Bandivadekar et al.[15] and Heywood et al.[154] addressed topics related to the evolution of vehicle technology and its deployment, the development of alternative fuels and energy sources, the impacts of driver behaviour, and the implications of all of these factors on future GHG emissions in the United States, Europe, China, and Japan[51]. The results generally indicate that vehicle production and end of life disposal make a significant, but fairly constant contribution to the overall lifetime performance. Moreover, a recent review study on LCA of electrified vehicles, carried out by Marmiroli et al. in [212], have proved a plethora of diverging and conflicting results. The main hurdle identified is the absence of a compete goal and scope definition, leading to an incorrect or delusive interpretation of results. Another gap is the lack of a transparent and complete Life Cycle Inventory (LCI). Ayres highlighted such point in [14]: 'The problem for LCA is much less sophisticated but much more urgent: it is the persistent use in LCAs of 'data' from unreliable sources that cannot be checked'. Both reviews identified **electricity production** as the most impactful phase when it adds up to climate change, and agreed on the need to find consensus on the appropriate **electricity mix**[212].

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[51] See table 3 in § 2.2.3 on page 30 from [15] and table 3.6 in § 3.3.2, on page 44 from [154]

3.6 The computational structure of LCA

Once the life-cycle inventory has been performed, numerical relationships of the subsystems within the entire system can be established, thus driving the model construction. This step consists of incorporating the normalized data and material flows into a **computational structure**, using a computer accounting program. In this context, the computational structure carrier two readings and have, therefore, to be considered individually [150]. The first captures the **arithmetical rules** that are behind an LCA study. The second comprises the **algorithmic rules** as well as related **data structures** that are necessary to yield information on a product.

3.6.1 Representation of processes and flows

A convenient way to represent processes is the notion of linear space. A linear space (or vector space) denotes a set of elements of any kind on to which certain operations (called addition and multiplication by a scalar) can be performed [8]. Therefore, a process can be described as a vector whose components denote the amount of exchanges that are generated and consumed within the system boundaries. A process has, thus, two characteristics: the economic part and the environmental part. The former accounts for the economic flows, i.e. those material and energy flows that are exchanged between processes. The latter consists of all environmental flows, i.e. flows that are exchanged between processes and their environment (examples are environmental entities that are extracted from, resp. emitted, to the environment without previous, resp. further, processes).

A process can be represented by a number r of economic entries a_j and by a number of environmental entries b_k, summarized in vector $\boldsymbol{p}$ in Equation 3.1.

$$\boldsymbol{p} = \begin{pmatrix} a_1 \\ \vdots \\ a_r \\ \hline b_1 \\ \vdots \\ b_k \end{pmatrix} \tag{3.1}$$

Large systems comprises many different unit processes and a concise notation for representing such resulting system is the construction of a process matrix $\boldsymbol{P}$ as in Equation 3.2.

$$\boldsymbol{P} = \left(\, \boldsymbol{p_1} \mid \boldsymbol{p_2} \mid \cdots \, \right) \tag{3.2}$$

This convention underscores individual unit processes as column vectors denoted by $\boldsymbol{p_j}$ in general. However, a suitable representation is to partition the process matrix into distinct parts: a technology matrix $\boldsymbol{A}$ and an intervention matrix $\boldsymbol{B}$.

$$\boldsymbol{P} = \left(\frac{\boldsymbol{A}}{\boldsymbol{B}} \right) \tag{3.3}$$

The next step is the specification of the required performance of the system. A reference flow ϕ is, therefore, defined in the final demand vector $\boldsymbol{f}$, as means to deliver the functional unit. It is denoted by a column vector of dimension r in which all f_i will be 0 except for the reference flow. This notation resembles the Iverson brackets [161] that represent functions that are 1 if the condition within the brackets is satisfied and 0 otherwise, as in Equation 3.4 [52].

$$f_i = \begin{cases} \phi, & \text{if } i = j \\ 0, & \text{otherwise} \end{cases} \tag{3.4}$$

The final aspect of representation is the **inventory table**, *i.e.* the set of all environmental flows associated with the reference flow under evaluation. The vector $\boldsymbol{g}$ is defined as a vector of environmental interventions - the inventory vector.

$$\boldsymbol{g} = \begin{pmatrix} g_1 \\ \vdots \\ g_j \\ \vdots \\ g_k \end{pmatrix} \tag{3.5}$$

Staking $\boldsymbol{f}$ and $\boldsymbol{g}$ provides an succinct reference to this system vector.

$$\boldsymbol{q} = \left(\frac{\boldsymbol{f}}{\boldsymbol{g}} \right) \tag{3.6}$$

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[52] Graham et al.[131] and Knuth[183] advocate this notation since it can encourage and clarify the use of characteristic functions and Kronecker deltas in sums and integrals

The technology matrix $\boldsymbol{A}$ can be scaled with a scaling vector $\boldsymbol{s}$ to supply exactly the economic flows given in $\boldsymbol{f}$. the scaling vector $\boldsymbol{s}$ is introduced in Equation 3.7.

$$\boldsymbol{s} = \begin{pmatrix} s_1 \\ \vdots \\ s_j \\ \vdots \\ s_r \end{pmatrix} \tag{3.7}$$

A balance equation is defined in Equation 3.8.

$$\boldsymbol{A}\boldsymbol{s} = \boldsymbol{f} \tag{3.8}$$

Given the technology matrix $\boldsymbol{A}$ and the final demand vector $\boldsymbol{f}$, the balance equation, under certain restrictions as recalled by Heijungs et al. [150], can be solved to yield the scaling vector $\boldsymbol{s}$:

$$\boldsymbol{s} = \boldsymbol{A}^{-\mathbf{1}}\boldsymbol{f} \tag{3.9}$$

where $\boldsymbol{A}^{-\mathbf{1}}$ denotes the inverse matrix of the technology matrix $\boldsymbol{A}$. The scaling vector provides a direct input to the final step in solving the inventory problem. It has to be recognized that the scaling vector affects both the economic flows and the environmental flows. This can be be expressed in matrix notation

$$\boldsymbol{g} = \boldsymbol{B}\boldsymbol{s} \tag{3.10}$$

If the expression of the scaling vector is inserted in the Equation 3.10, it leads to

$$\boldsymbol{g} = \boldsymbol{B}\boldsymbol{A}^{-\mathbf{1}}\boldsymbol{f} \tag{3.11}$$

Applying associative property to matrix multiplication, the Equation 3.11 can be rewritten as

$$\boldsymbol{g} = \left(\boldsymbol{B}\boldsymbol{A}^{-\mathbf{1}}\right)\boldsymbol{f} = \boldsymbol{\Lambda}\boldsymbol{f} \tag{3.12}$$

where the intensity matrix $\boldsymbol{\Lambda}$ is defined in Equation 3.13.

$$\boldsymbol{\Lambda} = \boldsymbol{B}\boldsymbol{A}^{-\mathbf{1}} \tag{3.13}$$

This notion clarifies that the matrix $\boldsymbol{\Lambda}$ can be evaluated for any particular system of unit processes, and then be applied to any final demand vector.

The final stage, *i.e.* the LCIA, as outlined in previous section, translates inventory data into potential environmental effects and resource consumptions. In a methodological sense, this means the selection of impact categories with associated indicators or, more formally, a definition of a characterization model that maps a point in the inventory space $\mathcal{G}$ to a point in the impact space $\mathcal{H}$:

$$\eta : \mathcal{G} \to \mathcal{H} \tag{3.14}$$

Thus, given a set of environmental interventions, a characterization model returns a number, h_i.

$$h_i = \eta_i(\boldsymbol{g}) \tag{3.15}$$

where η_i is the characterisation model for a category indicator (and hence an impact category) i. The relevant characterisation model addresses the environmental mechanism behind a given impact category, linking the life cycle inventory analysis result to the common unit of the category indicator (e.g., kg CO2-equivalents for greenhouse gases contributing to the impact category climate change). The outcome is a set of characterisation factors which are applied to individual substances within the impact category. However, such models are inherently non-linear, but for estimates linear approximations give reliable results. A linearisation of the the model may help to simplify the expression as:

$$h_i(\boldsymbol{g}) = \sum_j (\boldsymbol{q}_i)_j g_j \tag{3.16}$$

where the vector $(\boldsymbol{q}_i)_j$ represents the characterisation factor for the contribution of intervention j to impact category i. A general formula for characterisation is

$$h_i = \sum_j (\boldsymbol{q}_i)_j g_j \tag{3.17}$$

or

$$h_i = \boldsymbol{q}_i \boldsymbol{g} \tag{3.18}$$

If an impact method comprises several impact categories, the characterisation vectors can be juxtaposed to form the characterisation matrix $\boldsymbol{Q}$ as

$$\boldsymbol{Q} = \left(\ \boldsymbol{q_1} \ \middle| \ \boldsymbol{q_2} \ \middle| \ \cdots \ \right) \tag{3.19}$$

The formula to calculate the characterisation of various impact categories assumes the form

$$\boldsymbol{h} = \boldsymbol{Q}^T \boldsymbol{g} \tag{3.20}$$

The vector $\boldsymbol{h}$ is called impact vector or impact result vector. Two examples may help to clarify the inventory analysis and the estimation of the environmental profile.

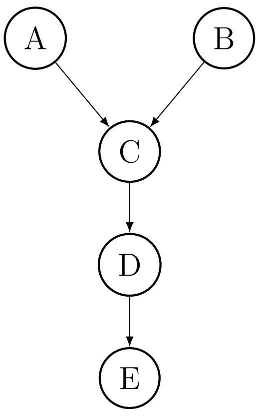
Example 1. As an example, an hypothetical system is composed of five processes ($r = k = 5$) with four environmental entities ($s = 5$) in table 3.1. The minus sign is a conventional indication for the direction of the flow. The negative co-ordinate indicates an input, while the other three positive coordinates indicate outputs.

entity	processes					demand
	A	B	C	D	E	
Kg steel	1	0	-1	0	0	0
MJ steam	0	1	-0.5	0	0	0
product (item)	0	0	1	-1	0	0
use of product (item)	0	0	1	1000	0	1000
disposed product (item)	0	0	0	1	-1	0
Kg CH_4 (resource)	0	-10	0	0	0	?
Kg CH_4 (emissions)	0	0.05	0	0	0	?
Kg CO_2	1	4	2	1	0.5	?
Kg SO_2	1.2	1.5	1	0	0.8	?
Kg solid waste	0	0	0	0	1	?

Table 3.1: Example of some processes which constitute a hypothetical process tree for a product. A = Steel pruduction; B = Steam generation; C = production of the good; D = use of the product; E = disposal of the product.

The collection of combined processes with their mutual relationship is called process tree. Figure 3.16 illustrates the process tree diagram and the corresponding matrix representation as discussed above.

Process flow diagram shows the interconnections between processes to form a commodity flow. The matrix method expresses the whole product system as a range of linear equations that could be solved simultaneously. In this simplified scenario, each process depend on the preceding one, thus resembling the different phases of the life cycle. These phases consist of industrial processes such as the production of materials, generation of energy (process A, B, and C), consumer processes such as the use and maintenance of the product (process D), and end-of-life processes as waste handling and recycling (process E). On the environmental side, the extraction of resources and the emissions of substances are distinguished. For example, CH_4 is a resource as well as an emission, CO_2 and SO_2 account for the combustion reactions, and solid waste is the result of a disposal of out-of-service product.



$$\Longrightarrow \begin{cases} \boldsymbol{A} = \begin{pmatrix} 1 & 0 & -1 & 0 & 0 \\ 0 & 1 & -0.50 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{pmatrix} \\ \\ \boldsymbol{B} = \begin{pmatrix} 0 & -10 & 0 & 0 & 0 \\ 0 & 0.05 & 0 & 0 & 0 \\ 1 & 4 & 2 & 1 & 0.50 \\ 1.20 & 1.50 & 1 & 0.80 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{cases}$$

Figure 3.16: Process flow diagram of a simplified product system and the corresponding technology and environmental matrix.

It is supposed that the system under study is used for 1000 times during its life time and, therefore, the functional unit of this product system is given by the final demand vector as

$$\boldsymbol{f} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{pmatrix} \tag{3.21}$$

From the above data, the inventory vector can be calculated as

$$\boldsymbol{g} = \begin{pmatrix} -5.00 \\ 0.025 \\ 6.50 \\ 3.75 \\ 1.0 \end{pmatrix} \tag{3.22}$$

Individual environmental interventions, contained in the inventory vector, have to be classified. This means sorting inventory data into their related impact categories and, therefore, grouping substances into one impact category. For example, CO_2, CH_4, and N_2O are grouped into global warming, whereas NOx and SOx are grouped into acidification. Characterizing impacts involves assessing the environmental impacts of impact categories.

In this example, three impact categories are considered: global warming potential (GWP), acidification potential (AP), and resource use, energy carrier (SOP). The relevant characterisation vectors are, thus, defined as

$$\boldsymbol{q}_{GWP} = \begin{pmatrix} 0 \\ 36.8 \\ 1 \\ 0 \\ 0 \end{pmatrix} [Kg\mathrm{CO_2}eq./Kg]$$

$$\boldsymbol{q}_{AP} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1.31 \\ 0 \end{pmatrix} [molH + eq./Kg] \tag{3.23}$$

$$\boldsymbol{q}_{SOP} = \begin{pmatrix} 46.8 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} [MJ/Kg]$$

The above three vectors can be juxtaposed to yield the characterisation matrix as:

$$\boldsymbol{Q} = \left(\ \boldsymbol{q}_{GWP} \mid \boldsymbol{q}_{AP} \mid \boldsymbol{q}_{SOP}\ \right) = \begin{pmatrix} 0 & 0 & 46.8 \\ 36.8 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1.31 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{3.24}$$

The impact vector is calculated using Equation 3.20 as

$$\boldsymbol{h} = \boldsymbol{Q}^T \boldsymbol{g} = \begin{pmatrix} 0 & 0 & 46.8 \\ 36.8 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1.31 & 0 \\ 0 & 0 & 0 \end{pmatrix}^T \cdot \begin{pmatrix} -5.0 \\ 0.025 \\ 6.50 \\ 3.75 \\ 1.0 \end{pmatrix} \tag{3.25}$$

$$= \left[\begin{array}{ccc} 7.42 & 4.91 & -234 \end{array} \right]$$

The coefficients in vector $\boldsymbol{h}$ represent the environmental loads of a functional unit (FU) sorted into their related impact categories: the emission of 7.42 Kg CO_2 eq./FU and of 4.91 mol H+ eq./FU, and 234 MJ/FU of energy use (mind the removal of the minus sign that, as said before, means an input to the system).

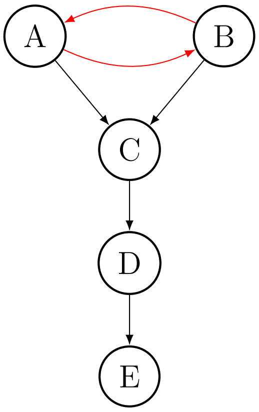
The impact results provide insights about their potential impacts on what is referred to as 'areas of protections' of the LCIA, *i.e.* the entities that should be protected.

The process matrix $\boldsymbol{P}$ is summarised as

$$\boldsymbol{P} = \begin{pmatrix} 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & -0.50 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1000 & 0 & 1000 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & -10 & 0 & 0 & 0 & -5.0 \\ 0 & 0.05 & 0 & 0 & 0 & 0.025 \\ 1 & 4 & 2 & 1 & 0.50 & 6.50 \\ 1.20 & 1.50 & 1 & 0.80 & 0 & 3.75 \\ 0 & 0 & 0 & 0 & 1 & 1.0 \end{pmatrix} \tag{3.26}$$

Example 2. The previous example showed a simple, although trivial, application of the sequential method for formulating and solving the inventory problem. Using plain algebra, the amount of commodities delivering a certain functional unit is obtained, and by multiplying the amount of environmental interventions generated to produce them, the LCI of the whole product system is calculated. On the other hand, the sequential method presents some significant limitations. When the linkage of the processes is not purely linear, but is a network which includes feedback loops or mutual dependency, the sequential method becomes clumsy. Feedback loops occur frequently in industrial systems. For instance, mining of coal needs electricity, while production of electricity needs coal, ad so on.

In this second example, the case of feedback loops is presented. Figure 3.17 illustrates the process flow diagram where the feedback loop consists of process A and B connected in a closed chain (two red arrows underscore the introduction of the closed cycle between process A and B). The corresponding technology matrix is modified accordingly (the concerned demand factors are in red colour as well).



$$\Longrightarrow \begin{cases} \boldsymbol{A} = \begin{pmatrix} 1 & -0.5 & -1 & 0 & 0 \\ -0.5 & 1 & -0.50 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{pmatrix} \\ \\ \boldsymbol{B} = \begin{pmatrix} 0 & -10 & 0 & 0 & 0 \\ 1 & 4 & 2 & 1 & 0.50 \\ 0 & 2 & 1 & 0.80 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{cases}$$

Figure 3.17: Process flow diagram with an internal commodity flow loop and the corresponding technology and environmental matrix.

The inventory vector is now

$$\boldsymbol{g} = \begin{pmatrix} -13.33 \\ 0.066 \\ 10.50 \\ 5.80 \\ 1.0 \end{pmatrix} \tag{3.27}$$

and the corresponding impact vector is

$$\boldsymbol{h} = \begin{bmatrix} 12.95 & 7.59 & -624 \end{bmatrix} \tag{3.28}$$

The resulting new process matrix $\boldsymbol{P}$ is thus

$$\boldsymbol{P} = \begin{pmatrix} 1 & -0.5 & -1 & 0 & 0 & 0 \\ -0.5 & 1 & -0.50 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1000 & 0 & 1000 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & -10 & 0 & 0 & 0 & -13.33 \\ 0 & 0.05 & 0 & 0 & 0 & 0.066 \\ 1 & 4 & 2 & 1 & 0.50 & 10.50 \\ 1.20 & 1.50 & 1 & 0.80 & 0 & 5.80 \\ 0 & 0 & 0 & 0 & 1 & 1.0 \end{pmatrix} \tag{3.29}$$

The representation of product systems in terms of a matrix inversion is apt to be translated into algorithmic instructions that could be interpreted by a computer.

3.6.2 Information processing

The matrix notation provides the ground to develop a LCA computer program[53] or software. The computational support can facilitate the definition of the system under investigation, the collection of data of appropriate quality, and performing the extensive calculations. Heijungs et al.[149] underscore the mediation role of the software:

> *The development of methodology for LCA is highly theoretical, whereas the collection of data has a direct connection with practice. Software takes a position in between: it contains the formalized methodology in a way that is accessible to the data, with its practical limitations. The development of software increases the practical usability of the methodology and the suitability of data within the theoretical framework. Software may thus act as a bridge between theory and practice.*

A LCA software is intended to supply information on the environmental impacts of products and processes along the entire life cycle. Software products typically comprise three modules :

- an input module, accounting for an user interface to easily access a database (or a collection of databases) and to build the model,

---

[53] A program (of instructions) is method planning, which defines a clearly specified sequence of computer instructions implementing an algorithm.

- a computational engine, responsible for carrying out the calculations without user-intervention,
- a report processor aimed at formatting impact results in graphical charts or tabular form.

Figure 3.18 illustrates the general structure of an LCA program designed according to the principles outlined above.

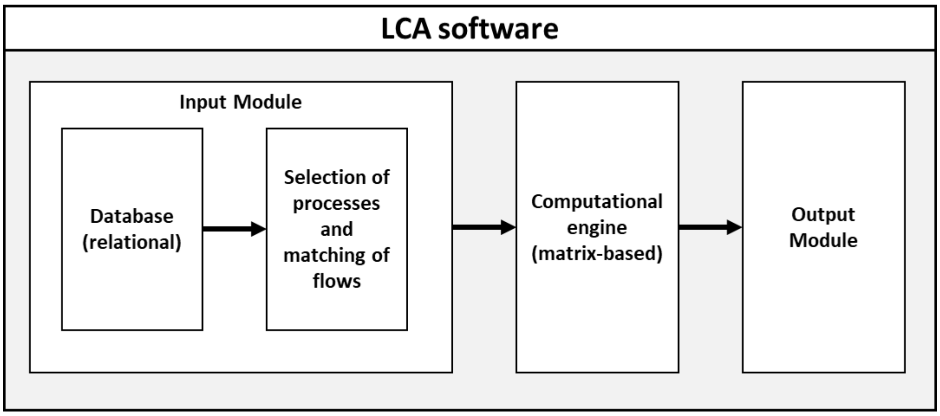


Figure 3.18: General design of LCA-software, distinguishing an input module, a computational module and an output module. [150].

There exist some commercially-available software tools that implement the above-mentioned model. According to Speck et al.[288], SimaPro and GaBi are the preferred choices for LCA practitioners submitting articles to*International Journal of Life Cycle Assessment*, and *Journal of Industrial Ecology* journals. However, besides proprietary versions, open source LCA software systems are now available. The openLCA framework is a professional open source LCA software [56]. It is developed in Eclipse, a Java based Integrated Development Environment (IDE) from IBM, which is open source as well. Eclipse provides an efficient Service Oriented Architecture (SOA) model. This allows to implement a broad variety of different methods and add-ons, yielding a rich-featured framework while simultaneously keeping the application small. Additionally, openLCA includes Jython, an implementation of the Python programming language for Java platforms, from which a programmer can import all Java libraries, including those for openLCA. The Python application programming interface (API) for openLCA allows direct access to the openLCA software core, circumventing the graphical user interface. That means that an user can write a Python script for generating the product system and organising the results, rather than having to enter all data and structures by hand.

In this thesis, openLCA software is used to carry out the LCA, with also the accompanying Python scripts to create and analyse multiple product systems.

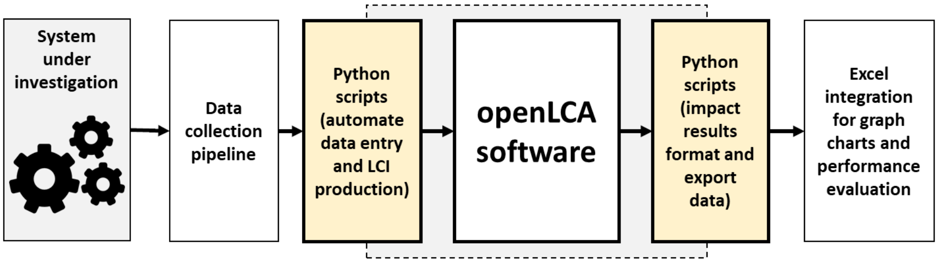


Figure 3.19: openLCA software and Python interfaces between input and output side.

Figure 3.19 summarises the entire elaboration process carried out in the thesis. The system under investigation (*i.e.* the hydrogen fuel cell bus) is scrutinized to collect relevant data on performance. This process is discussed in Chapter 4 and 5. The Python scripts, acting like a software layer, between the input and the output side of openLCA, can handle repetitive tasks, such as inventory generation, and customize results in graphical charts or export in text format.

The first step is to represent the properties of the inventory data in a form which is amenable to automatic treatment in openLCA. **JSON** (JavaScript Object Notation) is a text format that facilitates structured data interchange between all programming languages [284]. The JSON specification states that data can be structured in either of the two following compositions: a collection of key/value pairs or an ordered list of values. An inventory can be, therefore, conceived as a set of JSON objects, representing each process. Individual key denotes a specific property of the process. A process can be structured as a set of the following key properties (see Listing 3.1):

- **name** matches the name of the process;
- **RefId** indicates the UUID (Universally Unique IDentifier), that unequivocally identifies the process in the database,;
- **Category** indicates the complete category path in a Windows-like format;
- **LocationCode** indicates the three-letter code that indicates the geography location of the process (used by Ecoinvent and are defined by the ISO 3166);

- **LocationRefId** indicates the UUID that unequivocally identifies the country code in the database,
- **Exchange_DICT** indicates the array of exchange data objects. The exchange object is made up of the following keys:
    - **amount** sets the demand factor assigned to the selected exchange;
    - **isInput** indicates a boolean value that discriminates between an input or output exchange,
    - **amountFormula** indicates a string containing a formula used to calculate an amount based on previously defined parameters;
    - **isQuantitativeReference** indicates if the exchange is the delivery of the functional unit;
    - **FlowProperty** indicates the type of property an exchange may assume, *e.g.* a mass, an energy, a volume,..;
    - **flow** matches the properties of the selected flow;
    - **defaultProvider** matches the properties of the provider associated to the selected flow in the exchange.
- **Reference_flow_DICT** indicates the reference flow property object;
- **Input_Parameter_DICT** indicates the collection of parameter objects. The contents of the object consist of the parameter name and the associated object properties. A parameter is characterized by the following attributes:
    - **IsInputParameter** indicates if the parameter stores a constant numerical value or a calculated value from the associated formula;
    - **description** provides information on the parameter;
    - **name** matches the name of the parameter;
    - **formula** indicates a string containing a formula used to calculate a value based on previously defined parameters;
    - **value** sets a value to the parameter;

Listing 3.1: JSON format for a process

`columns`

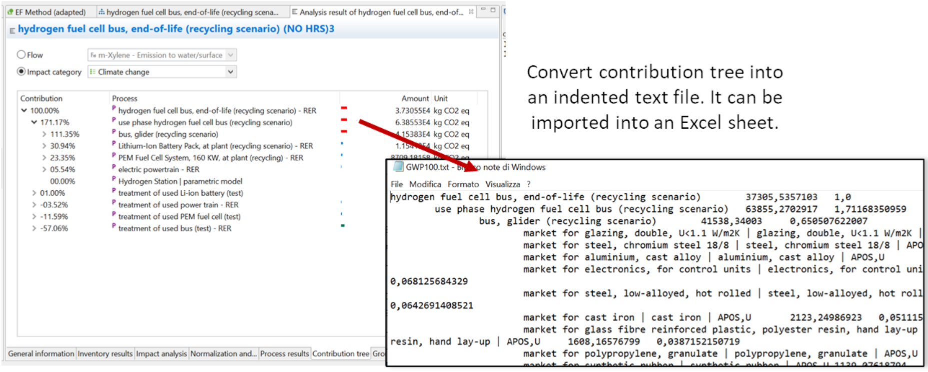
```
{
 "name": "PROCESS␣A",
 "RefId": "",
```

```
  "Category": "HIGHVLOCity␣Project/Hydrogen␣Production",
  "LocationCode": "RER",
  "LocationRefId": "d66c264e-1dbd-33e6-911d-3ffc70908e8e
     ↪ ",
  "Exchange_DICT": [
  {
    "amount": 1,
    "isInput": "False",
    "amountFormula": "functional_unit_amount",
    "defaultProvider": {
      "defaultProviderLocationRefId": "",
      "defaultProviderLocationCode": "",
      "defaultProviderName": "",
      "defaultProviderRefId": ""
    },
    "isQuantitativeReference": "True",
    "FlowProperty": "Mass",
    "flow": {
      "description": "",
      "flowtype": "FlowType_PRODUCT_FLOW",
      "name": "FLOW␣A",
      "referenceFlowProperty": "Mass",
      "refId": "",
      "category": ""
    }
  },...
  ],
  "Reference_Flow_DICT": {
    "name": "FLOW␣A",
    "ReferenceFlowProperty": "Mass",
    "refId": ""
  },
  "Input_Parameter_DICT": {
    "functional_unit_input": {
      "IsInputParameter": "True",
      "description": "",
      "name": "functional_unit_input",
      "formula": "",
      "value": 1
    },
    "functional_unit_amount": {
      "IsInputParameter": "False",
      "description": "",
```

```
      "name": "functional_unit_amount",
      "formula": "functional_unit_input",
      "value": 1
    },...
  }
}
```

The next step is to calculate the impact results and export data in a suitable format. The Python script in Listing 3.2 implements such tasks.

The idea behind the script is to convert the contribution tree data into an indent plain text format that is much easier to handle (see Figure 3.20). The information is stored into an object that can be recursively accessed to retrieve its child elements. At each recursion call, the indent level is increased by one unit. The resulting file is, therefore, saved on the disk.



Contribution	Process	Amount	Unit
100.00%	hydrogen fuel cell bus, end-of-life (recycling scenario) - RER	3.73055E4	kg CO2 eq
171.17%	use phase hydrogen fuel cell bus (recycling scenario)	6.38553E4	kg CO2 eq
111.35%	bus, glider (recycling scenario)	4.15383E4	kg CO2 eq
30.94%	Lithium-Ion Battery Pack, at plant (recycling scenario) - RER	[illegible]	kg CO2 eq
23.35%	PEM Fuel Cell System, 160 KW, at plant (recycling) - RER	8709.18158	kg CO2 eq
05.54%	electric powertrain - RER		
00.00%	Hydrogen Station | parametric model		
01.00%	treatment of used Li-ion battery (test)		
-03.52%	treatment of used power train - RER		
-11.59%	treatment of used PEM fuel cell (test)		
-57.06%	treatment of used bus (test) - RER		

```
hydrogen fuel cell bus, end-of-life (recycling scenario)        37305,5357103   1,0
        use phase hydrogen fuel cell bus (recycling scenario)   63855,2702917   1,71168350959
                bus, glider (recycling scenario)        41538,34003     0,650507622007
                        market for glazing, double, U<1.1 W/m2K | glazing, double, U<1.1 W/m2K |
                        market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | APO
                        market for aluminium, cast alloy | aluminium, cast alloy | APOS,U
                        market for electronics, for control units | electronics, for control uni
0,068125684329
                        market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot roll
0,0642691408521
                        market for cast iron | cast iron | APOS,U       2123,24986923   0,051115
                        market for glass fibre reinforced plastic, polyester resin, hand lay-up
resin, hand lay-up | APOS,U     1608,16576799   0,0387152150719
                        market for polypropylene, granulate | polypropylene, granulate | APOS,U
```

Convert contribution tree into
an indented text file. It can be
imported into an Excel sheet.

Figure 3.20: openLCA contribution tree and the indented format.

The main actions, carried out by the script, are summarized as follows:

1. import libraries;
2. initialise Ecoinvent database;
3. instantiate the database object references;
4. select impact method;
5. define associative arrays for the product system to evaluate;
6. define an associative array that maps a category name on to a file name that will store the impact results;

7. define an associative array that maps the process name and the indention level. A negative number means that the children nodes of that process will be not processed. The customisation may help to customise the contribution tree, containing only the interested data to look upon;

8. loop through the processes list to perform the analysis. This is the main block that carries out the calculations and export data.

   The elaboration steps are the specified in the following ”recipe”:

   8.1. get process object reference;
   8.2. check if the result object is already in the cache memory. If not, the script proceeds with the next step;
   8.3. build product system object;
   8.4. redefine process parameters;
   8.5. update the product system in the database;
   8.6. calculate impact results
   8.7. add impact results in the cache memory
   8.8. save all impact results in a test file

   The export is performed with a loop that cycles through all the impact category results:

   8.1. get contribution tree object reference;
   8.2. evoke the function **getUpstreamTreeData** that recursively iterates over the contribution tree to produce a pretty-print structure of nested impact node objects that is saved in a text file.

Listing 3.2: Python script’s program plan

`columns`

```
# TASK 1: import libraries

if __name__ == '__main__':

  # TASK 2: initialize database
  dataAssocArray = util.LoadJSONfile("{0}{1}".format(
     ↪ util.Config_CLASS.json_path, "ecoinvent35.json")
     ↪ )
```

```
db_dir = File("{0}{1}".format(util.Config_CLASS.
    ↪ db_path, dataAssocArray["
    ↪ ECOINVENT35_APOS_UP_REGIONALISED"]))

# TASK 3: instantiate the object references
db = DerbyDatabase(db_dir)
flow_dao = FlowDao(db)
fp_dao = FlowPropertyDao(db)
dao = ProcessDao(db)
Param_dao = ParameterDao(db)
category_dao = CategoryDao(db)
impact_method_dao = ImpactMethodDao(db)
product_system_dao = ProductSystemDao(db)
cache = MatrixCache.createLazy(db)
impact_category_dao = ImpactCategoryDao(db)

# TASK 4:
#
    ↪ *************************************************************
    ↪
# Impact Method refId
method_id = 'b0f6a3ba-a0be-3bfe-ae43-4e23c241e4b6'
# get method instance
method = impact_method_dao.getForRefId(method_id)
#
    ↪ *************************************************************
    ↪


h2fcbus_noeol = {"amount" : 800000, "paramRedefList" :
    ↪  {"HRS_enable" : 1.0, "HRS_selector" : 4.0}, "
    ↪ ImpactFilePrefix" : "h2fcbus_noeol_",
"processRefId" : "f9507a1d-4fde-43c5-9d45-fd8698f2803b
    ↪ ", "jsonFileName" : "
    ↪ h2fcbus_noeol_results_ALL_IMPACTS_DICT.json"}

processList = {
"transport,␣fuel␣cell␣bus␣(Only␣manufacturing␣-␣NO␣EOL
    ↪ )3" : h2fcbus_noeol
}

impactCategoryResultFileList = {"Resource␣use,␣energy␣
    ↪ carriers" : "ADP-f.txt",
```

```
"Ozone␣depletion" : "ODP.txt", "Respiratory␣inorganics
   ↪ " : "PMFP.txt", "Eutrophication␣marine" : "METP.
   ↪ txt", "Resource␣use,␣mineral␣and␣metals" : "SOP.
   ↪ txt", "Cancer␣human␣health␣effects" : "HTP-c.txt
   ↪ ", "Non-cancer␣human␣health␣effects" : "HTP-nc.
   ↪ txt", "Land␣use" : "LOP.txt", "Eutrophication␣
   ↪ terrestrial" : "TETP.txt", "Climate␣change" : "
   ↪ GWP100.txt", "Eutrophication␣freshwater" : "FEP.
   ↪ txt", "Climate␣change␣-␣biogenic" : "GWP100-b.
   ↪ txt", "Photochemical␣ozone␣formation,␣HH" : "
   ↪ HOFP.txt", "Climate␣change␣-␣land␣use␣and␣
   ↪ transform" : "GWP100-lu.txt", "Ionising␣
   ↪ radiation,␣HH" : "IRP.txt", "Ecotoxicity␣
   ↪ freshwater" : "FETP.txt", "Acidification␣
   ↪ terrestrial␣and␣freshwater" : "TAP.txt", "Water␣
   ↪ scarcity" : "WCP.txt", "Climate␣change␣-␣fossil"
   ↪  : "GWP100-f.txt"}

customLevelProcessList = {"bus,␣glider" : 1,
                          "Lithium-Ion␣Battery␣Pack,␣
                             ↪ at␣plant" : 3,
                          "PEM␣Fuel␣Cell␣System,␣160␣
                             ↪ Kw,␣at␣plant": 3,
                          "bus,␣glider␣(recycling␣
                             ↪ scenario)" : 1,
                          "Lithium-Ion␣Battery␣Pack,␣
                             ↪ at␣plant␣(recycling␣
                             ↪ scenario)" : 3,
                          "PEM␣Fuel␣Cell␣System,␣160␣
                             ↪ KW,␣at␣plant␣(
                             ↪ recycling)" : 3,
                          "electric␣powertrain" : 1,
                          "treatment␣of␣used␣Li-ion␣
                             ↪ battery␣(test)" : -1,
                          "treatment␣of␣used␣power␣
                             ↪ train" : -1,
                          "treatment␣of␣used␣PEM␣fuel␣
                             ↪ cell␣(test)" : -1,
                          "treatment␣of␣used␣bus␣(test
                             ↪ )" : -1,
                          "alkaline␣fuel␣cell␣(AFC)␣
                             ↪ stack␣(1KW)" : 1,
                          "diaphram␣compressor" : 2,
```

```
                          "market group for electricity, low voltage | electricity, low voltage | APOS,U" : -1,
                          "market for electricity, low voltage, label-certified | electricity, low voltage, label-certified | APOS,U" : -1,
                          "Hydrogen Refuelling Station (HRS) construction APOS,U" : -1,
                          "water, decarbonised, at user" : -1,
                          "hydrogen, liquid, from chlorine electrolysis, production mix, at plant (2016)" : 1,
                          "hydrogen, liquid, from steam methane reforming (SMR)" : 1,
                          "market for transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS,U" : -1}



for processName in processList:

  jsonFileName = processList[processName]["jsonFileName"]

  key = "{0}_results".format(processName)

  product_system_name = processName

```

```
    # process refId
    processRefId = processList[processName]["
       ↪ processRefId"]
    # get object instance
    processRefObj = util.get_process(dao, processRefId)
    log_text("processRefObj␣name␣=␣'{0}'".format(
       ↪ processRefObj.name))

    #
       ↪ *****************************************************************
       ↪
    appCache = Cache.getAppCache()
    result = appCache.remove(key)

    if result is None:
      log_text("Cache␣Empty")
      ProductSystemObj = create_product_system(
         ↪ processRefObj, product_system_name,
         ↪ processList[processName]["amount"])
      auto_link_system(ProductSystemObj)
      # Redef Paramters
      #
         ↪ ***************************************************************
         ↪
      if not processList[processName]["paramRedefList"]:
        log_text("paramRedefList␣is␣empty")
      else:
        log_text("Redefine␣a␣process␣parameter")
        # process Context list
        processContextList = processList[processName]["
           ↪ paramRedefList"]
        # loop thorugh process refid list
        for processContextRefId in processContextList:
          # get object instance
          processContextObj = util.get_process(dao,
             ↪ processContextRefId)
          log_text("processContextObj␣name␣=␣'{0}'".
             ↪ format(processContextObj.name))
          # get param list
          paramRedefList = processList[processName]["
             ↪ paramRedefList"][processContextRefId]
          # loop through the parameters list
          for pm_name in paramRedefList:
```

```
          # ****************************************************
          param_redef_attribute_DICT = {}
          param_redef_attribute_DICT[util.ParameterRedef_CLASS.contextId] = processContextObj.id
          param_redef_attribute_DICT[util.ParameterRedef_CLASS.contextType] = util.ModelType_CLASS.ModelType_DICT[util.ModelType_CLASS.ModelType_PROCESS]
          pmRedef = util.add_parameter_redef(pm_name, processList[processName]["paramRedefList"][processContextRefId][pm_name], param_redef_attribute_DICT)
          # ****************************************************
          log_text("parameterRedef␣name:␣'{0}'".format(pmRedef.name))
          # adds parameter redefinition to the selected product system
          ProductSystemObj.parameterRedefs.add(pmRedef)
          # ****************************************************
      # ********************************************************
      parameterList = ProductSystemObj.parameterRedefs
      log_text("parameterRedefs␣len:␣{0}".format(len(parameterList)))
      # ********************************************************

    # update product system
    product_system_dao.update(ProductSystemObj)
    # **********************************************************
```

```
   log_text("Product␣System␣refId␣=␣'{0}'".format(
     ↪ ProductSystemObj.refId))
   result = calculate(ProductSystemObj, method)
   log_text("Results␣OK")
   appCache.put(key, result)
   log_text("Add␣result␣data␣to␣Cache")
   util.getTotalResult(result, jsonFileName)
  else:
   log_text("Cache␣OK")
   appCache.put(key, result)
   ProductSystemObj = product_system_dao.getForName(
     ↪ product_system_name)[0]
   # Check Prodcut System
   if not ProductSystemObj:
    log_text("Product␣System␣to␣be␣created")
    ProductSystemObj = create_product_system(process
      ↪ , product_system_name, processList[
      ↪ processName]["amount"])
    auto_link_system(ProductSystemObj)
   else:
    log_text("Product␣System␣already␣present")
    #system = ProductSystemObj
   log_text("Product␣System␣refId␣=␣'{0}'".format(
     ↪ ProductSystemObj.refId))

  # TASK
  for impactCategoryResult in result.
    ↪ getTotalImpactResults():
   log_text("impactCategoryResult.impactCategory␣=␣
     ↪ '{0}'".format(impactCategoryResult.
     ↪ impactCategory.name))
   fileName = "{0}{1}".format(processList[processName
     ↪ ]["ImpactFilePrefix"],
     ↪ impactCategoryResultFileList[
     ↪ impactCategoryResult.impactCategory.name])

   ImpactFilePath = "{0}{1}".format(util.Config_CLASS
     ↪ .json_path, fileName)

   fileObj = open(ImpactFilePath, mode = 'wb')

   treeObj = result.getTree(impactCategoryResult.
     ↪ impactCategory)
```

```
        rootElem = treeObj.root
        log_text("rootElem name = '{0}'".format(rootElem.provider.process.name.encode('utf-8')))
        log_text("rootElem amount = '{0}'".format(rootElem.result))

        lst = [rootElem.provider.process.name.encode('utf-8'), str(rootElem.result).encode('utf-8').replace('.',','), str(1.0).encode('utf-8').replace('.',',')]
        fileObj.write('\t'.join(lst) + "\n")
        util.getUpstreamTreeData(fileObj, result, impactCategoryResult.impactCategory, rootElem, 5, customLevelProcessList, rootElem.result)
```

Chapter 4

Software tools: a bridge between the information systems and environmental experts

> *Man of the twentieth century has become just as* ***emancipated from nature*** *as eighteenth-century man was from history. History and nature have become equally alien to us, namely, in the sense that the essence of man can no longer be comprehended in terms of either category. On the other hand, humanity, which for the eighteenth century, in Kantian terminology, was no more than a regulative idea, has today become an inescapable fact. This new situation, in which 'humanity' has in effect assumed the role formerly ascribed to nature or history.*[1]

In addition to a methodology (as detailed in the previous chapter), the preparation of an LCA requires a great deal of data and software to manipulate the data. Computer programs can handle these data faster, more conveniently and with a better quality that human operator. In this context, a computer is an information processing machine that, fed with suitable instructions (called **program**) and information, also in a suitable form, can perform a sequence of actions and produce further information, namely a set of results. The development of software, i.e. a collection of related programs, dictates the way in which data should be collected, organized and processed, and improves the theoretical framework, as it forces to state the underlying

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[1] Arendt, Hannah, The Origins of Totalitarianism (1958; Cleveland and New York: Meridian Books, The World Publishing Company, 1967) p. 298.

principles clearly and unambiguously. According to Dijkstra 'the purpose of a program is to evoke computations and the purpose of the computations is to establish a desired effect')(Dahl et al.[73]). To achieve such 'desired effect' specific software tools are employed. First of all a distinction has to be made. This section addresses two types of software or programs. The first is the class of commercial or open source softwares that are designed to conform with an LCA protocol (e.g. **OpenLCA**, respectively). They can handle more processes than spread sheets, can be connected to LCA database (e.g. Ecoinvent) and incorporate some advanced features for exporting and charting results. The second is the class of scripting or programming languages[2] that serve to process a certain amount of data to compute figures or to customize data into a convenient format. **R**, **Python** and **VBA**[3] languages belong to this realm. They play an important role in the **inventory analysis** to convert and to structure information in such a way to fit the LCA data quality requirements and to compute the specific amounts of all components used in the system. In addition, the **LabVIEW** visual programming language has been employed to develop an application to analyse the FC bus recorded data and compute relevant figures of merit. An effective way to organize the resulted collections of related information is to map them on a **markup language schema** in ways that are easily understandable by both humans and computers. **Extensible Markup Language** (**XML**) is a standardized language intended to facilitate the authoring of structured documentation[4]. It encourages authors to concentrate on structure, which conveys meaning, rather than on how the document should be rendered. The XML is a child language of the **Standard Generalized Markup Language** (SGML). SGML grew out of an earlier language called Generalized Markup Language (GML) developed around 1970 by the IBM version called Doc-

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[2] According to ECMAScript Language Specification: 'ECMAScript was originally designed to be used as a scripting language, but has become widely used as a general-purpose programming language. A scripting language is a programming language that is used to manipulate, customize, and automate the facilities of an existing system. In such systems, useful functionality is already available through a user interface, and the scripting language is a mechanism for exposing that functionality to program control. In this way, the existing system is said to provide a host environment of objects and facilities, which completes the capabilities of the scripting language. A scripting language is intended for use by both professional and non-professional programmers'. (see www.ecma-international.org ➡)

[3] VBA stands for Visual Basic for Applications. Excel VBA is Microsoft's programming language for Excel and all the other Microsoft Office programs, like Word and PowerPoint. The Office suite programs all share a common programming language.

[4] It has other uses, such as data interchange. In The Chicago Manual of Style 16th ed. [53], markup is defined as the labels or annotations that are applied to a manuscript or other document in order to identify its structure and its components (www.chicagomanualofstyle.org ➡).

ument Composition Facility Generalized Markup Language (DCF GML). After several years of further development, Standard Generalized Markup Language (SGML) was issued in 1986 as Standard 8879 by the ISO. As a result of the attempt to make SGML generally suited to almost any markup text, what emerged is a ‘metalanguage for generating descriptive markup languages’[38] rather than any specific markup language. By 1993, SGML had become very popular[67]:

> *The rapid spread of SGML exceeds anything we anticipated in 1987 and does not appear to be slowing. It is far from a perfect markup system, but it has been very effective in focusing attention on document structure rather than transient formatting and in facilitating document interchange.*[5]

There are now two pillars that are central to information processing: **programs** and **data**. Essentially a program is a **communication**. One purpose is to communicate a sequence of actions to a computer (or a processor), which has to execute it. A second purpose is for the program text itself to be sufficiently understandable not only to the original programmer, but also to any programmers who is asked to emend it. Successful communication is achieved by using special languages which can be understood by programmers and by computers. As previously said, such languages have been designed to smooth over this task. On the complementary side, data represent the **content** (i.e. the message) that have to be transferred or used to represent a particular instance of the corresponding situation. So the primary use of representation is to convey information about important aspects of the real world to others, and to record this information in digital form. The subsequent two sections further develop the application of the above mentioned concepts. Each section examines the steps involved in making the LCA in systematic manner and illustrate the problems involved (i.e. how information should be properly structured) and the kind of results that can be produced. As a very preliminary conclusion, an environmental expert ought to be fully conversant with Information Technology to take advantage of the underlying concepts and mechanisms that could be exploited to compute an environmental figure of merit for a product and/or its major components.

4.1 Data collection pipeline: data modelling and information processing

The collection of data is done following three main parallel routes as depicted in Figure 4.1. The first one serves to obtain all figures pertaining to the hydrogen production rates and energy consumption of the production and refuelling stations. The second one focuses only on the fuel cell bus performances, i.e. hydrogen consumption and distance covered[6]. The data are recorded on daily basis, grouped by month and by year (the High VLO City project spans several years). The third one gathers all the information on the type of service, namely the operating status (regular service, special service, no operation due to regular maintenance, no operation due to failure/repair, no operation due to planning reasons) and type of failure (failure in: fuel cell system, h2 storage system, energy storage, electric drivetrain, electric driven auxiliaries and conventional vehicle part).

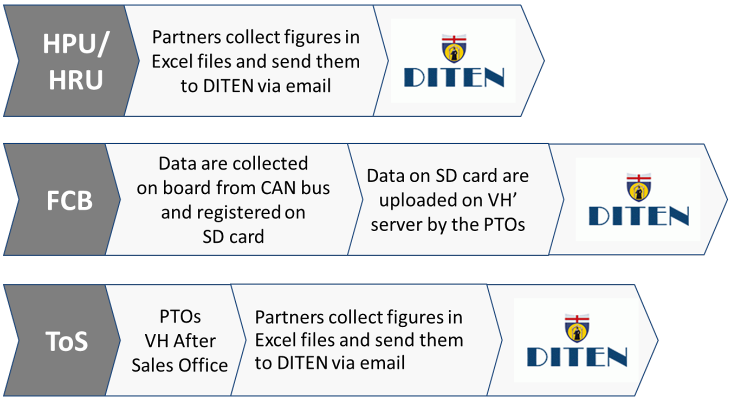


Figure 4.1: It shows the three main stages followed to get relevant data to perform the performance analysis

This section sets out to explain all the steps that comprise the second path of collecting data process on FC Bus performance. The results of this process is a collection of figures of merit pertaining the overall performance of the FC bus and the associated Hydrogen refuelling station: the amount of Hydrogen per 100 Km (KgH2/100Km), distance covered by the bus fleet (Km) and the energy consumed to produce and refuel the bus (KWh/KgH2). Such information, in a suitable form, can be added up and entered in the inventory table in the LCA software. A **Program structuring** approach is followed, which helped to define the building blocks, the control mechanisms, the data formats and the interfaces of the software's modules to produce the desired results. Program structuring encompasses the definition of: the software executive structure, modularity (including program and data modules), structure within each block, the interface points between levels and within levels, the choice of scripting languages (select which is the best suited for a

---

[6] Other data are recorded on the on board logger, but for KPI calculation the distance and consumption figures are used.

specific task). The output of this breakdown process is the arrangement of the following elaboration stages: Download data log files, Convert log files into text files, Decode log files, Data processing, KPI calculation, Update of the KPI table, Save data to XML file, Generate charts. These stages are summarized in Table 4.1.

Step	Software language or tool	Note
Download data log files	FileZilla	
Convert log files into text files	Executable file	
Decode log files	R language	
Data processing	R language	Save XML file ”MASTER_FCB_DATA”
KPI calculation	LabView	
Update of the KPI table	Excel VBA	
Save data to XML file	R language	Save XML file ”KPI_HIGHVLOCITY”
Generate charts	Python Language	

Table 4.1: Elaboration Stages

The subsequent subsections address each stage providing the rationale behind the programing language choice, the hierarchy of levels of abstraction (data structure, program decomposition,...), the description of the implemented algorithm (written in pseudocode) and the output that will be the input of the successive stage. Pseudocode, which is often suggested as an alternative to flowcharts, is a natural-language version of the code in which the program will actually be written. Just as in a flowchart, its primary purpose is to presents the logic that controls the flow of the program.

4.1.1 Download data log files

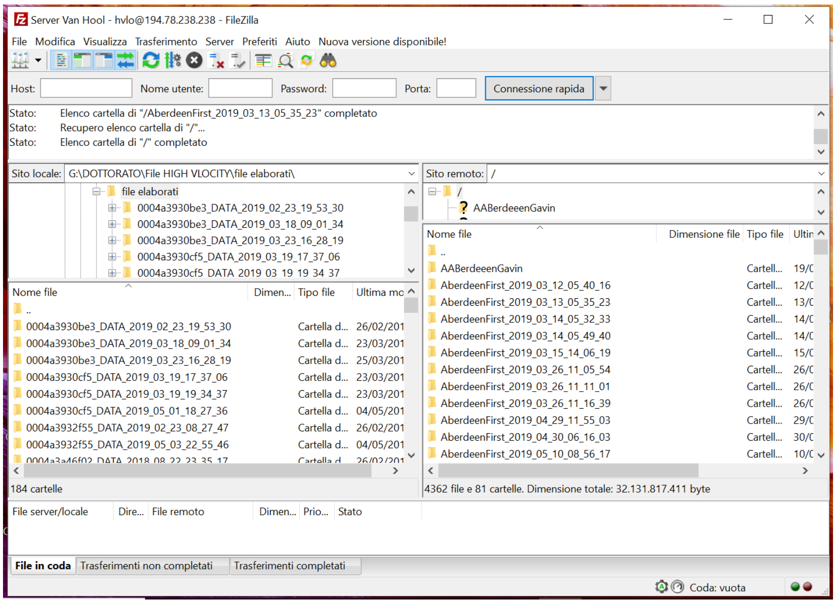
The user download the log files via a freely available FTP program (Figure 4.2 shows the FileZille application used to download the data from a VanHool server).

4.1.2 Convert log files into text files

Upon download completion, the user has to launch an executable file from each log directory to convert all files into ASCII-encoded files that can be processed with common elaboration tools. Figure 4.3 shows the resulting file content. Each row is made up of tab-separated items that comprises a single acquisition frame.

4.1.3 Decode log files

Ones the log files are ready to be turned in to computable numbers, some issues are apparent. The resulting files have an huge size that in some cases



Stato: Elenco cartella di "/AberdeenFirst_2019_03_13_05_35_23" completato
Stato: Recupero elenco cartella di "/"...
Stato: Elenco cartella di "/" completato

Sito locale: G:\DOTTORATO\File HIGH VLOCITY\file elaborati\

- file elaborati
  - 0004a3930be3_DATA_2019_02_23_19_53_30
  - 0004a3930be3_DATA_2019_03_18_09_01_34
  - 0004a3930be3_DATA_2019_03_23_16_28_19
  - 0004a3930cf5_DATA_2019_03_19_17_37_06
  - 0004a3930cf5_DATA_2019_03_19_19_34_37

Nome file	Dimen...	Tipo file	Ultima mo
..			
0004a3930be3_DATA_2019_02_23_19_53_30		Cartella d...	26/02/201
0004a3930be3_DATA_2019_03_18_09_01_34		Cartella d...	23/03/201
0004a3930be3_DATA_2019_03_23_16_28_19		Cartella d...	25/03/201
0004a3930cf5_DATA_2019_03_19_17_37_06		Cartella d...	23/03/201
0004a3930cf5_DATA_2019_03_19_19_34_37		Cartella d...	23/03/201
0004a3930cf5_DATA_2019_05_01_18_27_36		Cartella d...	04/05/201
0004a3932f55_DATA_2019_02_23_08_27_47		Cartella d...	26/02/201
0004a3932f55_DATA_2019_05_03_22_55_46		Cartella d...	04/05/201
0004a3a46f02_DATA_2018_08_22_23_35_17		Cartella d...	26/02/201

184 cartelle

Sito remoto: /

- /
  - AABerdeeenGavin

Nome file	Dimensione file	Tipo file	Ultin
..			
AABerdeeenGavin		Cartell...	19/0
AberdeenFirst_2019_03_12_05_40_16		Cartell...	12/0
AberdeenFirst_2019_03_13_05_35_23		Cartell...	13/0
AberdeenFirst_2019_03_14_05_32_33		Cartell...	14/0
AberdeenFirst_2019_03_14_05_49_40		Cartell...	14/0
AberdeenFirst_2019_03_15_14_06_19		Cartell...	15/0
AberdeenFirst_2019_03_26_11_05_54		Cartell...	26/0
AberdeenFirst_2019_03_26_11_11_01		Cartell...	26/0
AberdeenFirst_2019_03_26_11_16_39		Cartell...	26/0
AberdeenFirst_2019_04_29_11_55_03		Cartell...	29/0
AberdeenFirst_2019_04_30_06_16_03		Cartell...	30/0
AberdeenFirst_2019_05_10_08_56_17		Cartell...	10/0

4362 file e 81 cartelle. Dimensione totale: 32.131.817.411 byte

File server/locale	Dire...	File remoto	Dimen...	Prio...	Stato

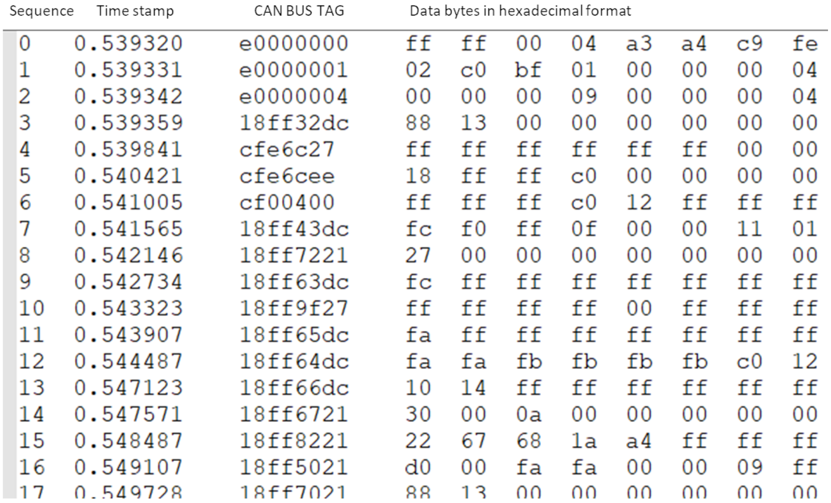
Figure 4.2: The user has to select the interested folders, select the destination folder and start the download.

could be greater than 1GB. This poses a significant challenge on how to handle such amount of data. A convenient means was the to implement the decoding scheme using **R** language that has a specific library to handle large ASCII files. Methods are provided to access and process files blockwise. Consequently, the construction of the decoding algorithm followed the above approach. The program, as shown in listing 4.1, is written in pseudocode.

The computation is decomposed into a time-succession of actions. A way of doing this is to write the textual succession of such (abstract) statements: "Declaration section, Select LOG data folders, Main loop through selected folders". The "Declaration section" serves to setup all the necessary data structures and supporting functions for the computation. The "Select LOG data folders" returns the list of LOG data folders, each containing the files to be processed. The selection is done via regular expression, i.e. a pattern describing a certain amount of text useful to match specific folders. The structured statement "Main loop through selected folders" is made up of four nested loops each performing a specific task. The outer loop, which is modelled on the 'for statement', yields the value (i.e. the folder name) of the corresponding element of the list of LOG data folders. In its turn, such value is used to select all the log data files. Then, each file is split into chunks of 500,000 rows that are processed individually[7] via selection of the CAN BUS

---

[7] In this case a while statement was used since the calculation of the exact number of



Sequence	Time stamp	CAN BUS TAG	Data bytes in hexadecimal format							
0	0.539320	e0000000	ff	ff	00	04	a3	a4	c9	fe
1	0.539331	e0000001	02	c0	bf	01	00	00	00	04
2	0.539342	e0000004	00	00	00	09	00	00	00	04
3	0.539359	18ff32dc	88	13	00	00	00	00	00	00
4	0.539841	cfe6c27	ff	ff	ff	ff	ff	ff	00	00
5	0.540421	cfe6cee	18	ff	ff	c0	00	00	00	00
6	0.541005	cf00400	ff	ff	ff	c0	12	ff	ff	ff
7	0.541565	18ff43dc	fc	f0	ff	0f	00	00	11	01
8	0.542146	18ff7221	27	00	00	00	00	00	00	00
9	0.542734	18ff63dc	fc	ff	ff	ff	ff	ff	ff	ff
10	0.543323	18ff9f27	ff	ff	ff	ff	00	ff	ff	ff
11	0.543907	18ff65dc	fa	ff	ff	ff	ff	ff	ff	ff
12	0.544487	18ff64dc	fa	fa	fb	fb	fb	fb	c0	12
13	0.547123	18ff66dc	10	14	ff	ff	ff	ff	ff	ff
14	0.547571	18ff6721	30	00	0a	00	00	00	00	00
15	0.548487	18ff8221	22	67	68	1a	a4	ff	ff	ff
16	0.549107	18ff5021	d0	00	fa	fa	00	00	09	ff
17	0.549728	18ff7021	88	13	00	00	00	00	00	00

Figure 4.3: A single row of data is a collection of adjacent tab-separated items, called fields that are organized as follows: the Sequence is just a row counter, the Time stamp stores the time of measurement generated by external sensor, the CAN BUS tag denotes the unique message identifier that is necessary to decode the subsequent 8 byte string of data.

TAG. At this stage a single text file is saved accordingly. The output is a collection of related files with respect to tags as illustrated in Figure 4.4.

---

chunks was time-consuming. The terminating condition was checking the length of the block. If it is zero, there are no more chucks so the computation can continue with the next file.

Listing 4.1: Script's program plan

columns
```
#****************************************************
# Library declaretion
#****************************************************
# Factors and Offsets
#****************************************************
# CAN BUS TAG declaretion
#****************************************************
# Function declaration
#****************************************************
# list of functions
#****************************************************
# Select LOG data files
#****************************************************
# Main loop through selected folders
#****************************************************
for(testFolder in input_folder_list){
#****************************************************
# Get file list
#****************************************************
# Get FC Bus code
#****************************************************
# Second loop through LOG files
#****************************************************
  for (fname in fileList){
    #****************************************
    # While loop for reading in chuncks at a time
    #****************************************
    while(lendata > 0){
      #****************************************
      # inner loop through TAG_Index_List
      #****************************************
      for(i in TAG_Index_List){
        # each row of the chunck is elaborated
        # according to the selected TAG
      }
    }
  }
}
```

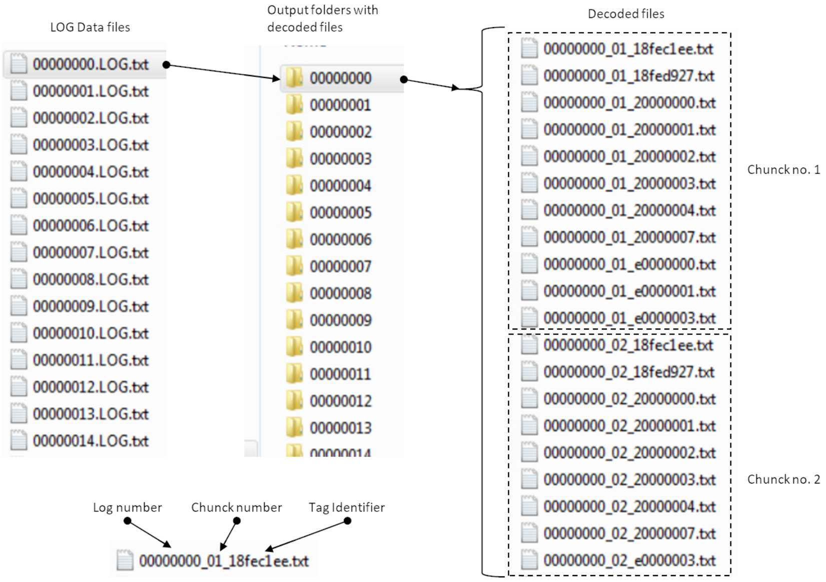


Figure 4.4: The figure shows the information architecture and decoding scheme for each file. This allows an effective way to handle different kind of data and shows the application of the abstraction process.

4.1.4 Data processing

This module aggregate the above mentioned files in one-dimensional arrays and save them in csv[8] format in dedicated folders to facilitate successive elaboration. Figure 4.5 shows the processed data is arranged in the proper folder. The consumption data are saved in the dedicate folder named ”consumi” that has two types of array: one for the distance covered by the bus and one for the hydrogen used during service.

The program used to implement the data processing is showed in Listing 4.2. As in the previous step, it is written in pseudocode to facilitate understanding. The implementation language is R.

Listing 4.2: Script’s program plan

columns

```
# Functions implementation
# CAN BUS TAG list
# Create CAN bus tag selection mask
# FC Bus dictionary
# Input folder selection associative array
# Select folder list
```

---

[8] A comma-separated values (CSV) file is a delimited text file that uses a comma to separate values.

```
# Main loop through selected folders
for (out_folder in out_folder_list){
  # XML object setup
  # Loop through Can Bus Tag list
  for (CAN_BUS_TAGitem in CAN_BUS_TAG_LIST) {
    # Loop through selected files
    for (file_index in file_index_list){
      # Selection of files according to CAN bus tag
      if ((CAN_BUS_TAGitem == "20000000") && mask[CAN_BUS_TAGitem]){
        # Add GPS_SIGNAL
      }
      if ((CAN_BUS_TAGitem == "20000001") && mask[CAN_BUS_TAGitem]){
        # Add GPS_LATITUDE
      }
      if ((CAN_BUS_TAGitem == "20000000") && mask[CAN_BUS_TAGitem]){
        # Add LONGIGTUDE
      }
      if ((CAN_BUS_TAGitem == "20000002") && mask[CAN_BUS_TAGitem]){
        # Add ALTITUDE
      }
      if ((CAN_BUS_TAGitem == "20000004") && mask[CAN_BUS_TAGitem]){
        # Add GPS DATE
      }
      if ((CAN_BUS_TAGitem == "20000007") && mask[CAN_BUS_TAGitem]){
        # Add GPS SPEED
      }
      if ((CAN_BUS_TAGitem == "18fec1ee") && mask[CAN_BUS_TAGitem]){
        # Add DISTANCE
      }
      if ((CAN_BUS_TAGitem == "0cfe6cee") && mask[CAN_BUS_TAGitem]){
        # Add SPEED
      }
      if ((CAN_BUS_TAGitem == "18fed927") && mask[CAN_BUS_TAGitem]){
        # Add H2CONDITIONS
```

```
            }
        }
    }
}
# Save gps dates to text file
# Add GPS DATE to XML file
# Save XML file
```

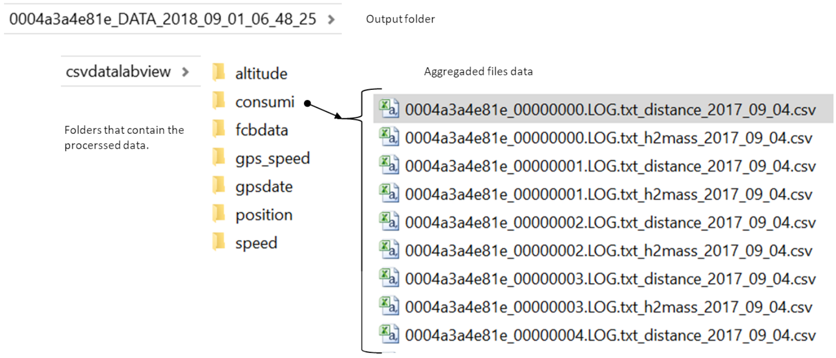


Figure 4.5: File data aggregation and folders' hierarchy.

The program is organized around these (abstract) statements: "Declaration section, Select output folders, Main loop through selected folders, Save XML file". The "Declaration section" and the "Select output folders" perform the same tasks as described in previous stage. The structured statement "Main loop through selected folders" is made up of three nested loops each performing a specific task. The outer loop, which is modelled on the 'for statement', yields the value (i.e. the folder name) of the corresponding element of the list of output folders. The second loop scans the CAN BUS TAG list and the selected tag item is used to match the corresponding files that are yielded in the last inner loop. In this way each decoded file is added up to build a comprehensive array of the same type. The last statement "Save XML file" saves the XML file which contains all the timestamp information of the log files (start date and end date of the log data file). Such file name is structured according to this pattern: "MASTER_FCB_DATA_<year>_<month>_<day>_<hour>_<minute>_<second>.xml". The XML architecture is illustrated in listing 4.3.

```
<FCB_LOGDATA FCBid="       ">
  <buschassis>       </buschassis>
  <ptosite>       </ptosite>
  <datetime>       </datetime>
    <gpsdate>
```

```
        <date>       </date>
      ...
    </gpsdate>
  <FCB_DATA>
    <LOG name="00000000.LOG.txt">
      <Datainiziale>       </Datainiziale>
      <Datafinale>       </Datafinale>
    </LOG>
  ...
  </FCB_DATA>
</FCB_LOGDATA>
```

Listing 4.3: FCB LOGDATA XML file

4.1.5 Update KPI table

The computed values as result of the previous step are entered in an Excel file that serves as a storage medium of all the performance figures of the bus. A VBA program exports all the data in two-dimensional arrays and save them in tab-separated values format. The destination folders are named to reflect the year-basis fashion. Figure 4.6 shows the resulting elaboration process.

4.1.6 Save KPI data to XML file

The raw log data undergo to successive elaborations stages that produced customized information. Such information can be structured in a XML-tagged document so as to create an efficient way to share it among different media. The XML schema is illustrated in Listing 4.4.

```
<?xml version="1.0"?>
<KPI_HIGHVLOCITY>
  <SITE name="Antwerp">
    <FCB_LOG>
      <FCB FCBid="       " BusChassis="       ">
      <DATE year="2015">
        <MONTH month="Jan">
        <DISTANCE Type="Odometer" Unit="Km">       </DISTANCE>
        <DISTANCE Type="Logged" Unit="Km">       </DISTANCE>
        <H2_MASS Unit="Kg">       </H2_MASS>
        <FUEL_EFFICIENCY Unit="Kg/100Km">       </
            ↪ FUEL_EFFICIENCY>
```

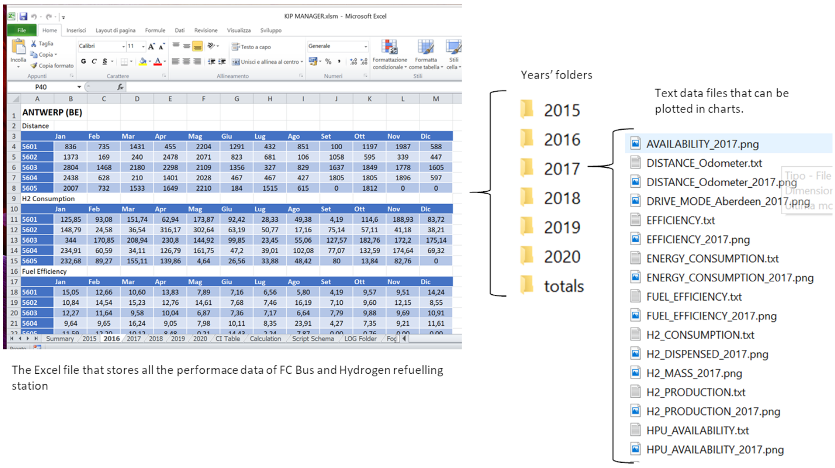
```
    </MONTH>
    ....
  </DATE>
  ...
</FCB>
<HRU>
  <DATE year="2015">
    <MONTH month="Jan">
      <H2_DISPENSED Unit="Kg"></H2_DISPENSED>
      <REFILL Unit="Number"></REFILL>
      <ELECTRIC_CONSUMPTION Unit="Kwh"></
          ↪ ELECTRIC_CONSUMPTION>
    </MONTH>
    ...
    </DATE>
  ...
</HRU>
</SITE>

<SITE name="Aberdeen">
    <FCB_LOG>
  <FCB FCBid="" BusChassis="">
  <DATE year="2015">
    <MONTH month="Jan">
    <DISTANCE Type="Odometer" Unit="Km"></DISTANCE>
    <DISTANCE Type="Logged" Unit="Km"></DISTANCE>
    <H2_MASS Unit="Kg"></H2_MASS>
    <FUEL_EFFICIENCY Unit="Kg/100Km"></
        ↪ FUEL_EFFICIENCY>
    </MONTH>
    ....
  </DATE>
  ...
</FCB>
<HPU>
  <H2_PRODUCTION>
    <DATE year="2015">
      <MONTH month="Jan">
      <ELECTROLYER_1 Unit="Kg"></ELECTROLYSER_1>
      <ELECTROLYSER_2 Unit="Kg"></ELECTROLYSER_2>
      <ELECTROLYSER_3 Unit="Kg"></ELECTROLYSER_3>
```

```
          </MONTH>
          ...
      </H2_PRODUCTION>
      <ENERGY_CONSUMPTION>
        <DATE year="2015">
          <MONTH month="Jan">
          <ELECTROLYSER_1 Unit="Kwh"></ELECTROLYSER_1>
          <ELECTROLYSER_2 Unit="Kwh"></ELECTROLYSER_2>
          <ELECTROLYSER_3 Unit="Kwh"></ELECTROLYSER_3>
          </MONTH>
          ...
        </DATE>
      </ENERGY_CONSUMPTION>
      <SPECIFIC_ENERGY>
        <DATE year="2015">
          <MONTH month="Jan">
          <ELECTROLYSER_1 Unit="Kwh/Kg"></ELECTROLYSER_1>
          <ELECTROLYSER_2 Unit="Kwh/Kg"></ELECTROLYSER_2>
          <ELECTROLYSER_3 Unit="Kwh/Kg"></ELECTROLYSER_3>
          </MONTH>
          ...
        </DATE>
      </SPECIFIC_ENERGY>
      <EFFICIENCY>
        <DATE year="2015">
          <MONTH month="Jan">
          <ELECTROLYSER_1 Unit="%"></ELECTROLYSER_1>
          <ELECTROLYSER_2 Unit="%"></ELECTROLYSER_2>
          <ELECTROLYSER_3 Unit="%"></ELECTROLYSER_3>
          </MONTH>
          ...
        </DATE>
      </EFFICIENCY>
      <HPU_AVAILABILITY>
        <DATE year="2015">
          <MONTH month="Jan">
          <HPU_AVAILABILITY Unit="%"></HPU_AVAILABILITY>
          </MONTH>
          ...
        </DATE>
      </HPU_AVAILABILITY>
```

```
    </HPU>
    <HRU>
      <DATE year="2015">
      <MONTH month="Jan">
        <H2_DISPENSED Unit="Kg">        </H2_DISPENSED>
        <TOTAL_HYDROGEN_DISPENSED Unit="Kg">        </
            ↪ TOTAL_HYDROGEN_DISPENSED>
        <NUMBER_FILLS_HIGHVLOCITY Unit="Number">        </
            ↪ NUMBER_FILLS_HIGHVLOCITY>
        <NUMBER_FILLS_TOTAL Unit="Number">        </
            ↪ NUMBER_FILLS_TOTAL>
        <SPECIFIC_ENERGY_CONSUMPTION Unit="Kwh/Kg">        </
            ↪ SPECIFIC_ENERGY_CONSUMPTION>
        <AVAILABILITY Unit="%">        </AVAILABILITY>
      </MONTH>
      ...
      </DATE>
      ...
    </HRU>
  </SITE>
</KPI_HIGHVLOCITY>
```

Listing 4.4: KPI HIGHVLOCITY XML file



ANTWERP (BE)

Distance

	Jan	Feb	Mar	Apr	Mag	Giu	Lug	Ago	Set	Ott	Nov	Dic
5601	836	735	1431	455	2204	1291	432	851	100	1197	1987	588
5602	1373	169	240	2478	2071	823	681	106	1058	595	339	447
5603	2804	1468	2180	2298	2109	1356	327	829	1637	1849	1778	1605
5604	2438	628	210	1401	2028	467	467	427	1805	1805	1896	597
5605	2007	732	1533	1649	2210	184	1515	615	0	1812	0	0

H2 Consumption

	Jan	Feb	Mar	Apr	Mag	Giu	Lug	Ago	Set	Ott	Nov	Dic
5601	125,85	93,08	151,74	62,94	173,87	92,42	28,33	49,38	4,19	114,6	188,93	83,72
5602	148,79	24,58	36,54	316,17	302,64	63,19	50,77	17,16	75,14	57,11	41,18	38,21
5603	344	170,85	208,94	230,8	144,92	99,85	23,45	55,06	127,57	182,76	172,2	175,14
5604	234,91	60,59	34,11	126,79	161,75	47,2	39,01	102,08	77,07	132,59	174,64	69,32
5605	232,68	89,27	155,11	139,86	4,64	26,56	33,88	48,42	80	13,84	82,76	0

Fuel Efficiency

	Jan	Feb	Mar	Apr	Mag	Giu	Lug	Ago	Set	Ott	Nov	Dic
5601	15,05	12,66	10,60	13,83	7,89	7,16	6,56	5,80	4,19	9,57	9,51	14,24
5602	10,84	14,54	15,23	12,76	14,61	7,68	7,46	16,19	7,10	9,60	12,15	8,55
5603	12,27	11,64	9,58	10,04	6,87	7,36	7,17	6,64	7,79	9,88	9,69	10,91
5604	9,64	9,65	16,24	9,05	7,98	10,11	8,35	23,91	4,27	7,35	9,21	11,61

The Excel file that stores all the performace data of FC Bus and Hydrogen refuelling station

Text data files that can be plotted in charts.

Figure 4.6: From Excel to file.

The program, as reported in Listing 4.5, builds the above XML structure, that serves as a template for writing data in its nodes, and save it in the file ”KPI_HIGHVLOCITY.xml”. The main actions resolve around a set of statements that progressively build each single XML node of the document and assemble them to construct the whole XML-tagged structure. One of the advantage of R language is the possibility to create **named list**. A named list is data structure that allows the programmer to assign names to list members, and reference them by that names instead of numeric indexes. This feature further simplifies the code, enhancing its understanding, since it reduces the cognitive load necessary to manipulate a symbolic representation of data structures. So a collection of named lists of nodes, that can be map on the XML document structure, is incorporated into the instruction sequences. The subsequent three nested loops dynamically build up the entire XML tree structure.

Listing 4.5: Script’s program plan

```
# Function to create an XML node template to polulate
# Initialize associstive array
# Create Root Node "KPI_HIGHVLOCITY"
# Create Child Node "FCB"
# Build list named "FCB_Node_List"
# Add child nodes
# Build XML Node for Antwerpt Site
# Build HRU Node List for Antwerp site
# Build XML node for Aberdeen site
# Build Node list for ELECTROLYSER Production
# Build Node list for ELECTROLYSER Energy consumption
# Build Node list for ELECTROLYSER energy per Kg H2
# Build Node list for ELECTROLYSER Efficiency
# Build Node list for HPU availability
# Build Child Node list for HPU
# Build XML Child Node for HPU
# Build XML node List for HPU Node
# Add Child node to parent HPU Node
# Add Child node to parent Node HPU fro Aberdeen site
# Setup XML node "HRU" for Aberdeen site
# Build list with HRU Node List
# Add child node to parent node "HRU" for aberdeen site
# Loop through sites to build the complete XML tree
for (site in names(PTOsite_dict)){
  print(site)
  SITE_Node <- newXMLNode("SITE", attrs = c("name" = site))
  FCB_LOG_Node <- newXMLNode("FCB_LOG")
```

```
  addChildren(SITE_Node, FCB_LOG_Node)
  addChildren(KPI_HIGHVLOCITY_Node, SITE_Node)
  # Loop through each FC bus
  for (FCBitem in names(PTOsite_dict[[site]])) {
    BusChassis <- PTOsite_dict[[site]][[FCBitem]]$BusChassis
    FCB_Node <- newXMLNode("FCB", attrs = c("FCBid" = FCBitem,
        ↪ "BusChassis" = BusChassis))
  # loop through template nodes to be added to the FCB_Node
    for (nodeItem in AddNodes(FCB_Node_list, year_lst, month_
        ↪ lst)) {
      addChildren(FCB_Node, nodeItem)
    }
    addChildren(FCB_LOG_Node, FCB_Node)
  }
  if (site == "Antwerp") {
    addChildren(SITE_Node, HRU_Node_Antwerp)
  } else {
    addChildren(SITE_Node, HPU_Node_Aberdeen)
    addChildren(SITE_Node, HRU_Node_Aberdeen)
  }
  #*********************************************************
}
# Save XML file to disk
```

The program, illustrated in Listing 4.6, performs nodes' update, reading the values from the collections of data files, saved at the previous stage, and edit the selected node in the file ”KPI_HIGHVLOCITY.xml”. In computing context the above three abstract actions can be composed of more ”primitive” actions that establish the desired net effect[9]. The first step is to build the supporting data structures (in this case named lists or associative arrays) that represent the XML template structure that have to be manipulated. The result is a concatenation of the following (abstract) statements: ”Build FCB code associative array, Build Sites associative array, Build XML node associative array, Build data files associative array, Build XPATH associative array”. ”XPATH associative array” is the named list that stores the **XPath expressions** that allow to identify nodes of interest that match a particular criterion. The set of matching nodes corresponding to an XPath expression are returned in R as a list. These elements can be iterated over and processed depending on the requested operations. This is accomplished in the last step,

---

[9] Some author call them ”prime program”.

where a nested structure of loops navigate the entire tree and update the nodes accordingly.

Listing 4.6: Script's program plan

```
# Steup FCB code associatiave array
# Setup Sites associative array
# Build XML node associative array
# Build data files associative array
# Build XPATH associative array
# Edit FCB nodes (all sites)
for (site in names(PTOsite_dict)){
  for (FCBitem in names(PTOsite_dict[[site]])){
    for (year in as.character(year_lst)){
      # build xpath string
      xpath <- sprintf("//KPI_HIGHVLOCITY/SITE[@name = '%s']/
         ↪ FCB_LOG/FCB[@FCBid = '%s']/DATE[@year = '%s']/MONTH
         ↪ ", site, FCBitem, year)
      # loop through node item
      for (itemNode in names(XPATH_MAP[[site]][["FCB"]])[c
         ↪ (1,3,4)]){
        # build xpath string
        selection_xpath <- sprintf("%s/%s",xpath, XPATH_MAP[[
           ↪ site]][["FCB"]][[itemNode]])
        # Select TXT File
        file_data <- FILES_MAP[[site]][["FCB"]][[itemNode]]
        # Open TXT File
        conn <- file(file.path(data_files_folder, year, site,
           ↪ file_data), open="r")
        # read data
        rows_List <- readLines(conn)
        # loop through data rows
        for (itemRow in rows_List){
          data_elements_lst <- unlist(strsplit(itemRow, "\t"))
          data_map[[data_elements_lst[1]]]<- data_elements_lst[c
             ↪ (2:13)]
        }
        # Select BusChassis to select row in the file
        BusChassis <- PTOsite_dict[[site]][[FCBitem]]$
           ↪ BusChassis
        # Select XML Node
        Selected_Node_LIST <- getNodeSet(KPI_HIGHVLOCITY_Node,
```

```
           ↪ selection_xpath)
        # Loop through Months
        for (i in 1:length(Selected_Node_LIST)){
          # Update Node Value
          xmlValue(Selected_Node_LIST[[i]]) <- data_map[[
             ↪ BusChassis]][i]
        }
      }
    }
  }
}
# Edit HRU nodes (Antwerpt site)
# Edit HPU nodes (Aberdeen site
# Edit HRU nodes (Aberdeen site)
# Save updated XML files
```

4.1.7 Generate charts

In the last stage all the saved data are plotted in bar charts for presentation purposes (to add them in a PowerPoint presentation or in a report to facilitate the communication of the achieved results). The program is written in **Python** language and, as showed in Listing 4.7, reads the values in the "KPI_HIGHVLOCITY.xml", plots them in bar charts and saves the generated figures in PNG[10] image format.

Listing 4.7: Script's program plan

```
# Import relevat Python library
# Build XPATH map
# Chart customization map
# Create FC Bus identification Class
# Define function"plot_barchart"
# Define function"plot_chart"
# Calculate and plot monthly dustances covered by FC buses
   ↪ fleet
# plot Antwerp HRU node data
# plot Aberdeen HPU node data
```

---

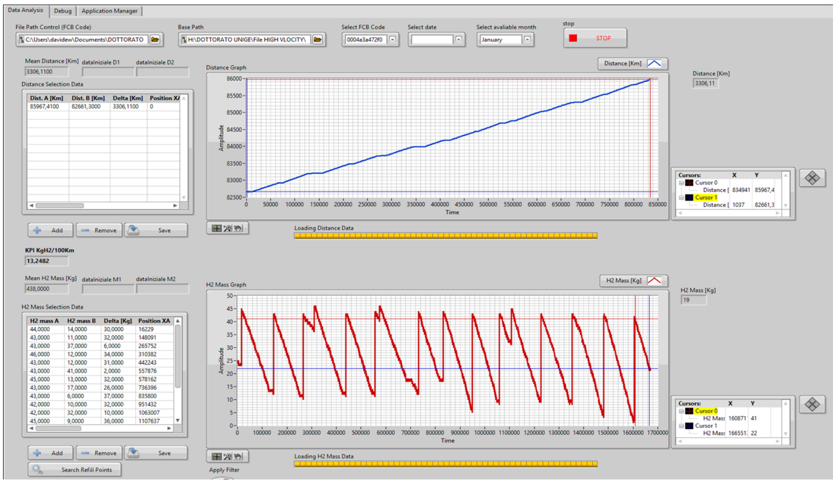
[10] A PNG file is an image file stored in the Portable Network Graphic (PNG) format. It contains a bitmap of indexed colors and uses lossless compression, similar to a .GIF file but without copyright limitations. PNG files are commonly used to store graphics for web images.

```
# plot Aberdeen HRU node data
```

Chapter 5

KPI calculation (Labview application)

This section will cover only the FC bus performance index calculation. To fulfil this task a specific LabVIEW application has been developed. The scope of this application is to read and plot the distance and consumption files data, let the user to easily calculate the corresponding fuel economy figures (KgH2/100Km) and export such data in a suitable format for further analysis and plotting charts. The reasons to develop the application using the National Instruments LabVIEW programming environment are mainly due to the following. LabVIEW is a graphical programming environment tailored to handle huge numeric data and includes excellent information presentation capabilities. This permits very rapid hands-on the recorded data and to carry out performance analysis. Figure 5.1 illustrates the front panel of the LabVIEW main application. It is made up of the following interface widgets: **combo boxes** that allow the user to select an option from a drop-down list, **waveform charts** to display the distance and consumption data, **multicolumn list boxes** that contains data in 2D array of string data type and **push buttons** to perform some actions on such data (add values into the multicolumn list box, delete a row in the multicolumn list box and save the content of the multicolumn list box into an XML file). Every action performed on the widget is managed by an event handler using the LabVIEW Event structure. As can be seen in Figure 5.2, the modularity of LabVIEW programming allows to simplify the programming structure by using reusable sub-modules. The application is therefore made up of two main blocks. The first one, named **Initialization Sequence**, is dedicated to initialize the front panel's controls to their default values. The second one, termed **Execution Unit**, handles the events that occur in the application. The description of the each blocks is reported in the following sections.



File Path Control (FCB Code): C:\Users\davidew\Documents\DOTTORATO

Base Path: H:\DOTTORATO UNIGE\File HIGH VLOCITY\

Select FCB Code: 0004a3a472f0

Select date:

Select avaliable month: January

Mean Distance [Km]: 3306,1100

dataIniziale D1:

dataIniziale D2:

Distance Selection Data

Dist. A [Km]	Dist. B [Km]	Delta [Km]	Position X
85967,4100	82661,3000	3306,1100	0

Distance [Km]: 3306,11

Cursors:	X	Y
Cursor 0		
Distance [	834941	85967,4
Cursor 1		
Distance [	1037	82661,3

KPI KgH2/100Km: 13,2482

Mean H2 Mass [Kg]: 438,0000

dataIniziale M1:

dataIniziale M2:

H2 Mass Selection Data

H2 mass A	H2 mass B	Delta [Kg]	Position XA
44,0000	14,0000	30,0000	16229
43,0000	11,0000	32,0000	148091
43,0000	37,0000	6,0000	265752
46,0000	12,0000	34,0000	310382
43,0000	12,0000	31,0000	442243
43,0000	41,0000	2,0000	557876
45,0000	13,0000	32,0000	578162
43,0000	17,0000	26,0000	736396
43,0000	6,0000	37,0000	835800
42,0000	10,0000	32,0000	951432
42,0000	32,0000	10,0000	1063007
45,0000	9,0000	36,0000	1107637

H2 Mass [Kg]: 19

Cursors:	X	Y
Cursor 0		
H2 Mass	160871	41
Cursor 1		
H2 Mass	166551	22

Figure 5.1: It is the graphical interface to select data and calculate figures

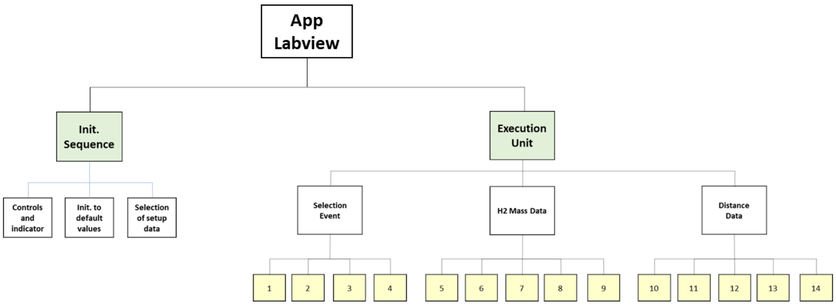


Figure 5.2: A schematic of the structure of the Labview application, showing the relationships between parts of the blocks.

5.1 Initialization Sequence

The **Initialization Sequence** is just a Flat Sequence structure[1] composed by three frames. The first frame just shows all the controls and indicators references and relevant clusters are defined (it can be seen as a declarative portion of the program). The second one contains a For Loop Structure (as in Figure 5.3) that scans all the controls in the Front Panel[2]. A Case Structure is used to execute specific subdiagram upon ClassName value. The same pattern is applied to controls that consist of sub items. For example, the Tab Control is made of pages and tabs that can be accessed via array indexing.

---

[1] A generic Flat Sequence structure consists of one or `moresubdiagrams`, or frames, that execute sequentially. It is used to ensure that a subdiagram executes before or after another `subdiagram`.

[2] The array of all controls is passed into the loop, thus enabling `auto-indexing`.

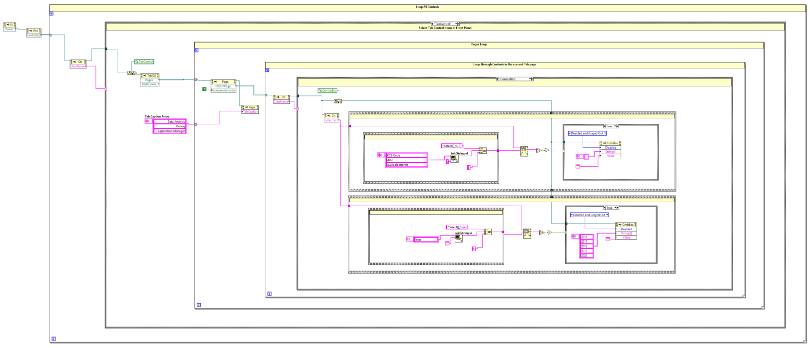


Figure 5.3: Hierarchically organized loops set default values in selected controls and reset indicators. A master loop select all the controls in the block diagram. Grouping elements such as tabs are probed in search of controls to initialize. Therefore, inner loops are possible to serve this purpose.

It is apparent the nested structure of loops and selection structures used to properly configure and initialize all the interface components. Upon completion of the initialization loop, the execution shifts to the last frame, where a simple event handler allow the user to select the file containing the FC bus identification codes and to select the base path of the log files. The latter event triggers the end of the event handler loop and transfers the control to the following Execution Unit.

5.2 Execution Unit

The **Execution Unit** is the core of the entire application. To facilitate the comprehension of the underlying machinery, the events are grouped according to their commonalities (see Figure 5.2), leading to three sets. The first one collects the events caused by selection. The second gathers the events related to H2 mass data, and the last one related to distance data. The latter two sets share the same architecture, therefore only one of the latter two will be described

5.2.1 Selection event

The first group brings together the following selection events: select a specific date from a list, select a month and select FC bus identification code. The selection can be done independently from one another. The two task of date or a month selection both share the same programming blocks. The distinction between date and month is done using a flag. The task is organized around three flat sequence structures: the first one bundles data and set values for date or month; the second one loads log data and plots them; and the third one resets controls to their default values to be consistent with the new selection. The selection event of the FC bus identification code is handled by two flat sequences: the first one bundles data to build a specific cluster with relevant control's references; the second one resets controls to their default values to be consistent with the new selection.

5.2.2 Performance analysis

The second group collects events related to performance analysis. The task is composed of five sub diagrams which handle the actions the user performs. The first one manages the events generated when the user moves a cursor either by clicking and dragging the cursor on a graph. This action is necessary to select two measure points to calculate distance or fuel consumption. To gather the information about a specific point on the plot (i.e. the associated data file name and timestamp), an information retrieval data structure has been conceived as diagrammed in Figure 5.4. The idea behind is the following. The plot is made of combining log files, sorted by date. In their turn, each log file is made of various chunks, ordered by date as well. The choice of the concerned chunk is done selecting in which range the point is found. Each range is indexed and via an associative table the corresponding data file is picked up, including its timestamp. Such data is temporally stored in related indicators, that are ready to be written in the multicolumn list box. At the first the control's references are bundled and passed in a subVI that arrange data according to the row format in the Multicolumn list box.

The second one adds a data points to the multicolumn list box and calculate the mean value of the set of performance values, previously added.
The third one removes a specific row of data from the multicolumn list box and updates mean value accordingly.
The fourth and the fifth let the user to load data from an XML file and save the data to an XML file, respectively. Each column in the multicolumn listbox has its own meaning. To save all the rows in a consistent manner and let them available in a plain text format, XML was used to describe and identify information accurately and unambiguously. As diagrammed in Figure 5.5, each single column of a row in the multicolumn listbox is mapped onto an XML structure. Each element plays a specific role in such structure. For example the "H2A" value is coded as a text node in the node tagged "Y", conveying the meaning of the data; the "Delta" value is coded as an attribute of node tagged "DELTA" and so on. This associative table leads

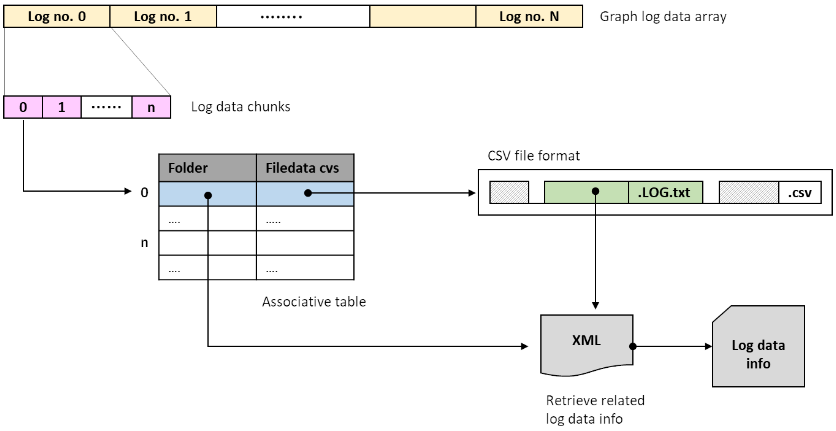


Figure 5.4: As the cursor moves on the plot, the program gets the file name of the selected point

to a marked up document that can be saved and shared for further analysis.

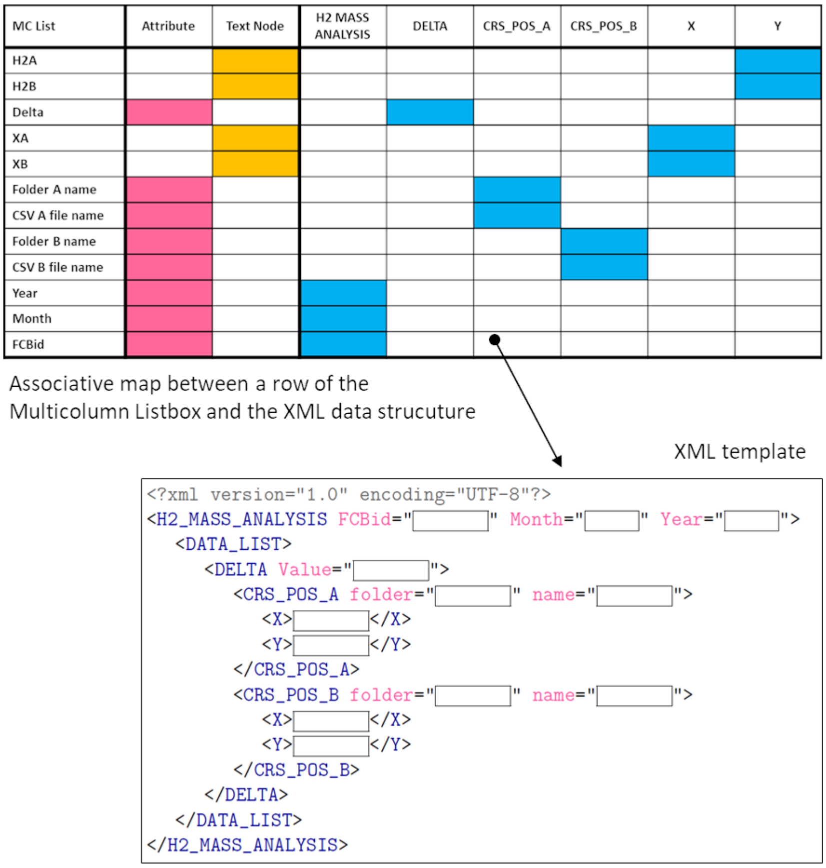
The implementation of the above XML document is done arranging a several XML node template block diagrams to resemble the entire document structure as in Figure 5.6. Each single node is configured with its own attributes and text values. A child node is connected to the "Child node Ref" terminal of its parent node. Sibling nodes are just connected via their "Parent node Ref" terminal, sharing the same parent node. The closure tag blocks are inserted to complete the entire document.

The XML node template block diagram is depicted in Figure 5.7. Each block performs a specific task to build a single XML node. The first one allows the assignment of the configuration values (attributes and text values) to the node. The next step is to create a new node element. The reference of the such element is used to add its attribute values, append it to its parent node and add a text value, if present.

As previously mentioned, the fourth block is conceived to select an XML file data, to populate the corresponding multicolumn listbox, and reset controls' status. A single flat structure, divided into four frames, performs the task.

At first step, A sub diagram loads the selected XML file and populate the multicolumn listbox.

The second step calculates the corresponding mean value of the consumed hydrogen. The third step updates the KPI on fuel economy. The last step enables the concerned controls that allow the user to delete a row in the multicolumn listbox and save the data tables. As previously said, the task of loading XML file and populate the corresponding multicolumn listbox is



MC List	Attribute	Text Node	H2 MASS ANALYSIS	DELTA	CRS_POS_A	CRS_POS_B	X	Y
H2A		🟧						🟦
H2B		🟧						🟦
Delta	🟥			🟦				
XA		🟧					🟦	
XB		🟧					🟦	
Folder A name	🟥				🟦			
CSV A file name	🟥				🟦			
Folder B name	🟥					🟦		
CSV B file name	🟥					🟦		
Year	🟥		🟦					
Month	🟥		🟦					
FCBid	🟥		🟦					

Associative map between a row of the
Multicolumn Listbox and the XML data strucuture

XML template

```
<?xml version="1.0" encoding="UTF-8"?>
<H2_MASS_ANALYSIS FCBid="" Month="" Year="">
   <DATA_LIST>
      <DELTA Value="">
         <CRS_POS_A folder="" name="">
            <X></X>
            <Y></Y>
         </CRS_POS_A>
         <CRS_POS_B folder="" name="">
            <X></X>
            <Y></Y>
         </CRS_POS_B>
      </DELTA>
   </DATA_LIST>
</H2_MASS_ANALYSIS>
```

Figure 5.5: Associative map.

implemented in a sub diagram "GetXML_CURSOR_DATA_ARRAY". Such sub module is structured in two main sub diagrams.
The sub diagram named "GetDATA_ANALYSIS_XML_File " returns the root node attributes and the one dimensional array of the child nodes that contains the information.
The second sub module named "LOOP_XML_DELTA_NODES " returns the two dimensional array with order data that will populate the multicolumn listbox. Such task is divided into three stages that are executed inside a loop structure as many times as the child nodes. The array is built progressively adding a new row of data at each loop step. The first stage return the DELTA node attribute value. The second stage builds the array with the two cursors' attribute values. A loop structure is used since such nodes are children of the DELTA nodes. So this solution simplify the programming load. The last stage arranges the incoming arrays into a single row of data that is dynamically concatenated to the resulting two dimensional array. Lastly, the

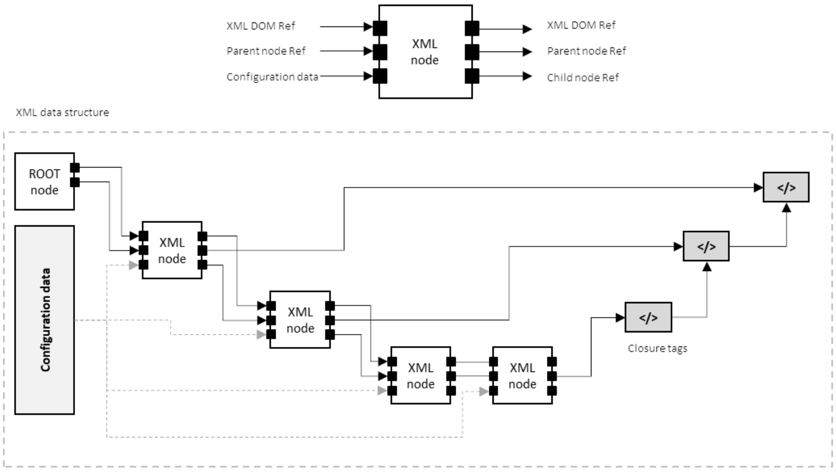


Figure 5.6: It uses a template module for a generic XML node that can be customized. Each module is arranged in a hirarchical fashion corresponding to requested XML structure

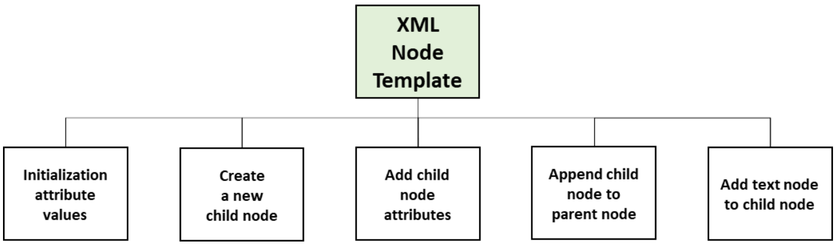
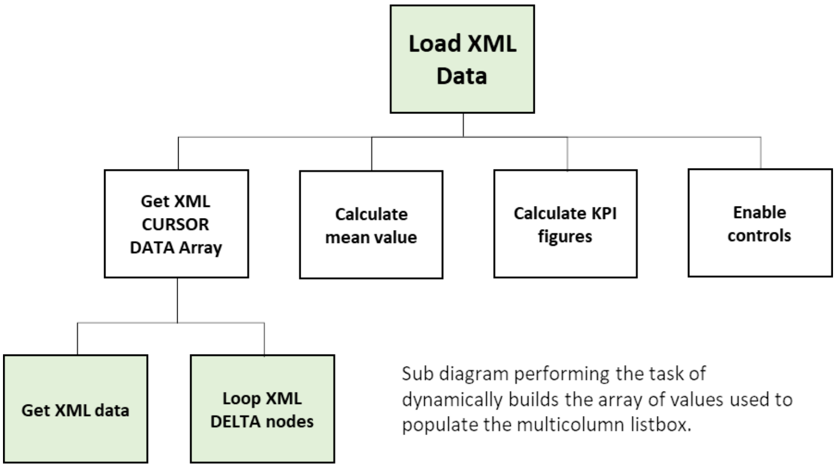


Figure 5.7: XML Node breakdown structure.

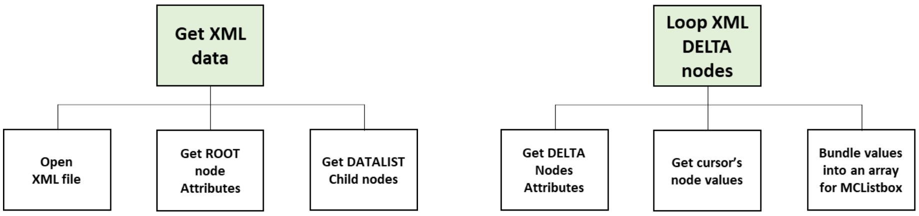
fifth sub diagram is designed to save the content of the multicolumn listbox into a XML file document consistent with the above mentioned pattern. The general architecture is composed of the functionally distinct sections: the first is for setup and initialization, the second runs the loop to convert all the rows of data into an XML data structure and the third save the XML document into a text file.

In the first section four sub frames perform the following tasks: the first sub frame returns the complete XML file name; the second combines node related information into a cluster; the third just include all the configuration clusters for each node; and the last frame creates the root node appending it to the XML document and set its attribute values.

Once the configuration has terminated, the content of the multicolumn listbox is scanned in a loop that serves to build the associated XML document. Each row is rearranged accordingly. The bundled data feed the template XML node sub modules with the data and the XML document is dynamically built. The first instance of the "DATA_LIST" node is created; the



(a) Load XML Data breakdown strucuture.



(b) A diagram showing the releshionship between parts of the program.

(c) A diagram showing the releshionship between parts of the program.

Figure 5.8: Sub diagrams that manage the XML data files.

instances of the ”DELTA”, ”CRS_POS_A”, ”CRS_POS_B”, ”X” and ”Y” nodes follow according the implemented structure. The last sub diagram saves the XML file.

Chapter 6

Environmental performance of fuel cell buses: a life cycle analysis of greenhouse gas emissions

6.1 Introduction

6.1.1 Policy context

Sustainable Urban Mobility

Transport is a complex system, engaging multiple subsystems, each of the latter being, in turn, hierarchic in structure. Such complexity is reflected in the significance of transport to almost every field of human endeavour in modern times and this centrality is what makes it multidimensional. Related statistical figures could clarify the composite nature of the transport sector. The European transport industry represents 6.3% of the Union's GDP [102] and employs nearly 13 million people [100]. In contrast, it has an impact on the environment and human health. Transport sector accounts for 30.8% of final energy consumption [101], represents 27% of Europe's Greenhouse Gas (GHG) emissions [98], and is the main cause of air pollution in cities, due to the strongest reliance on fossil fuels. Of these emissions, road transport is responsible for almost 72% (including international aviation and shipping). Travel by car still accounted for 83% of passenger-kilometres across the EU [104]. Moreover, in 2017, around three quarters (76.7%) of inland freight was transported by road ([103]). According to the recent European Environmental Agency (EEA) analysis [97], fine particulate matter (PM2.5) alone caused around 412,000 premature deaths in 41 European countries in the same year. About 374,000 of those deaths occurred in the European Union (EU), as explained in [97]. Such figures are accentuated by the high degree of urbanization. Almost three quarters (72.5%) of EU-28 inhabitants live in cities, towns and suburbs in 2014 [99]. Although relatively low rate of population growth, an uneven expansion of urban areas across the continent is also reported. The urgent need to curb emissions from transport sector has led the European Union (EU) to set forth policies and related supportive measures. The EU Communication 'Strategy for smart, inclusive, and sustainable growth' [334] highlighted the importance of a modernised and sustainable European transport system for the future development of the Union and underscored the need to address the urban dimension of transport. The European Commission (EC) has developed the concept of a sustainable urban mobility plan (SUMP) to tackle transport-related problems in urban areas more efficiently. As per EU guidelines, a SUMP is 'a strategic plan designed to satisfy the mobility needs of people and businesses in cities and their surroundings for a better quality of life. It builds on existing planning practices and takes due consideration of integration, participation and evaluation principles' [339]. The SUMP is adapted to the particular circumstances of each Member State and then actively promoted at national and regional levels, as recalled in [312].

Transport Policies Review

In the transport sector, exactly which elements are of concern, when the term 'sustainable' is applied, is a contentious matter. As mentioned above, the transport sector consumes resources of various kind: energy, settlement patters, individual's labour, and natural resources which erode the Earth's carrying capacity [1]. But solutions that alters one of these, may tip the system disastrously. A converging body of evidence has revealed that the notion of sustainable development (SD) is compelling and cuts across a wide range of matters, and the lack of operative definitions and disagreement, over what should be sustained, is the obstacle to meaningful synthesis of findings and consistent application in practice [162], [74]. Since 1990s several international bodies have tried to develop and operationalize the concept of sustainable transport (ST) into a suitable set of related policies. These initiatives approached the question across different perspectives [85]. During the 1990s, Europe began to suffer from congestion in certain areas and on certain routes, threating the economic competitiveness of the euro area. This warning was made in the 1993 White Paper on 'Growth, Competitiveness and Employment - The challenges and ways forward into the 21st century' [335].

The document claims that traffic jams, bottlenecks and missing links in the infrastructure fabric could endanger the competitiveness of the European Community. The Cardiff European Council in June 1998 set the process in motion by asking a number of sectoral Councils to develop concrete integration strategies 'for giving effect to environmental integration and sustainable development within their respective policy areas' [303]. The Transport Council defined its strategy in October 1999 during the European Council summit in Helsinki, highlighting five sectors in which measures should be pursued, namely (i) growth in CO2 emissions from transport, (ii) pollutant emissions and their effects on health, (iii) anticipated growth in transport, in particular due to enlargement, (iv) modal distribution and its development, and (v) noise in transport [323]. The EU White Paper 'European transport policy for 2010: time to decide' [304], issued in September 2001, incorporated the above strategy, claiming that the inclusion of SD could offer an opportunity for adapting the common transport policy. This programme was updated in the mid-term review of 2006 [305]. Approaching the end of the 10-years period, the Commission decided to launch a debate on the main challenges and opportunities for the transport sector in the long term (20 to 40 years). The aim was to produce a Communication on the Future on Transport, adopted by the Commission in June 2009 [307], preparing the ground for the next White Paper issued in 2011. The overall objective of the EU, regarding sustainable transportation, is 'to ensure that our transport systems meet society's economic, social and environmental needs whilst minimising their undesirable impacts on the economy, society and the environment' [320]. The above definition echoes the notion of SD as articulated by the Brundtland Commission in 1987 [37], thus underscoring that: 'sustainable mobility is transportation undertaken using a sustainable transport system' (EU, 2011c). In 2007 the European Commission (EC) presented the Green Paper 'Towards a New Culture for Urban Mobility' [306]. This Green Paper marked the starting point for a broad consultation process with all relevant stakeholders involved in the possible role the EU could have and the possible actions it could take. The consultation confirmed the added value of EU-level intervention in a number of urban transport-related areas. As a consequence, the EC published an 'Action Plan on Urban Mobility' (APUM) in 2009 [308], with 20 concrete EU-level actions to implement within 2012. The last White Paper 'Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system' no. COM(2011) 144 [340], published in 2011, presents the proposals for a sustainable transport systems of the EU until year 2050. It is claimed that the greenhouse gas emissions will be reduced 60% in 2050 compared to 1990, and rate of oil-based transport and the congestions will be decreased accordingly. As regards clean and efficient vehicles, this policy is guided by Communication no. 2010/0186 [309], which sets out a technologically neutral approach between alternative fuels for internal combustion engines (ICEVs), electric (EVs) and hydrogen fuel cell vehicles (HFCVs). In December 2019, the EC presented the 'European Green Deal', an ambitious roadmap for making Europe the first climate-neutral continent by 2050 [313]. The European Green Deal covers all sectors of the economy - notably transport, energy, agriculture, buildings, and industries - to foster the efficient use of resources by moving to a clean, circular economy and to stop climate change.

6.1.2 Hydrogen fuel cell bus in urban transport

The role of hydrogen in the EU's energy system

In July 2020, the EC unveiled its strategy to upscale hydrogen as a clean solution to the environmental crucible [315]. According to the EU strategy hydrogen can support the decarbonisation of industry, transport, power generation and buildings across Europe. The parallel Communication no. 299 [314] set out a vision on the transition towards a more integrated energy system and poses hydrogen as one of the pillars capable of supporting climate change and energy security goals. To help achieve this Strategy, in March 2020, the EC launched the European Clean Hydrogen Alliance with industry leaders, civil society, national and regional ministers, and the European Investment Bank. The aforementioned strategy resembles the so-called 'hydrogen economy' [167], namely an economy based on the hydrogen vector. This trend means the transition from the fuels with a larger ratio of carbon to those with a larger ratio of hydrogen [238]. In an integrated energy system, as outlined in [314], hydrogen can connect different layers of infrastructure, thus delivering low-carbon energy services. Staffell et al. [290] provide a comprehensive state-of-the-art update on hydrogen across different sectors. In particular, the authors analysed transport sector, evidencing that hydrogen may be the best realistic zero-carbon option for high-utilization, heavy-duty road transport vehicles such as buses and trucks. Such fossil-fuelled vehicles cause local air and noise pollution as well as vibrations that are harmful to health and impact the quality of living in urban areas [20].

Hydrogen fuel cell technology

Hydrogen and fuel cell technologies were identified amongst the new energy technologies needed to achieve a 60% to 80% reduction in greenhouse gases by 2050, in the European Strategic Energy Technology Plan presented along with the Energy Policy Package in January 2008 [336]. It was revised in the following years to effectively line up with the EU's Energy Union research and innovation priorities [313]. Fuel cell vehicles (HFCVs) have the potential of zero vehicle emissions and high efficiency when fuelled with hydrogen [237]. Fuel cells convert energy stored in a fuel directly into electricity without combustion. Unlike a battery, a fuel cell will continue to generate a current as long as the reactants are supplied [208]. The energy is produced from the controlled oxidation of molecular hydrogen [345]. A fuel cell consists of an anode, a cathode, and an electrolyte. The hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode, where oxygen is introduced. At the cathode, the oxygen binds with the hydrogen ions to form water. To complete the process, the free electrons released at the anode must join with the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates a current that can be used to power an electric device [208]. Fuel cells for transportation must meet more stringent requirements in terms of size and weight limits than those for stationary applications. Firstly, fuel cells are characterized by the kind of electrolyte that they use and then subcategorized by the type of fuel they use. The two broad categories of fuel cells are acid and alkaline (referring to the chemical nature of the electrolyte). The leading fuel cell technology for the automotive sector is the Proton Exchange Membrane (PEM) fuel cell, used in Gemini mission [196]. According to the National Fuel Cell Research Center [140] and to [108], PEM have greater than 55% efficiency (fuel cell only) when running on hydrogen. [153] highlighted the following attributes that make PEM FC suited to automotive use: they operate at relatively low temperatures (less than 100°C); have a high power density [111] and fast response; have safe and easy handling during manufacture and operation; quick start-up and shutdown. While use of fuel cells can lower local air pollutants, their production has environmental impacts. Martin Pehnt, of the German Aerospace Agency, has examined the resource and environmental impacts of PEM fuel cells by looking at the full production process Pehnt in [247], [246], [244], [243], [245]. In terms of cumulative environmental impact, the platinum group metals (PGMs), which act as catalysts, account for most of the greenhouse gas (climate change), sulphur (acidification), and nitrogen (eutrophication) emissions. Therefore, Pehnt suggests several options for improving the ecological impact of fuel cells. PGM requirements can be further reduced and the metals recycled; the electricity source can be shifted to renewable energy; and components of the fuel cell stack can eventually be eliminated or recycled. The above challenges triggered significant efforts in researching and developing PEM FCs, which could fit a variety of applications. Hydrogen-powered buses are the logical first step for introducing fuel cells because they can handle larger and heavier ones, can store large amounts of compressed hydrogen gas in tanks on the roof, and can be refuelled at central locations. Additionally, fuel cell buses are relatively mature at Technology Readiness Level (TRL) 7 to 8 [96].

Hydrogen fuel cell bus demonstration projects

The Decision No 1982/2006/EC [327] of the European Parliament and of the Council of 18 December 2006, concerning the Seventh Framework Programme (FP7) of the European Community (EC) for research, technological development and demonstration activities (2007-2013), identified key issues and priorities for accelerating deployment of a wide range of applications (from portable to stationary and transport): 'Integrated action to provide a strong technological foundation for competitive EU fuel cell and hydrogen industries, for stationary, portable and transport applications. The Hydrogen and Fuel Cells European Technology Platform contributes to this activity by proposing an integrated research and deployment strategy'. This led to the formation of a Public Private Partnership - the 'Fuel Cells and Hydrogen Joint Undertaking' (FCHJU) - between the European Commission, industry, and the research community. Formally set up by a Council Decision No 521/2008 [321] (EU, 2008), it is responsible for implementing the Fuel Cells and Hydrogen Joint Technology Initiative (FCH JTI), the political initiative proposing this public-private partnership in fuel cell and hydrogen technologies. Under the FP7, FCHJU funded several projects in the application area of 'Transport and Refuelling Infrastructure'. Work has been encouraged at local level through a succession of hydrogen bus demonstration projects. Three flagship European fuel cell bus demonstration projects paved the way for hydrogen transportation system in the urban context: Clean Urban Transport for Europe (CUTE), Ecological City Transport System (ECTOS), and HyFLEET:CUTE. CUTE and ECTOS projects ran from 2001 to 2005 and demonstrated 30 fuel cell buses in 10 European cities (Amsterdam (NL), Barcelona (ES), Beijing (CN), Hamburg (DE), London (UK), Luxembourg (LUX), Madrid (ES), Perth (AU), Reykjavik (ISL)), in addition to providing buses to partner programs in Perth and Beijing. The project showed that fuel cell buses could be delivered using series production and used safely and reliably in public transit routes. Refuelling stations were constructed and operated in each of the project cities, incorporating on-site renewable production of hydrogen and achieving station availability of 80%. HyFLEET:CUTE was the next bus project run in the EU, from 2006 to 2009. It built upon the work done in CUTE/ECTOS, using the existing station infrastructure (plus one additional station built in Berlin) to demonstrate 47 hydrogen-powered buses in public transit in 10 cities on three continents. The project also covered the design, construction, and testing of next-generation fuel cell buses, in addition to improvements of the existing refuelling stations. Although the project did show significant improvements in the performance of the technologies, government-funded projects were still necessary to carry the technology forward towards commercialization. The Clean Hydrogen in European Cities (CHIC) project was, therefore, launched in 2010 to address these challenges and leading to full commercialization starting in 2015. Throughout the project lifetime, 54 fuel cell buses operated in the canton of Aargau (CH), in Bolzano (IT), London (UK), Milan (IT), Oslo (NO), Cologne (DE), Hamburg (DE), and Whistler (CA) (during 2010 Winter Olympics Games). By leveraging the experiences of past fuel cell bus projects, the High V(Flanders).L(Liguria) O(ScOtland)-City (High V.LO-City) project aimed at significantly increasing the 'velocity' of integrating these buses on a larger scale in European bus operations. The project run from 2012 to 2019. Fourteen fuel cell buses operated in Aberdeen (UK), Sanremo (IT), Antwerp (BE), and Groningen (NL). Since the start of the project, more than 900.000km have already been travelled by the buses, saving more than 900 tons of carbon dioxide.

Alternative fuel vehicles literature survey

The assessment of emerging transportation modes, fostered by the aforementioned policies, is addressed at different levels of analysis. One field of scholarship concentrates on grand patterns of scenario analysis spanning multi decal periods, presenting several alternative future developments. These studies emphasize recent energy efficiency policies and multi-criteria assessment (MCA) to help assess likely progress against a range of objectives.

Segments of such enquiries reflect on the conditions that drive technological transitions [271], [129], [128], [130]; on the systemic interplay of technological innovation and social learning [355], [254]; on the importance and performance ratings of technological innovations in the urban bus transport [197], [362]; on the role of institutions - Groningen and Phoenix cases are reported - in the pursuit of sustainable mobility [157]; and on the impact of transport on the global climate [50]. Another stream of research directs attention to environmental impact assessment, performing comparative analysis of alternative powertrain technologies and associated fuel pathways.

The Life Cycle Assessment (LCA) and Well-to-Wheel (WTW) approaches are the preferred methodologies to calculate the magnitude of a system's emissions through its entire life cycle (the former) or use phase (the latter). For instance, Lozanovski et al. in [201] assessed the sustainability of HFCB against environmental, economic, and social criteria. Navas-Anguita et al. in [228] compiled a techno-economic database for road transportation fuels, with focus on alternative fuels (such as hydrogen, biomass, and electricity). Orsi et al. in [239] performed a WTW analysis of different passenger vehicles and associated fuel supply infrastructures, while Hagos et al. in [138] concentrated solely on natural gas vehicles in Denmark. Offer et al. in [236] argued that a combination of electricity and hydrogen as a transport fuel could reduce the carbon emissions and bring also economic advantages to the end user. Saxe et al. in [277] reported the main operational results of the fuel cell buses operated in the CUTE project. Additionally, relevant updated reports are usually released in specialized groups of interests [124], [119]. A dedicated internet repository summarises all the main projects that promote hydrogen fuel cell buses in many European cities [123]. Bodek et al. in [23] and Heywood et al. in [154] addressed topics related to the evolution of vehicle technology and its deployment, the development of alternative fuels and energy sources, the impacts of driver behaviour, and the implications of all of these factors on future GHG emissions in the United States, Europe, China, and Japan [92]. The results generally indicate that vehicle production and end of life disposal make a significant, but a constant contribution to the overall lifetime performance. A recent review study on LCA of electrified vehicles, carried out by Marmiroli et al. in [212], have proved a plethora of diverging and conflicting results. The main hurdle identified is the absence of a compete goal and scope definition, leading to an incorrect or delusive interpretation of results. The authors identified electricity production as the most impactful phase when it adds up to climate change, and agreed on the need of finding consensus on the appropriate electricity mix [212]. In the EU, the EU-Directive 2000/53/EC [325] on end-of-life vehicle (ELV) was enacted in 2000. It aims to control the generation and disposal of wastes from automobiles and to enhance environment-consciousness among parties involved in ELV treatment, through the promotion of reuse, recycling and collection of ELVs and their components. The Directive is based on the subsidiary principle[1] and on the extended producer responsibility (EPR) principle [166]. According to the subsidiary principle, EU member states must establish their national legislations on the ELV recycling system. Targets that member states must meet for 'reuse and recovery' and 'reuse and recycling' rates are 95% and 85 %, respectively, since 2015. The index of 'reuse and recovery' includes energy recovery in addition to 'reuse and recycling'. Hence, the energy recovery is accepted up to 10% since 2015. Furthermore, the

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[1] Article 5(3) of the Treaty on European Union (TEU) and Protocol (No 2) on the application of the principles of subsidiarity and proportionality.

desirable rates of final disposal are less than 5% since 2015. Lithium-ion battery recycling has an outstanding role in tackling and diminishing the life cycle environmental impact of traction batteries and, therefore, of the rising electric mobility industry. Recycling might not only contribute to displace the production of energy intensive primary materials but is also a solution to a continuously growing waste stream. Nevertheless, recycling processes for lithium-ion batteries shall be implemented considering a broader environmental scope. Cerdas et al. in [46] highlight that the largest amount of GHG emissions avoided through the displacement of primary material production processes was found to be driven by the materials recovered during the dismantling phase, underscoring that current recycling technology is still energy-intensive and in some cases could yield lower quality secondary materials out of recovered materials. Dunn et al. in [83] hold the same conclusions because the energy consumed in assembly is so high. The gathered data depicted a direct relationship between process complexity and the variety and usability of the recovered fractions. Indeed, only processes employing a combination of mechanical processing, and hydro- and pyrometallurgical steps seemed able to obtain materials suitable for LIB (re)manufacture. On the other hand, processes relying on pyrometallurgical steps are robust, but only capable of recovering metallic components Velázquez-Martínez et al. in [354]. The production of LIBs has so far taken place almost exclusively in China, South Korea, and Japan. Hence, battery waste is mainly recycled in Asian and only a few European and North American plants. American and European recycling companies show a wide variety of technologies but lack the volumes of spent batteries for profitable operation. Avoiding high investments for dedicated process equipment, spent LIBs are also fed as secondary feed in existing metallurgical plants [360]. PEM FC recycling is problematic too, as argued by Wittstock et al. in [366]. Duclos et al. in [81] suggested a recycling process for the platinum catalyst contained in the MEA of a PEM fuel cell. The results reveal that the MEA life-cycle impact can be reduced by 60% if electrode recycling is carried out at the end-of-life stage of the fuel cell by the H2O2/Solvent recycling process. However, the proposed process is at laboratory scale and needs further optimization and subsequent industrialisation. Stropnik et al. in [293] proposed an implementation of the above process to ascertain the impacts on a 1KWh PEMFC system. They argue that '[w]ith proper recycling strategies in the EoL phase for each material, and by paying a lot of attention to the critical materials, the environmental impacts could be reduced, on average, by 37.3% for the manufacturing phase and 23.7% for the entire life cycle of the 1-kW PEMFC system'.

6.1.3 Hydrogen supply perspective

The hydrogen industry is well established and has decades of experience in industry sectors using hydrogen as a feedstock. The largest share of hydrogen demand is from the chemicals sector for the production of ammonia and in refining for hydrocracking and desulphurisation of fuels. Other industry sectors also use hydrogen, such as producers of iron and steel, glass, electronics, specialty chemicals and bulk chemicals, but their combined share of total global demand is less than ten percent [122].
Figure 6.1 provides an updated and comprehensive outline of the status of hydrogen technologies and their possible future development.

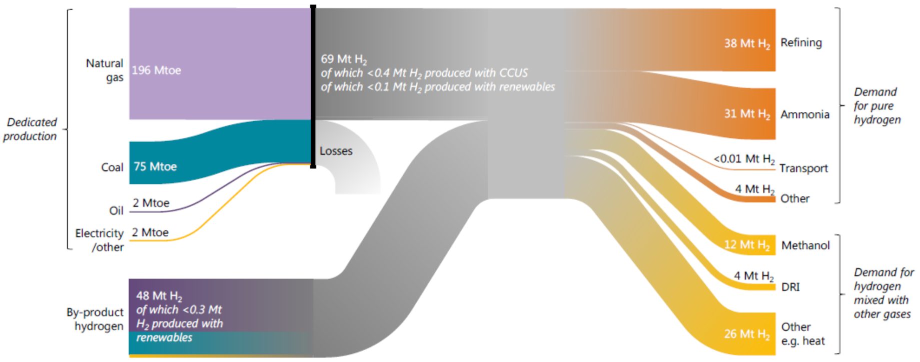

Figure 6.1: Today's hydrogen value chains [159].

Demand for pure hydrogen is around 70 Mt per year, and over 95% of current hydrogen production is still fossil-fuel based, with significant associated CO2 emissions [159]. Steam-methane reforming (SMR) is the most common way of producing hydrogen. Oil and coal gasification are also widely used, though to a lesser extent than SMR [122]. Only around 4% of global hydrogen supply is produced via electrolysis, mainly with chlor-alkali processes [122]. On the other hand, IEA suggested about 2% of share [159]. One-third of global supply is 'by-product' hydrogen, meaning that it comes from facilities and processes designed primarily to produce something else. This by-product hydrogen often needs specific types of cleaning and can then be sent to a variety of hydrogen-using processes and facilities. Most hydrogen is currently produced near to its end use, using resources extracted in the same country [159]. For example, the hydrogen refuelling station for the Groningen site is in the Chemical Cluster Delfzijl, close to AkzoNobel plant. Overall, less than 0.7% of current hydrogen production is from renewables or from fossil fuel plants equipped with carbon capture, utilization, and storage (CCUS). In total, hydrogen production today is responsible for 830 MtCO2/yr [159]. As mentioned above, hydrogen is made at large scale today (mostly from natural gas) for use in chemical processes such as oil refining and ammonia production. A variety of hydrogen production processes are commercially available today, including thermochemical methods, which are used to derive hydrogen from hydrocarbons, and electrolysis of water, during which electricity is used to split water into its constituent elements, hydrogen and oxygen. In this study, three main methods of hydrogen production, are described: electrolysis of water, chlor-alkali electrolysis, and thermochemical production methods (for relevant details see C).

6.1.4 Main Gaps in the Literature

However, many significant issues relevant to city bus mobility remain to be explored. For example, until now no studies in the research literature examine hydrogen-powered bus fleet's life cycle assessment impacts with alternative hydrogen production options, including the refuelling stations, and based on vehicle's real performance data. Previous articles point out the general lack of data for bus design, operation, and manufacturing ([68], [95]), and for refuelling stations as well [368]. For example, Harris et al. [143] conclude that there is a need for additional LCA studies covering the full vehicle equipment life cycle, while underscoring the difficulties in acquiring component composition and manufacturing data.

In response to existing gaps in the research field, this thesis aims at reporting a comprehensive LCA case study that uses real-world operations data to investigate the environmental impacts of High V.LO-City hydrogen fuel cell bus system (i.e. H2FC bus, hydrogen production routes, and refuelling stations) against a conventional Euro-6 Diesel bus. Specifically, three methods of hydrogen production are considered: electrolysis of water, chlor-alkali electrolysis, and steam methane reforming process.

6.2 Materials and Methods

6.2.1 Methodology

Life Cycle Assessment (LCA)

In this paper, to objectively and holistically evaluate the environmental benefits that are associated with all stages of H2FC buses, a Life Cycle Assessment (LCA) is performed to analyse energy consumption and greenhouse gas (GHG) emissions during H2FC bus's entire lifetime. A vehicle's LCA is comprised of two cycles: a vehicle life cycle that includes vehicle assembly, maintenance, dismantling, and recycling; and a fuel life cycle that involves all processes from harnessing a primary energy flow or stock to different forms of conversion, distribution, storage, and use in the vehicle [231]. The fuel life cycle is also referred to as the well-to-wheels (WTW) cycle. The term fuel is related to an energy carrier produced by a single or several resources as the source of primary energy [86].

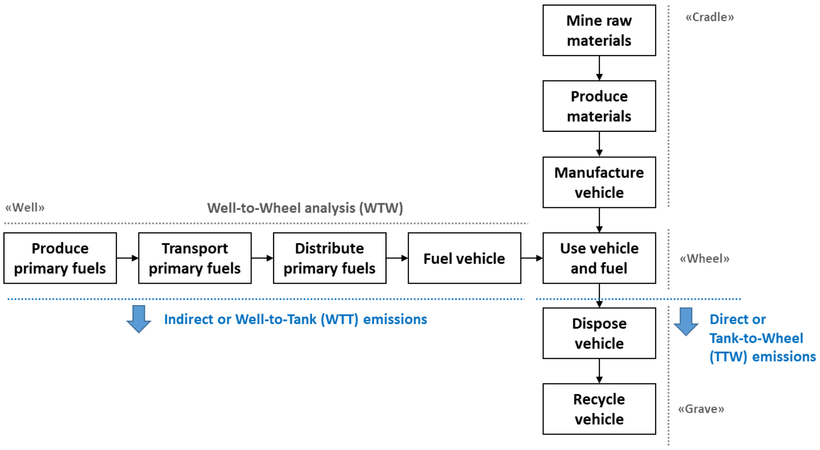

Figure 6.2: Concepts of well-to-wheel (WTW) and lifecycle analysis (LCA). Elaborated from [231] and [20].

The fuel life cycle integrates two independent stages. The first one, well-to-tank (WTT), includes energy generation, delivery pathway, and energy storage. The second one, tank-to-wheel (TTW), comprises energy utilization for traction power during vehicle operation [231]. At the regulatory level, WTW analysis is the preferred methodology used to assess GHG and energy savings in the transport sector. Such methodology is recalled, for example, by the European Union (EU) in the Fuel Quality Directive [333] and in Renewable Energy Directive [330] (EU, 2009). A WTW study could be considered one type of LCA of vehicles, which focuses exclusively on the life cycle of the energy carrier used to propel the vehicle, such as fuel (liquid or pressurized), or electricity. Within this scope, WTW analysis concentrates on the most energy and pollution-intensive links [62]. Advanced, fuel-efficient buses employ new components, such as fuel cells, battery packs, electric motors, and power electronics, in addition to new technologies that are necessary for producing and recycling these components. Therefore, such impacts must be considered during the assessment of a new vehicle technology as pointed out by Edwards et al. in [86]. This analysis is substantiated in the vehicle life cycle or materials cradle-to-grave (CTG) life cycle analysis represented by the vertical flow in 6.2.

Life-cycle calculations

The life-cycle analysis draws on software package OpenLCA 1.10.2 (OpenLCA, 2020), integrating Ecoinvent database v 3.5. This software allows the user to investigate the entire supply chain, back to the extraction of materials and fuels, providing detailed estimates of resource and energy use as well as environmental discharges. These potential impacts are evaluated for magnitude and significance in the life cycle impact assessment (LCIA) phase, using Environmental Footprint (EF) method which is the impact assessment method of the Product Environmental Footprint (PEF) framework, established in 2013 with a specific Recommendation no. 2013/179/EU [301], within the framework of the 'Single Market for Green Products' communication no. COM(2013) 0196 [311]. The PEF is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. PEF information is produced for the overarching purpose of seeking to reduce the environmental impacts of goods and services taking into account supply chain activities (from extraction of raw materials, through production and use, to final waste management). The PEF has been developed in the context of one of the building blocks of the Flagship initiative of the Europe 2020 Strategy - 'A Resource-Efficient Europe' no. COM(2011) 571 [310]. The European Roadmap [310] proposes ways to increase resource productivity and to decouple economic growth from both resource use and environmental impacts, taking a life-cycle perspective. In fact, one of its objectives is to: '[e]stablish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life-cycle ('environmental footprint')' (in [310] at pag. 7). A detailed description of the methodology is provided by [107]. The following midpoint environmental impact categories were considered: Resource use, energy carriers (ADP-f), Ozone depletion (ODP), Respiratory inorganics (PMFP), Eutrophication marine (MEP), Resource use, mineral and metals (SOP), Cancer human health effects (HTP-c), Non-cancer human health effects (HTP-nc), Land use (LOP), Eutrophication terrestrial (TEP), Climate change (GWP100), Eutrophication freshwater (FEP), Climate change - biogenic (GWP100-b), Photochemical ozone formation (HOFP), Climate change - land use and transform (GWP100-lu), Ionising radiation, HH (IRP), Ecotoxicity freshwater (FETP), Acidification terrestrial and freshwater (AP), Water scarcity (WCP), and Climate change - fossil (GWP100-f). However, for a better overview and comparability, the impact categories shown are limited to the ones that are the most widely used within studies: Climate change (GWP100), Photochemical ozone formation potential (HOFP), Acidification potential (AP) and Eutrophication potential (EP). Supporting Information in Appendix A and B provides results for a wide range of impact categories.

6.2.2 Case Study

Goal and scope of the case study

Demonstration projects are necessary to showcase transport technologies in action and to implement EU energy policy commitments [324]. The Seventh Framework Programme (7th FP) of the European Community [324] builds on such existing strategic initiatives and on subsides to deploy innovative mobility solutions. To date, this has included the development of hydrogen fuel and related infrastructure for transport, led by a Public-Private Partnership - the 'Fuel Cells and Hydrogen Joint Undertaking' (FCHJU), established by a Council Regulation on 30 May 2008 [321]. The High V.LO.-City demonstration project is part of this overarching strategy and addresses the integration of H2FC buses in the public transport (HighVLOCity). According to [120], demonstration 'provides evidence of the viability of a new technology that offers potential economic (and societal) advantage but cannot be commercialised directly. The act of demonstrating (i) proves the functional performance, including operability, reliability and economics and (ii) enhances public awareness and public acceptance of the applied technology'. The above definition offers a solid background to apply the case study research strategy within the bus fleet demonstration context. In fact, such condition is well explained by Yin in [369]: 'the need to use case studies arises when an empirical inquiry must examine a contemporary phenomenon in its real-life context, especially when the boundaries between phenomenon and context are not clearly evident'. Therefore, the High V.LO. City project can be regarded as an instance of a case study, since it fits Yin's definitional scheme. The objective of the project is the exploration of a bounded system in both space and time 'hydrogen powered buses in public transport', by addressing key environmental and operational concerns that local transport authorities are facing today. The project's context comprises four demonstration sites (denoting the embedded units of analysis in Yinian sense) for hydrogen refuelling stations and fourteen hybrid fuel cell (H2FC) buses:

- Aberdeen (UK) site operational since March 2015 (four buses). The bus fleet is operated by First Group a British multi-national transport group, based in Aberdeen, Scotland. The refuelling station houses an electrolyser system for on-site hydrogen production.

- Antwerp (BE) site operational since December 2014 (five buses). The bus fleet is operated by De Lijn, the local transport authority. The hydrogen is produced using residual hydrogen as a waste product from existing industrial activities in the Solvay Antwerp plant.
- Groningen (NL), site operational since November 2017 (two buses). The bus fleet is operated by Qbuzz (owned by Italian railways), the local transport authority. The hydrogen is produced using by-product hydrogen as a waste product from adjacent Akzo-Nobel chlorine plant (located in the Delfzijl Chemical Cluster).
- San Remo (IT) site operational since November 2018 (three buses). The bus fleet is operated by Riviera Trasporti, the local transport authority. The hydrogen is produced via SMR from industrial activities in the Air-Liquide plants and transported to the refuelling station via tube-trailer truck.

The goal of the present study is to investigate whether the above-mentioned options of hydrogen production routes are environmentally robust for urban transport in the coming years. In this context, as recalled in [289], robust means having comparatively low environmental impacts against a reference scenario (a Euro-6 Diesel Bus), underlying which conditions make hydrogen transport a viable option.

Data Collection Procedure

In this project, an in-depth longitudinal examination of each bus and hydrogen refuelling station is conducted, thus, offering a systematic way of collecting data, analysing information, and reporting the bus fleet's performance over a long period of time. Data on the bus performance are hydrogen consumption, kilometres driven, and availability, whereas data on the refuelling stations are hydrogen refuelled, plant availability, number of refills, and electricity used to power the dispenser to fill the bus.

6.2.3 Description of unit processes

The first step, as for ISO 14040 standard [90] and [91], is to define what belongs to the product system [133]. Two aspects have been considered: definition of the boundaries between the HRI-FCB and environment system, and the distinction between relevant and less relevant processes related to the HRI-FCB. The system described above can be represented diagrammatically with the main interactions shown as lines. This is done in 6.3 where the following unit processes are, thus, distinguished: (1) The Hydrogen refuelling infrastructure (HRI), which, in its turn, is composed by a Hydrogen Production Unit (HPU), applicable to water electrolysis plant, and a Hydrogen Refuelling Unit (HRU) that delivers the hydrogen to the bus, (2) Hydrogen fuel cell bus (H2FCB).

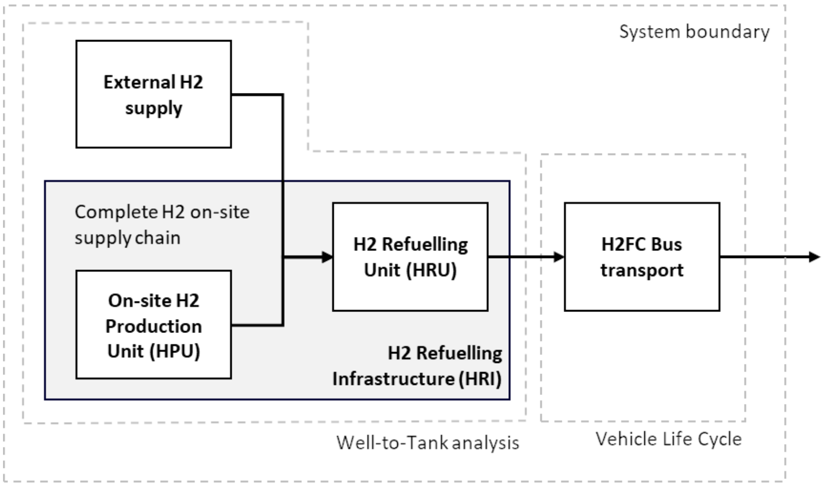

Figure 6.3: Schematic of system boundary which includes Hydrogen supply chain and FC Bus transport service.

Hydrogen infrastructure

Figure 6.4 shows a generalised schematic of hydrogen infrastructure facilities. Hydrogen is generated on site from electricity, natural gas and water, or supplied by truck from external sources. It is compressed, stored, and dispensed on demand to the buses. Dispensing requires a pressure differential between the on-site storage and the vehicle tanks (decanting). Depending on the design of the station, namely the pressure level of the on-site storage, filling may have to be completed with a booster compressor (booster mode). The compressor that charges the station storage and the one for completing the filling can be the same physical unit that is able to operate in different modes.

The physical boundaries of the refuelling stations encompass relevant input flows: electricity, water supply (for electrolyser), external hydrogen supply (as a by-product of a chemical plant). The amount of hydrogen dispensed

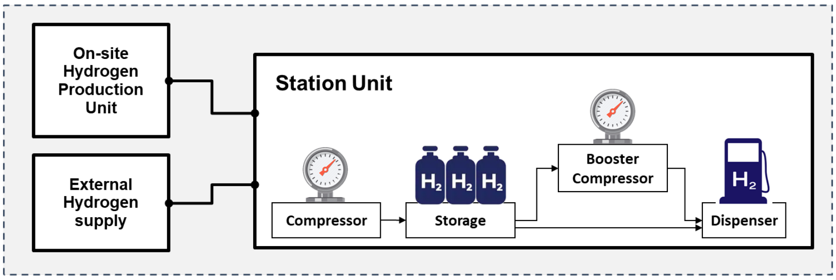

Figure 6.4: Generalised schematic of the hydrogen refuelling infrastructure.

to the bus is the reference flow and, hence, the functional unit of the HRI. 6.1 summarises the intervening processes. The reported values are normalized with respect to 1 Kg of Hydrogen produced or dispensed to the bus. Based on the above collected data, three individual unit processes, one for each hydrogen path, have been conceived and implemented.

HRI with on-site water electrolyser. The process is modelled using project data on the electrolier performance and energy used to power the plant. The material and energy used to build the station are based on information gathered from Aberdeen site and from literature [368]. The plant consists of three HySTAT(tm)60 electrolyser, capable of producing 360kg of hydrogen per day, two compressors, and a 420-Kg storage unit. The hydrogen generating unit is based on the principles of alkaline water electrolysis. In alkaline electrolysis the reaction occurs in a solution composed of water and liquid electrolyte (30% potassium hydroxide, KOH) between two electrodes. When a sufficient voltage is applied between the two electrodes, at the cathode water molecules take electrons to make OH? ions and H2 molecule. OH? ions travel through the 30% KOH electrolyte towards the anode where they combine and give up their extra electrons to make water, electrons, and O2. The recombination of hydrogen and oxygen at this stage is avoided by means of the highly efficient and patented IMET(r) ion-exchange membrane. The gases produced are cooled, purified, compressed, and stored. The alkaline cell inventory, including the stack arrangement, and additional balance of plant required to turn an AFC stack into a functional unit, is calculated from (Staffell et al., 2010). The compressor data are drawn on [204] who elaborated the inventory for a hydrogen refuelling station from HydroStaoil assembled in Reykjavik. The energy demand of the plant is the following: the production unit requires 65.26 KWh/KgH2, the dispenser 6.2 KWh/KgH2. The values are collected from the infrastructure performance figures delivered by Aberdeen City Council on a monthly basis.

HRI supplied by hydrogen as by-product from Chlor-alkali Electrolysis. As recalled in the introduction section, the main technologies applied for chlor-alkali production are mercury (19.7%), diaphragm (13.6%), and membrane (65.3%) cell electrolysis, mainly using sodium chloride (NaCl) as feed or to a lesser extent using potassium chloride (KCl) for the production of potassium hydroxide. Therefore, the result unit process is a weighted average of the above-mentioned production technologies. The gas is delivered to the station via underground pipes. The electricity demand of the station is relevant to the dispenser to fill the bus with the gas (about 7.1 KWh/KgH2). The material and energy used to build and maintain the station are considered in the model.

HRI supplied by hydrogen from SMR process. The process is modelled drawing on [241], [220] and Ecoinvent database. The electricity demand is relevant to the filler unit and is calculated from actual consumption data (about 8.8 KWh/KgH2). The gas is delivered to the station via tubes trailer trucks. As mentioned above, the material and energy used to build and maintain the station are also included in the inventory. It is worth to underscore that the differences in electricity demand at the refuelling station are mainly due to different dispenser unit configuration and setup, thus leading to specific energy demand to power the station. The electricity supply inventory is calculated from EU electricity mix ('group market' for electricity from Ecoinvent database), as described in [343] and [344]. Additionally, 'green' electricity from renewables is modelled from label-certified electricity which represents a special market for renewable electricity supply in Ecoinvent [343] and [344].

Hydrogen supply components	Water Electrolysis plant	Chlor-alkali Electrolysis plant	Steam Methane Reforming
Refuelling Unit Electricity demand [KWh/KgH2]	6.2	7.1	8.8
Electrolyser Electricity demand [KWh/KgH2]	65.26	-	-
Water Use [L/KgH2]	22.25	-	-
External Hydrogen Supply	-	As a by-product of chlor-alkali electrolysis [33]	From steam methane reforming [241]
Refuelling station (building, operation, and decommissioning)	Project data, Ecoinvent, and Wulf et al. [368]	Project data, Ecoinvent, and Wulf et al. [368]	Project data, Ecoinvent, and Wulf et al. [3

Table 6.1: Hydrogen Refuelling Unit (HRI) product system summary, components' demand factors, and inventory data sources.

Hydrogen Fuel Cell Bus

The vehicle, object of the present study, is a A330 hybrid fuel cell buses from Van Hool (Belgium), belonging to vehicle category M3 as per Directive 2007/46/EC [328] (namely, as reported in the Annex II: 'Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes'). In such new buses, the fuel system and internal combustion engine have been replaced by a high-pressure (350 bar) hydrogen storage system, two polymer electrolyte (PEM) fuel cell stacks (overall 150 KW of rated power), including balance of plant components (fuel cell auxiliary systems), a lithium-ion battery (17 KWh), a DC/AC inverter, and two electric motors. The electric motors power a standard low floor rear axle through an automatic gearbox, similar to the configuration of the conventional bus. Most auxiliaries except those specific to the fuel cell system are standard. The general model structure is illustrated in Figure 4. The modelled transport components are linked in a unit process referred to as 'transport, hydrogen fuel cell bus'. To link the various transport components to the reference flow of '1 Km driving distance' (Van Mierlo et al., 2017), the demand factors are determined. Demand factors for bus components, i.e. bus glider manufacturing, electric power train supply, bus operation, and bus disposal, are calculated as the inverse of the bus's lifetime transport performance, denoted by the 'FCB_life' parameter. As the FC stack lifetime is less than the bus lifetime, the stack has to be exchanged twice over the bus lifetime. While the lithium-ion battery has to be replaced around four times. The ratio between the bus lifetime and their individual lifetime denotes the replacement schedule number (including the item that is at the beginning of the vehicle lifecycle). Such values, rounded down to the nearest multiple, are further dived by the bus lifetime to obtain the correct demand factor on a per-Km basis. The negative demand factor in the end-of-life process is consistent with the Opposite Direction Approach (ODA) or double-negative approach implemented in OpenLCA under the use of a product flow as a quantitative reference of the waste treatment process.

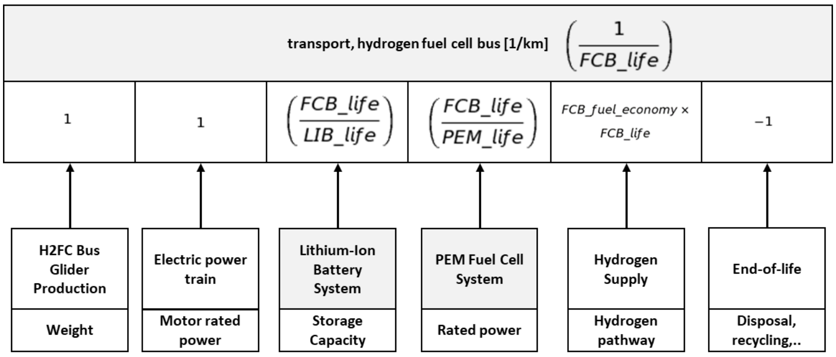

Figure 6.5: Principle model structure and transport components and their relationship.

H2FC Bus Manufacture. Data on the production of the H2FC bus are based on Ecoinvent and on project's partners support. The inventory of the FC systems (i.e. fuel cell stack and related balance of plant (BOP)) is obtained from [222]. Their model was scaled to 150 KW of rated power. The Lithium-Ion battery is modelled from [209]. Though the study is based on Ecoinvent 2.2, the corresponding processes in Ecoinvent 3.5 have been found and applied to the model. The electrical powertrain is composed by two electric motors, two gear boxes, two inverters, and a power management system. The inventory of the electrical motor is based on the Siemens Drive Motor 1PV5138-4WS24 technical information sheet. The gear box coupled to the motor is a Flender gear unit delivering 22,000 N torque. The electric module comprises a Siemens MONO inverter and a Siemens DICO (Digital Input Control) drive system controller. Their inventory is calculated from their datasheets.

H2FC Bus Operation. For the H2FC bus use life cycle stage, operational energy is calculated on estimated fuel economy and on the lifetime of FC stack and lithium-ion battery. The average hydrogen use is calculated by dividing the kilometres driven in service by the hydrogen consumed. The obtained figure is 10.54 KgH2/100Km driven. Although H2FC buses have no tail-pipe emissions, the environmental burdens depend on the hydrogen supply route chosen for the scenario assessment. The expected H2FC bus lifetime is set equal to 800.000 Km as required by EU Directive 2009/33/EC [330].

H2FC Bus End-of-Life. End-of-life (EoL) treatment of the bus's steel and metal parts was modelled to reflect current legislation in Europe for end-of-life vehicles, namely 95% reuse and/or recycling and 5% landfilling as recalled in the Directive no. 2000/53/EC [326]. EoL treatment of all remaining vehicle components (electrical system, tyres, glazing, wood, lube oil, refrigerant) was modelled reflecting standard practice: open-loop recycling for glass, incineration for tyres and plastic mixtures, and landfilling treatment for all other parts. The recycling of spent lithium-ion battery comprises a hydrometallurgical process to extract metals. Required processes are from Ecoinvent. The treatment of exhausted fuel cell stacks relies on a mechanical and chemical process, as mentioned above, to recover precious material (platinum and metals). The modelled process is built on [293] and [81]. The calculation of the environmental credits ensuing from EoL material recycling and energy recovery was performed based on the average mix of the best available technologies and on the assumption in consequential LCAs [226]. 6.2 summarises the main characteristics of the product system which includes the H2FC bus lifetime, fuel cell system, ion-lithium battery, and fuel economy.

Demand factor	Average 13 m H2FC Bus	Inventory source
Fuel economy (KgH2/100Km)	10.54	Average value computed from buses operational data
Assumed Bus lifetime (Km)	800,000	EU Directive 2009/33/EC [330]
Assumed FC stack lifetime (Km)	240,000	Miotti et al.[222]
Li-Ion battery capacity (KWh)	17	Project's partner data
Assumed Li-Ion battery lifetime (Km)	150,000	Pagliaro et al.[240]
Bus weight (ton)	15	Project's partner data and Ecoinvent
Drive power (KW)	2 x 85	Project's partner data

Table 6.2: Characteristics of the hydrogen fuel cell bus product system.

Reference vehicle

The Mercedes-Benz Citaro O530 Euro-6 bus was chosen as a basis for comparison. It is a 13-meter long vehicle equipped with a 220KW diesel engine and has an estimated fuel economy of about 34.25 L/100Km. The fuel consumption figure is calculated from the onboard monitoring system, thus providing information under realistic driving conditions. Relevant inventory data for manufacturing, operation, and disposal are from Ecoinvent database. The bus is currently in service in the municipality of Groningen and is operated by Qbuzz.

6.3 Results

The Life Cycle Impact Assessment (LCIA) of the H2FC bus system is articulated in three steps. The first addresses the overall environmental impacts and consumption of resources associated with the vehicle cycle. The second includes the evaluation of the potential environmental emissions and resource use stemming from fuel cycle. The third combines the above two assessments to provide the comprehensive picture of the H2FC bus system life cycle.

6.3.1 H2FC bus contribution analysis

Figure 6.6 summarises the LCIA of the H2FC bus. The credits from recycling stage have been separated from the overall impacts. The contribution of individual hydrogen bus components, during the vehicle's entire lifetime, are reported. The outcome relevant to lithium-ion battery is consistent with previous LCA studies [209] and [72]. The environmental impacts of the PEM FC system show that the catalyst accounts for a large share of overall emissions in most of the impact categories. The main causes are the emissions originating from the mining of platinum [222]. Furthermore, as underscored by [233], metal refining to sufficient purities frequently requires energy-intensive and precisely-controlled melting stages, often powered by fossil-fuel inputs. The bus manufacturing drives most of the total emissions. The supply of metals and the assembly stage are energy-intensive processes in the vehicle cycle. The trend is confirmed by previous project results (ECTOS and CHIC, for example).

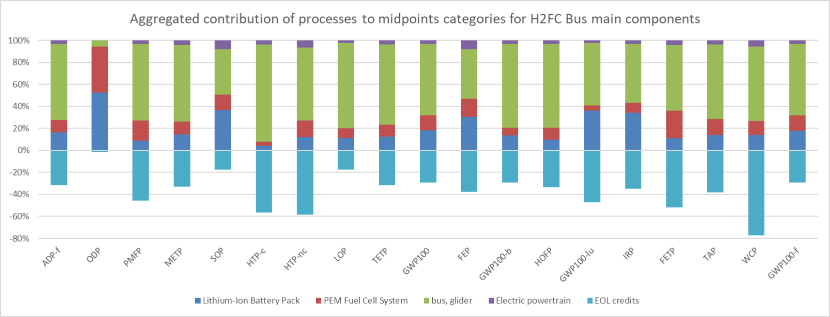

Figure 6.6: Life cycle impacts, including recycling credits. Impacts refer to one H2FC bus during its entire lifetime. The recycling credits are expressed as a percentage of the total burden. Impact categories: Resource use, energy carriers (ADP-f), Ozone depletion (ODP), Respiratory inorganics (PMFP), Eutrophication marine (MEP), Resource use, mineral and metals (SOP), Cancer human health effects (HTP-c), Non-cancer human health effects (HTP-nc), Land use (LOP), Eutrophication terrestrial (TEP), Climate change (GWP100), Eutrophication freshwater (FEP), Climate change - biogenic (GWP100-b), Photochemical ozone formation (HOFP), Climate change - land use and transform (GWP100-lu), Ionising radiation (IRP), Ecotoxicity freshwater (FETP), Acidification terrestrial and freshwater (AP), Water scarcity (WCP), and Climate change - fossil (GWP100-f).

Climate change (GWP100)

The source for CFs for climate change at midpoint is the fifth assessment report of IPCC (IPCC, 2013), for a time horizon of 100 years including climate-change carbon feedbacks for both CO2 and non-CO2 substances. The values with feedbacks are applied to ensure consistency, as feedbacks are already included for CO2 [107]. The effects on global warming come mainly from the production of components or metal mine operations in countries where fossil fuel dominates electricity mixes. Bus life cycle accounts for nearly 65% of the total climate change impacts. The supply of the chromium steel, the aluminium, the double glass panels, the glass fibre reinforced plastic, the synthetic rubber, and the electronic modules represent the main impacting processes, covering almost 90% of the entire share. Li-ion batteries cause significantly impacts during the manufacturing stages. Most impacts from the positive electrode paste (around 39%) are predominantly the result of the use of tetrafluoroethylene, lithium iron phosphate (about 59%), N-methyl-

2-pyrrolidone, and carbon black. The electricity used to meet the energy requirements for battery cell production contribute to 13% of the battery's total GWP. Moreover, BMS, negative electrode paste, and battery packaging take around 40%. PEM FC system life cycle contributes 14% to this category. The fuel cell stack manufacturing process accounts for 54% of the above-mentioned share. The results show that PEM, Catalyst, Bipolar Plates (BPP), and Gas Diffusion Layer (GDL) are the main contributors to the manufacturing stage. The use of tetrafluoroethylene, polyethylene, sulphur trioxide, platinum, organic solvent, and carbon black results in such high impacts.

Photochemical ozone formation (HOFP)

Photochemical ozone formation is a measure for estimating airborne substances potential to form atmospheric oxidants, these oxidants can in turn, in the presence of sunlight, react with oxygen in the air and form ground level ozone. Typical oxidants are nitrogen oxides, carbon monoxide (CO) and volatile organic compounds (VOC) [146][2]. The negative impacts from the photochemically generated pollutants are due to their reactive nature which enables them to oxidise organic molecules on the surfaces they expose [371]. Bus life cycle accounts for nearly 76% of the total impacts. The production and supply of double glass panels (36%), natural-rubber-based seal (20%), electronics units (5%), chromium steel (5%), aluminium (5%) are the top five contribution to HOFP category. Li-ion batteries holds 10%. Battery management system (BMS) (38%), Positive electrode paste (25%), electricity supply (10%), Module and Battery Packaging (8%), and Negative electrode substrate (5%) contribute to around 86% of the share. PEM FC system life cycle covers the remaining 7%. Catalyst (65%), Bipolar Plates (BPP) (18%), and GDL (8%) have the upper most load contributing up to 91% of the PEM FC share in this category. As reported in the SOP category section, the obtained values are from the production of PWBs, the supply of copper, lithium, platinum, and the manufacturing of special solvents such as N-methyl-2-pyrrolidone and tetrafluoroethylene.

Acidification terrestrial and freshwater (TAP)

Terrestrial/freshwater acidification or Accumulated Exceedance (AE) is the result of atmospheric deposition of emitted pollutants, namely, nitrogen ox-

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[2] When solvents and other volatile organic compounds are released to the atmosphere, most of them are degraded within a few days to weeks. Initiated by sunlight, nitrogen oxides (NOx) and volatile organic compounds (VOCs) react to form ozone.

ides (NOx), ammonia (NH3) and sulfur dioxide (SO2), and their subsequent deposition, which may in turn decrease the soil's or water's solution pH. A pH decrease may induce loss of plant species of terrestrial and freshwater ecosystems [274]. The TAP equivalency factor is the number of moles of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released. Bus life cycle accounts for nearly 69% of the total impacts. Double glass panels (39%), aluminium supply (15%), electronics devices (8%), chromium steel (6%), and copper and steel (5%) are the top five contribution to the TAP category. Li-ion batteries lifecycle makes the 17%. Battery management system (BMS) (37%), positive electrode paste (30%), module and battery packaging (10%), negative electrode substrate (5%), electricity supply (5%), and negative electrode paste (4%) account for almost of the this share. PEM FC system life cycle account for the 11%. Fuel Cell Stack (54%) and BoP (30%) stand for the major contributors to the share.

Eutrophication Potential (EP)

Eutrophication Potential (EP) addresses the impacts from the macro-nutrients nitrogen and phosphorus in bio-available forms on aquatic and terrestrial ecosystems. Aquatic eutrophication accounts for all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic ecosystems. Aquatic eutrophication is, in its turn, divided into freshwater eutrophication and marine eutrophication, each characterized by specific substances [107]. Terrestrial eutrophication is caused by deposition of airborne emissions of nitrogen compounds like nitrogen oxides (NOx = NO and NO2) from combustion processes and ammonia, NH3 from agriculture. Airborne spreading of phosphorus is not prevalent, and terrestrial eutrophication is therefore mainly associated with nitrogen compounds [107]. The Accumulated Exceedance (AE) characterizes the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.

Eutrophication marine (MEP). Bus lifecycle has a large impact in this category. It accounts for nearly 70% of the total. The production of the glazing glass panels with lower conductivity, the supply of various metal alloys and of plastic materials cover 95 percent of the share. The PEM FC follows with 12%. The platinum supply used in the catalyst is responsible for the 97% of that share. The li-ion battery covers the rest 14%. The PWBs used in BMS, the Lithium iron phosphate, the N-methyl-2-pyrrolidone, and the tetrafluoroethylene, used in the positive electrode paste, cover the entire share.

Eutrophication freshwater (FEP). The bus life cycle accounts for nearly 45% of the total impacts. The impact potential is dominated by the electronic devices supply, followed by the copper, double glass panels, steel and aluminium. Li-ion batteries accounts for 30%. Battery management system (BMS) (63%), Positive electrode paste (17%), and electricity (9%) contribute to 90% of the above share. As explained in previous sections, the production and supply of PWB and the use of lithium compounds in the cathode are the main contributors to the total impact. PEM FC system life cycle holds 17%: Balance of Plant (BoP) (54%) and Fuel Cell Stack assemblies (44%) cover nearly the entire share.

Eutrophication terrestrial (TEP). The bus life cycle accounts for 73% of the total impact in this category. The supply of glass panels, of electronics units, of aluminium, of chromium steel, of copper, of cast iron, of glass fibre reinforced plastic, of synthetic rubber, and of granulate polypropylene cover around 90% of the share. Li-ion batteries life cycle contributes 13% to this category. The production of individual battery components (BMS, positive electrode paste, module and battery packaging, negative electrode substrate, cell container, and negative electrode paste) takes 85% of that share, while the electricity used for the final assembly covers 10%. PEM FC system life cycle contributes 11% to this category. The platinum metal used to produce the catalyst layer covers nearly 52%. The injection moulding process, the phenolic sealants manufacturing, and the graphite supply are the main factors that intervene in the BPP production, representing 19% of the share. Additionally, the following materials, that constitute the GDL, contribute 16% of the concerned share: the woven carbon fabrics, the glass fibre reinforced plastic, the selective coat, the tetrafluoroethylene, and the carbon black.

6.3.2 LCIA results of the hydrogen production

The stages classified in the fuel cycle are the following: feedstock production, feedstock transportation, fuel production, and fuel distribution.

Climate change (GWP100)

The carbon dioxide emissions dominate the GWP and they are mainly related to the energy conversion process (production of electricity, chlor-alkali electrolysis, and steam reforming) of non-renewable energy resources. The main difference between the electrolysis, the chlor-alkali electrolysis, and the steam reforming process is that the CO2 emissions for water electrolysis are ‘indirect’ while at the latter two the emissions are direct. Therefore, as the operation phase is the dominating phase, the GWP is directly related to the energy sources and related transformation processes. 6.7 summarises the above. The use of renewable energy source significantly reduces the emissions related to electricity generation, but not remarkably in chlor-alkali and SMR plants. In the latter two production paths, the renewable energy is mainly used in the refuelling stations to fill the buses with the gas. However, the use of ‘green’ electricity in such plants could further reduce the emissions by 85%.

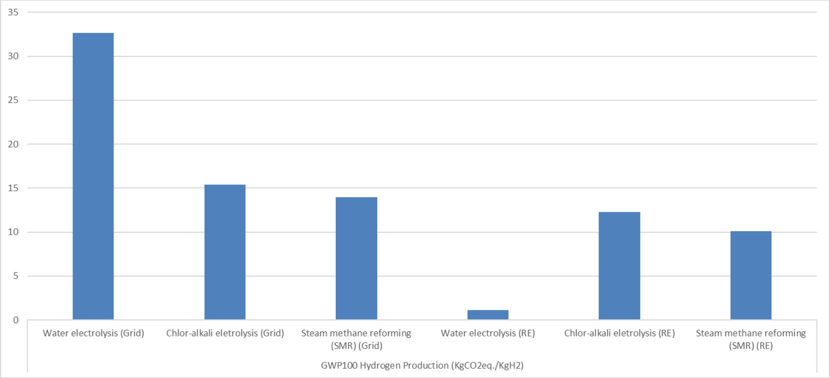

Figure 6.7: GWP100 Hydrogen Production (KgCO2eq./KgH2). Grid = Electricity mix from EU grid. RE = electricity generated by EU renewable sources.

Photochemical ozone formation (HOFP)

As shown in Figure 7, non-methane volatile organic compounds (NMVOC) in hydrogen production stages are emitted during the electricity generation (from 18% to 99%) and by the chlor-alkali electrolysis and steam reforming process (81% and 51% respectively). The use of renewable energy improves all the considered scenarios, especially in water electrolysis.

Acidification terrestrial and freshwater (TAP)

The hydrogen production by electrolyser using the EU grid mix has the highest acidification potential (see 6.9). This is related to the H2S emissions, which is responsible for approximately 99% of the AP from electricity generation. The chlor-alkali electrolysis process accounts for nearly 75%. The steam reforming reaction holds the 14% of the total impacts, while the reaming 86% is due to electricity that is mainly used to power the filling station. The renewable energy could contribute to the reduction of the acidifying effect of substances in all three production pathways.

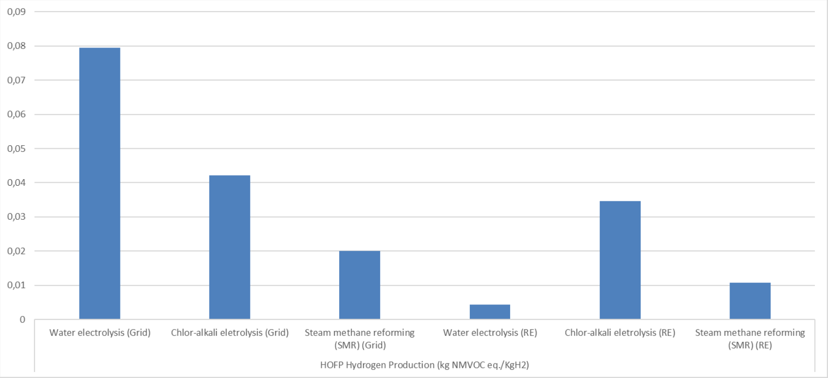

Figure 6.8: HOFP Hydrogen Production (kg NMVOC eq./KgH2).

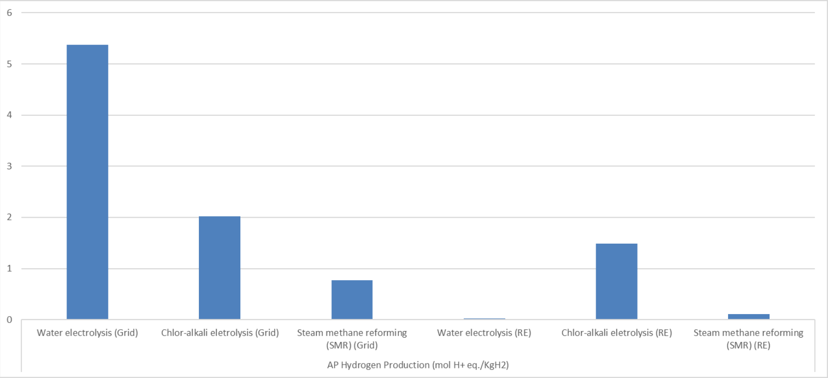

Figure 6.9: AP Hydrogen Production (mol H+ eq./KgH2).

Eutrophication Potential (EP)

The main contribution to the eutrophication potential of all considered scenarios is related to NOx emissions, nitrogen (N), and phosphorus (P). While for electrolyser the NOx emission are at least 99% coming from energy production, in case of steam reformer approximately 55% are direct emissions by the reforming process, and 44% are related to the consumed electricity for utilities and compression. In the chlor-alkali processes the NOx emissions are driven by the electrolytic process (83%) and by the electricity supplied to the plant and to the filling station (17%). In aquatic systems, the addition of nutrients is mainly caused by the electricity generation processes (99% and 85%). The introdution of renewable energy is enevironmentally benign in electrochemical proceses which require electrical energy input. 6.10 summaries the three eutrophication categories.

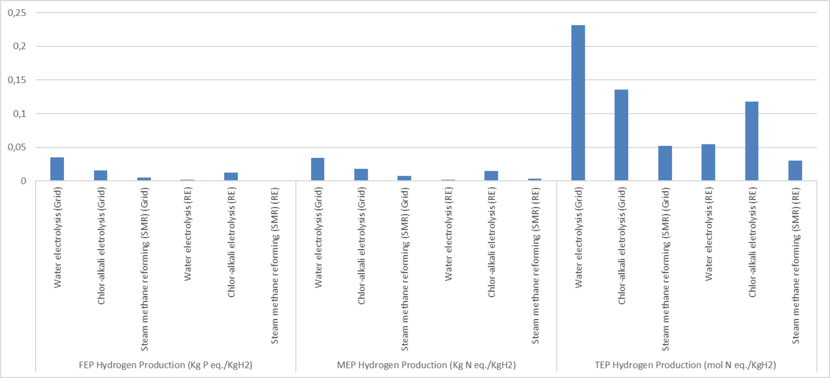

Figure 6.10: Eutrophication Aquatic and Terrestrial.

6.3.3 LCIA results of the complete bus Life Cycle

Figure 6.11 summarises the H2FC bus system environmental impacts, combining the bus manufacturing, the hydrogen supply pathways, the operation of the buses, and the End of Life. The comparison is carried out arranging the three above-mentioned patterns of hydrogen production, parametrized by electricity stemming from EU average mix and from renewable sources. In the case of H2FC bus powered by hydrogen from chlor-alkali processes and from fossil fuels, the renewable electricity drives the filling stations. The contribution of the different lifecycle stages to the total score is presented by the stacked elements inside the bars. Results indicate that the performance of the H2FC bus system is tied to the electricity feedstocks used during the operational stage. Renewable sources demonstrate to have lower impacts throughout the lifecycle of H2FC bus, but the operation stage still dominates the entire lifecycle of the vehicle. The following sections evaluate individual hydrogen production pathways against a standard EURO 6 Diesel bus. The reported figures are on a per-Km basis.

Climate change (GWP100)

The **electricity-based hydrogen** bus system produces significantly higher GWP than the reference EURO 6 Diesel bus. As showed in 6.12, the full life-cycle greenhouse gas emissions of the production of electricity-based hydrogen depends on how the electricity is produced. The GHG emissions using the average EU electricity mix (based on Ecoinvent 3.4 data) are around 3.5 KgCO2eq./Km, while those from the production of renewable hydrogen are significantly low, around 0.16 KgCO2eq./km. On the other hand, the emissions from fossil-based and by-product hydrogen have comparable emissions (1.67 KgCO2eq./km and 1.51 KgCO2eq./km), although higher than

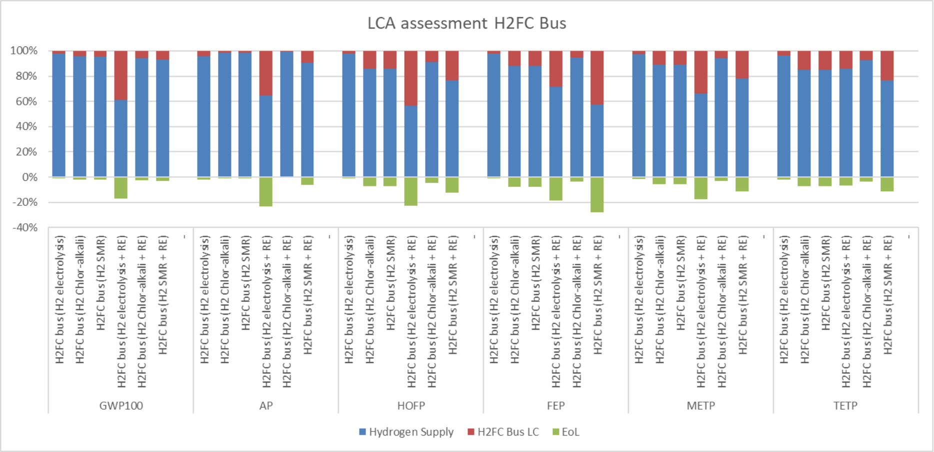

Figure 6.11: Summary of LCA assessment of H2FC Bus. H2FC bus (H2 electrolysis) = H2FC bus powered by hydrogen produced via electrolysis, H2FC bus (H2 Chlor-alkali) = H2FC bus powered by hydrogen produced via chlor-alkali processes, H2FC bus (H2 SMR) H2FC bus powered by hydrogen produced via steam reforming, H2FC bus (H2 electrolysis + RE) = H2FC bus powered by hydrogen produced via electrolysis using renewable electricity, H2FC bus (H2 Chlor-alkali + RE) = H2FC bus powered by hydrogen produced via chlor-alkali processes using renewable electricity to power filling stations, H2FC bus (H2 SMR + RE) H2FC bus powered by hydrogen produced via steam reforming using renewable electricity to power filling stations.

the reference vehicle (1.14 KgCO2eq./km). Renewable sources could help to mitigate the impact.

Photochemical ozone formation (HOFP)

Photochemical ozone formation potential is attributable to the combustion stage of the diesel engine, to chlor-alkali electrolysis, to natural gas reforming process, and to electricity generation. Electricity-base hydrogen accounts for the largest contributor (0,0085 kg NMVOC eq./Km), while the reference vehicle (namely, the Diesel bus) emissions are around 0,0027 kg NMVOC eq./Km. It should be noted that the hydrogen production emissions are displaced from the point of use. As summarized in 6.13, renewable sources could improve the overall picture at some extent. Only renewable hydrogen has the lowest POFP value (0,00062 kg NMVOC eq./Km). According to [280], the application of CCS does not affect significantly the POFP impact values.

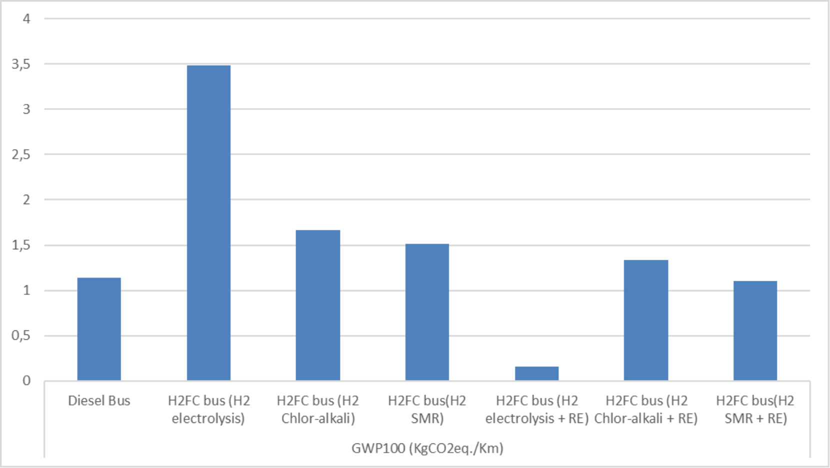

Figure 6.12: Global Warming Potential 100yr, GWP100 (KgCO2eq./Km). Diesel Bus = standard EURO 6 diesel bus.

Acidification terrestrial and freshwater (TAP)

Acidification Potential is particularly acute in electricity-based hydrogen (0,566 mol H+ eq./Km), as displayed in 6.14. Renewable hydrogen and SMR with renewable electricity are environmentally benign (0,0025 mol H+ eq./Km and 0,0118 mol H+ eq./Km). Although the majority of the emissions is driven by the hydrogen production pathways and use phase, significant SO2 emissions occur during platinum group metals extraction and sulfidic tailings due to mining activities (in particular for copper, iron, and aluminium extraction). It is worth to underline that the environmental burdens from PGMs life cycle are particularly high, as evidenced in [233].

Eutrophication Potential (EP)

Figure 6.15 arranges the three eutrophication categories. The two aquatic eutrophication categories (MEP and FEP) share the same bar patterns, but different values. In FEP category, the Diesel bus has the lowest impact (0,000065 Kg P eq./Km) against the investigated H2FC bus systems. The combustion processes in electricity generation drive the impacts in electrolytic processes to produce hydrogen (0,0037 Kg P eq./Km in water electrolysis and 0,0016 Kg P eq./Km in chlor-alkali electrolysis), while renewable hydrogen has a lower impact (0,00022 Kg P eq./Km). In MEP category, the renewable hydrogen holds the lowest impact (0,00022 Kg N eq./Km) if compared tothe Diesel bus impact (0,00032 Kg N eq./Km). The electrolytic processes show the largest impacts (0,0036 Kg N eq./Km and 0,0019 Kg N eq./Km). SMR impacts are in the between 0,00079 Kg N eq./Km and

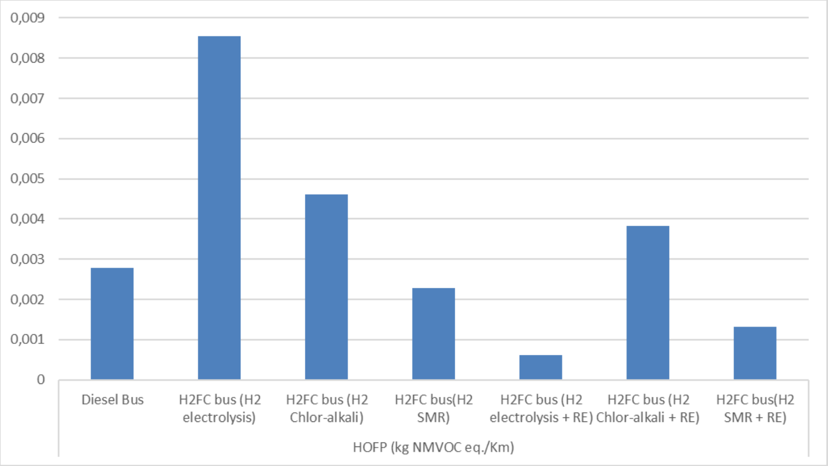

Figure 6.13: H2FC Photochemical ozone formation (Kg NMVOC eq./Km). Diesel Bus = standard EURO 6 diesel bus.

0,00038 Kg N eq./Km if in the latter, renewable sources are used. In TEP category, the above-mentioned considerations are applicable.

When looking into the local emissions, that are emitted inside EU boundaries, the H2FC bus has a better performance against a diesel bus, mainly because of zero tailpipe emissions and high energy efficiency. However, the fuel cells and lithium-ion batteries manufacturing triggers high impacts for most of the concerned categories. Moreover, from the chart, the vehicle life cycle impacts seem to be negligible, thus potentially misleading the assessment. Therefore, in considering these benefits, it is important to address concerns of problem shifting.

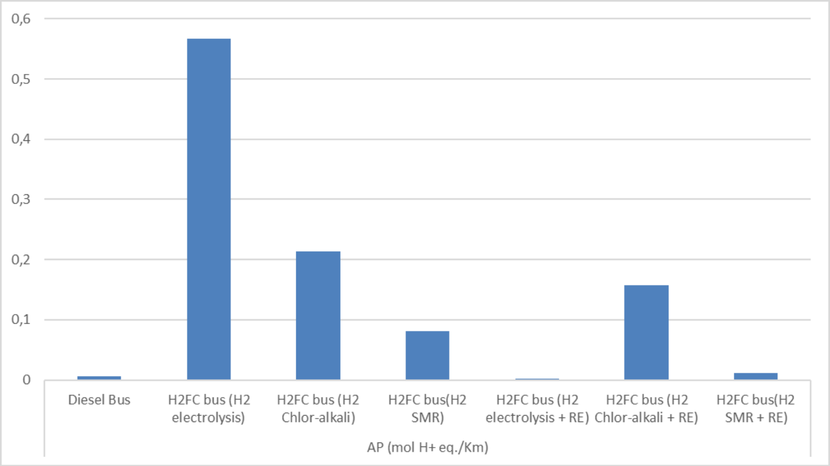

Figure 6.14: Acidification Potential (mol H+ eq./Km). Diesel Bus = standard EURO 6 diesel bus.

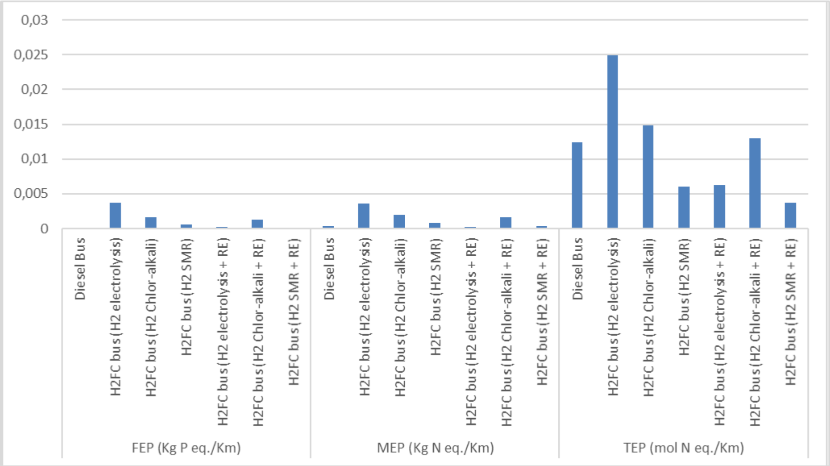

Figure 6.15: H2FC Bus Eutrophication Aquatic and Terrestrial. Diesel Bus = standard EURO 6 diesel bus.

Chapter 7

Conclusions

This thesis (as per Task **4.3** from **Work Package 4** of the **High V.LO City Project**) performed a quantitative assessment on the environmental impact of the hydrogen refuelling infrastructures and the buses involved in the High V.LO. City project. A comprehensive Life Cycle Assessment of the use of hydrogen fuel cell buses in urban context, compared with diesel was conducted along the project. This included a cradle-to-grave assessment of the project buses and related infrastructure in conjunction with WTW balances. Data concerning the production and specifications of the buses and hydrogen infrastructure were provided by the corresponding partners of the project, complemented with literature survey and with Ecoinvent databases. Although only **Global Warming Potential** (GWP) is at the core of this report, the assessment of three more environmental impact categories has been provided to complement the study.

By analysing the refuelling stations for the various local conditions (feed water, type of electricity supply and transportation service), the following considerations can be drawn.

First, embedded the substantial knowledge and experience gained from previous H2FC bus projects (i.e. CUTE and CHIC projects), **High V.LO. City** project aimed at significantly increasing the integration of these buses on a larger scale in European public transport. Fuelling station availability increased towards **99%** and the fuel economy is around **10.54 KgH2/100Km**). During the trials, the hydrogen refuelling stations confirmed to be safe and reliable. They were powered by renewable resources (wind-powered electricity) and the hydrogen was produced on-site via **electrolysis** (Aberdeen) or supplied as a **by-product of chlor-alkali processes** (Antwerp, Groningen and Sanremo). The deployment of a hydrogen supply infrastructure is one of the most critical issues that must be addressed for market transition to fuel cell buses in the public transportation sector (Changzheng Liu[49]). The successive demonstration projects, funded in this eighteen years, have largely proved that it is possible to build a reliable and safe system for storing, distributing and delivering the gas. Nevertheless, improvement of **logistic supply chain** of critical spare components of the bus is required to minimize supply lead time in order to quickly put the vehicle on service. Therefore, the **associated network externalities** are critical to sustain the long-term operational availability of the buses' fleet and open new market opportunities (Winebrake et al.[365]). From **end-of-life vehicle perspective**, most processes for **recycling critical components** (i.e. fuel cell system and lithium-ion battery) are **still stuck in laboratories** and yet to make them scaled to production to meet a future rising demand. We have assessed various classes of recovery processes (above all pyro-metallurgy and hydro-metallurgy) which are still very energy intensive, showing significant emissions in their recycling chain. **Enforcing European norms** regarding **recovery and reuse of valuable metals** of such components and **increase subsides in scaling up new recycling technologies** at industrial level are the next political challenge to be addressed.

Second, as evidenced in the report, the introduction of any new transportation fuel is a, difficult, uncertain, and multi-decadal process - it demands a linked introduction of a **new fuel distribution system** (hydrogen refuelling installation) and **new vehicles** (i.e. fuel cell buses), because neither is useful without the other (Keith et al.[176]). This process requires successive **government actions** (i.e. funded projects) over several decades. Since energy systems change over the course of time, incremental approach would maximize learning-by-doing. In this view, the first step is the conversion of many specialized vehicle fleets (in this case buses in public transportation) that use centralized fuelling facilities. The many results of these demonstration projects, have substantially proved that the **niche route** is the most appropriate way to employ the useful services of the new hydrogen technology (Winebrake et al.[365]), (Grubler et al.[132]) and (Farrell et al.[106]).

Third, **hydrogen, whose clean credentials depend on how it is produced, still polarises opinion**, with critics questioning costs, safety and its effective role in decarbonising the world energy system. On the enthusiast side, we signal the recent IEA report 'The Future of Hydrogen'[159] (released 14 June 2019) which strongly supports hydrogen's potential to play a key role in a clean, secure and affordable energy future and describes 2019 as a year of 'unprecedented momentum'[159] for hydrogen, with around 50 mandates and policy incentives in place globally to directly support its development. Conversely, opponents claim that hydrogen is far from tantalising promises of cleaner industry and emissions-free power[1] for technical and economic reasons.

Fourth, the **increasing demand of electricity**, for electrolysis and battery recharging stations, is fraught with contradictions. Governments' incentives to promote zero-emission vehicles into the market[2] could lead to a substantial growth of 'hidden' CO2 emissions or could potentially result in **shifts in the ranking of environmental burden**. A striking example of such issue is the Norway's generous range of subsides in supporting electric mobility. According to some critics, it could afford to finance such tax exception and other incentives scheme because of the immense wealth it derives from oil and gas. Hydrocarbons produced by the state energy company **Equinor** (formerly rebranded from Statoil) generated **310Mt of indirect greenhouse gases**[3] in 2017. That is almost as much as the total carbon dioxide (CO2) emitted by UK[4], a country with about 12 times Norway's population.

Fifth, according to Distinguished Professor **Vaclav Smil**[5], during the next half-century, the basic nature of global energy supply will not drastically change, and the **world will remain highly dependent on fossil fuels**. However, moving toward a system dominated by hydrogen is clearly consistent with the long-term vision of decarbonising modern energy supply, but the **progress will be gradual** and large-scale transition to a hydrogen economy is not at moment expected during the coming generation. Moreover, Staffell et al.[290] argue that in the next future hydrogen will be a **flexible and versatile complement to electricity**, but several challenges must still be overcome for hydrogen and fuel cell to finally live up to their potential.

In conclusion, the next 15 years will be critical for climate change. We are just at the earliest phase of this transition to a carbon-free energy system, but this challenge requires a muscular government action at global scale to curb the world's addiction to fossil fuels. Israeli historian, professor and author **Yuval Noah Harari** claims that embracing eco-friendly technologies to

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[1] See FT article: "Energy from hydrogen has no significant role" ➡.

[2] See: norwegian-ev-policy ➡.

[3] The reported emissions belong to Scope 3 category. For definitions see: www.carbontrust.com ➡.

[4] According to UK statistics, the carbon dioxide emissions are about 367 Mt in 2016.

[5] Distinguished Professor Emeritus at the University of Manitoba and a Fellow of the Royal Society of Canada. See: vaclavsmil.com ➡.

combat climate change is one way out, but warns us that ‘the only sure way to stop global warming is to stop economic growth, which no government is willing to do’ (Harari[141] at p. 252). Consequently, the poor will be the first to bear the cost of such economic stagnation and so ‘protecting the environment is a very nice idea, but those who cannot pay their rent are worried about their overdraft[6] far more than about melting ice caps’ (Harari[141] at p. 253).

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[6] It is a deficit in a bank account caused by drawing more money than the account holds.

Appendix A

Supporting information - LCIA results of H2FC Bus life cycle

A.1 Environmental performance

Present appendix completes the environmental picture of the H2FC Bus life cycle, including the EF impact categories that were not mentioned in the Chapter 6.

Bus life cycle dominates nearly all the assessed impact categories. Lithium-ion battery and PEM FC system are particularly relevant in ODP, covering nearly the 95% in that category, and are responsible for a bigger impact in terms of aquatic eutrophication and mineral resource scarcity stemming from sulfidic tailings linked to mining activities.

It is remarkable the indirect resource depletion effects caused by the co-extraction of metals from mixed ores. In that, the resource depletion potential per kg of produced battery is driven only partially by the electrode materials. In four impact categories, cell manufacturing is responsible for greater than 50% of the total impacts, namely: ODP, HTP-c, LOP, and GWP100. One of the key drivers for resource depletion appears to be the metals (and co-products) in electronic components required for the BMS, a module rather independent from the actual battery chemistry. The BMS dominates four impact categories: SOP, HTP-nc, FEP, and FETP.

A.1.1 Resource use, energy carriers (ADP-f)

As suggested by Van Oers et al. [352], and implemented in CML method since 2009 version, a separate impact category for fossil fuels is defined, based on their similar function as energy carriers. CFs for fossil fuels are expressed as MJ/MJ, i.e. the CF is equal to 1 for all fossil resources.

The bus lifecycle requires significant amount of energy (about 69%) for specific materials. The supply of glazing glass with lower conductivity accounts for about 38%) of total energy requirements, while the supply of metals, plastics, and electronic components contributes around 52%.

The li-ion battery, during its lifetime, is responsible for 17% of energy use. This share is from the BMS assembly, the negative and positive electrode paste manufacturing, battery packaging, and electricity used in the assembly process.

The PEM FC covers around 11% of the energy amount. The impact is caused by the FC Stack assembly (54% of energy requirement), by the BoP, and by the hydrogen tanks manufacturing (34% and 12% respectively).

The remaining 3% is caused by the electric powertrain. The electric motor supply and related PMS are the only two contributors.

A.1.2 Ozone depletion (ODP)

The Ozone Depletion Potential (ODP) is a measure of the extent of ozone layer depletion by a given ozone depleting substance, relative to that depleted by CFC-11[1].

Li-ion batteries cause significantly more impacts (53%) than PEM FC system (42%) and bus (5%) during the entire lifecycle. The production of polytetrafluoroethylene, lithium iron phosphate, and N-methyl-2-pyrrolidone, used in Li-ion batteries, are the main contributors to the ozone layer depletion (ODP) category and also an important source of global warming (GWP) emissions as well[2].

The FC stack and the BoP of the PEM FC system cover, with 62% and 38% respectively, the 42% share of impacts. The refrigerant used in bus is responsible for the rest of the impacts.

A.1.3 Respiratory inorganics (PMFP)

Respiratory inorganics category addresses the disease incidence due to kg of PM2.5 emitted. The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.

Bus lifecycle has a large impact in this category. It accounts for nearly 69% of the total. The production of the glazing glass panels with lower

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[1] (Link) - (Link)

[2] (Link)

conductivity, the supply of various metal alloys, and of plastic materials cover almost 95% of the share.

The PEM FC follows with 19%. The platinum supply used in the catalyst is responsible for the 99% of that share.

The li-ion battery covers the rest 9%. The PWBs used in BMS, the Lithium iron phosphate, N-methyl-2-pyrrolidone, and tetrafluoroethylene (used in the positive electrode paste) cover the remaining share.

A.1.4 Resource use, mineral and metals (SOP)

Abiotic resource depletion encompasses both the use of non-renewable and renewable abiotic resources (e.g. wind, flowing water etc.), but SOP limits the definition to the depletion of non-renewable resources only. For resources depletion, mineral and metals, at midpoint, the recommended model is the Abiotic Resource Depletion (ARD), "ultimate reserves" version, described in Van Oers et al. [352], based on the models of Guinée et al. [135]. CFs are given as Abiotic Depletion Potential (ADP), quantified in kg of antimony-equivalent (Sb-eq) per kg extraction.

The bus and lithium-ion batteries lifecycle altogether cover nearly 80% of the impacts in this category (37% bus lifetime and 41% lithium-ion battery lifetime).

The bus manufacturing is particularly material demanding. In that, glazing glass, aluminium, and polypropylene account for 55%, 16%, and 10% respectively of the concerned share. The BMS is up to 88%. The reason lays in the production of integrated circuits used to balance the cells, in the copper wires used to connect the cells to assemble the module, and in the copper used in the tab terminals.

The PEM FC holds about 14% of the total impact. The BoP and the FC stack contribute to nearly 90%. The auxiliary devises that comprise the BoP require a significant amount of metals and related alloys, while the supply of platinum, used in the catalyst layer, consume a large amount of energy and in turn resulted in huge exploitation of natural resources.

A.1.5 Cancer human health effects (HTP-c) and Non-cancer human health effects (HTP-nc)

HTP-c accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to cancer. Conversely, HTP-nc accounts for non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation. Comparative Toxic Unit for human (CTUh) expresses the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).

USEtox is a scientific consensus model endorsed by the Life Cycle Initiative hosted at United Nations Environment for characterizing human and ecotoxicological impacts of chemicals. The main output is a database of recommended and interim characterization factors including fate, exposure, and effect parameters [273].

The bus lifecycle is particularly relevant in human health categories (about 88% for HTP-c and 66% for HTP-nc). The cause lays in the metals and the double glass panels supply chain. The involved processes are particularly energy intensive due to ore and related transformation operations.

The lithium-ion batteries lifecycle holds about 4% for HTP-c and 12% for HTP-nc impact share. In both impact categories, the positive electrode paste and battery management system (BMS) have the major shares in contributing to adverse effects on human health.

The PEM FC follows with about 4% for HTP-c and 15% HTP-nc. Balance of Plant (BoP) and Fuel Cell Stack are the most contributor to both impact categories.

A.1.6 Land use (LOP)

The impact category ‘land use’ describes the environmental impacts of occupying, reshaping, and managing land for human purposes [358], [29]. The CFs for land use at midpoint were calculated starting from the sets presented in [25] for the LANCA(r) (Land Use Indicator Value Calculation in Life Cycle Assessment) v 2.2 LCIA model. LANCA(r) provides five indicators for assessing the impacts due to the use of soil: erosion resistance, mechanical filtration, physico-chemical filtration, groundwater regeneration and biotic production.

The bus life cycle accounts for 78% of the total impact in this category. The supply of metals alloys, glass panels, glass fibre reinforced plastic, electronic modules, plywood, and sawn wood cover around 95% of the share. Such activities have significant environmental impacts related to physical occupation and transformation of land areas.

The lithium-ion batteries, PEM FC system, and PMS lifecycle represent the 11%, 9%, and 2% of the total impact, respectively. The production of lithium iron phosphate, used in the positive electrode assembly, and of integrated circuits in the BMS are the main factors of impact. In the FC stack assembly process, the Gas Diffusion Layer (GDL), the Bipolar Plates (BPP), and the catalyst manufacturing stages are the most impactful processes, covering nearly 90% of the concerned share.

It is worth to highlight that land use is one of the main drivers of biodiversity loss, as argued by De Baan et al. [78]. The recycling of waste materials at the end of life could mitigate the impact (favouring a reduction of about 20%), but further improvements are necessary to clean the supply chain of virgin materials and the yield of the recycling chain.

A.1.7 Photochemical ozone formation, HH (HOFP)

Photochemical ozone formation is a measure for estimating airborne substances potential to form atmospheric oxidants, these oxidants can in turn, in the presence of sunlight, react with oxygen in the air and form ground level ozone. Typical oxidants are nitrogen oxides, carbon monoxide (CO) and volatile organic compounds (VOC) [147][3].

The negative impacts from the photochemically generated pollutants are due to their reactive nature which enables them to oxidise organic molecules on the surfaces they expose [371].

Bus life cycle accounts for nearly 76% of the total impacts. The production and supply of double glass panels (36%), aluminium (20%), polypropylene (5%), electronic devices (5%), chromium steel (5%) are the top five contribution to HOFP category.

Li-ion batteries holds 10%. Battery management system (BMS) (38%), Positive electrode paste (25%), electricity supply (10%) contribute to around 75% of the share.

PEM FC system life cycle covers the remaining 11%. Catalyst (65%), Bipolar Plates (BPP) (18%), and GDL (8%) have the upper most load contributing to nearly 90% of the PEM FC share in this category.

As reported in the SOP category section, the obtained values are from the production of PWBs, the supply of copper, lithium, platinum, and the manufacturing of special solvents such as N-methyl-2-pyrrolidone and tetrafluoroethylene.

A.1.8 Ionising radiation, HH (IRP)

The same framework for human toxicity (HTP) and ecotoxicity (FETP) applies for ionizing radiation: the modelling starts with releases at the point of emission, expressed as Becquerel (Bq), and calculates the radiative fate

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[3] When solvents and other volatile organic compounds are released to the atmosphere, most of them are degraded within a few days to weeks. Initiated by sunlight, nitrogen oxides (NOx) and volatile organic compounds (VOCs) react to form ozone.

and exposure, based on detailed nuclear physics knowledge [117]. The Ionizing Radiation Potentials quantifies the impact of ionizing radiation on the population, in comparison to Uranium 235.

Bus life cycle accounts for nearly 53% of the total impacts. The supply of double glass panels (34%), aluminium (19%), electronics units (9%), electricity (9%), and chromium steel (5%) are the top five contribution to IRP category.

Li-ion batteries account for 34%. The electricity supply (70%), Battery management system (BMS) (14%), Positive electrode paste (8%) are the main drivers of LIB impacts.

PEM FC system life cycle holds the 9%. Fuel Cell Stack (49%) and Balance of Plant (BoP) (37%) contribute to the most of PEM FC share. The calculated values are mainly due to PEM manufacturing and auxiliary devices production and supply.

A.1.9 Ecotoxicity freshwater (FETP)

The effect factor expresses the ability of a substance to cause toxic effects to the exposed freshwater ecosystems. The elements of the effect factor matrix for ecotoxicity (EFw) directly relate the dissolved concentration in the freshwater compartment of the environment to the species response, represented as the fraction of the species which are potentially affected [151]. Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg). USEtox consensus model (multimedia model).

Bus life cycle accounts for nearly 60% of the total impacts. Double glass panels (24%), aluminium (20%), polypropylene (13%), electronic units (11%), and chromium steel (10%) are the top five contributions to FETP category.

PEM FC system life cycle makes the 25%. Fuel Cell Stack (80%) and BoP (16%) cover much of this share in the FEPT category.

Li-ion batteries hold the 11%. Battery management system (BMS) (59%) Positive electrode paste (19%), Negative electrode substrate (7%), Module and Battery Packaging (3%), and cell container, tab and terminals (3%) contribute to the LIB share.

A.1.10 Water scarcity (WCP)

Water consumption can lead to deprivation and negative impacts on human health and ecosystems quality [118]. The Relative Available WAter REmaining (AWARE) method assesses the relative potential of water deprivation, to either humans or ecosystems. The indicator in the AWARE method builds on the assumption that the less water remaining available per area, the more likely another user will be deprived [26].

Bus life cycle accounts for nearly 68% of the total impacts. Double glass panels (34%), aluminium (20%), polypropylene (13%), electronic units (9%), and chromium steel (5%) are the top five contributions to the WCP category.

Li-ion battery lifecycle covers the 14%. Battery management system (BMS) (42%), Positive electrode paste (24%), Module and Battery Packaging (10%), Negative electrode paste (4%), Cell container, tab and terminals (4%), and electricity supply (3%) account for nearly 95% of the battery impact share.

PEM FC system life cycle holds the 13%. Fuel Cell Stack (46%) and BoP (38%) cover almost the entire share of the PEM FC impact.

Appendix B

Supporting information - LCIA results of hydrogen production routes

B.1 Environmental performance

Life cycle inventory flows of each production technology were used to calculate 19 life cycle midpoint impact category indicators to identify the key midpoint environmental performance indicators and subsequently identify the main processes responsible for the potential impacts of the evaluated hydrogen production processes. For water-related effect, AWARE LCA based method was used to analyze the environmental performance of hydrogen production methods.

The electrolytic processes with grid electricity has the worst performance in most of the impact categories. The highest score of impact category in terms of absolute values is observed for global warming potential (GWP), human non-carcinogenic toxicity (ADP-f), (FETP), Land Use Potential (LOP), water consumption potential (WCP), and ionizing radiation (IRP). The electricity is identified as a major contributor in electrolytic production pathways (see Figure B.1). Irrespective of electrolyzer technology, electrolysis is an energy-intensive production method, where the environmental footprint is limited to the electricity supply chain. The manufacturing phase will prevail when renewable resources are used, keeping in mind that the absolute emission values decrease. The fossil fuel-based hydrogen production method SMR is seen to be most environmentally harmful methods. Similar observations were reported from Bhandari et al.[21] showing that GWP of electrolysis with grid electricity from the union for the coordination of transmission of electricity (UCTE) showed the worst performance, followed by conventional pathways and ranking of alternatives changed upon the change of electricity source. The environmental values might vary in literature depending on geographical location, fuel choices for electricity generation, and system boundary assumptions. Electrolysis with renewable energy sources can produce relatively low levels of global warming potential (GWP), fossil fuel scarcity (FFP), and toxicity-related impacts.

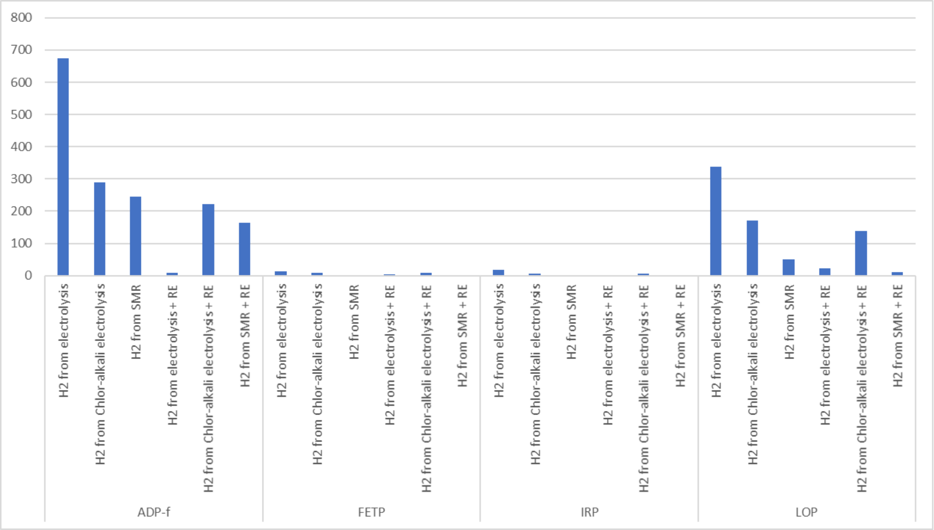

Figure B.1: Aggregated contribution of processes to midpoint categories for hydrogen production technologies.

For the fossil-based system the environmental impacts are mainly determined by the raw material used in production processes (Figure B.1). The GWP was estimated 12.13 kg CO2-eq/kg H2 being in the range from 8.9 to 12.9 kg CO2-eq/kg H2 [21]. For the same process, Pamela L. Spath[241] report a value 11.8 kg CO2-eq/kg H2. Even, in the fossil-based system can offer promising improvement of the environmental performance when integrated with carbon capture and storage. Coupling SMR with carbon capture and storage (CCS) can produce a GWP of 3.4 kg CO2-eq/kg H2 which is significantly lower than SMR stand-alone system. Although CCS offers a great advantage to reduce the GWP, it requires additional electricity and water which will lead to benefits and trade-offs for air pollution. Electricity and water usage for CCS are 0.8 kWh/kg H2 and around 1.8 kg of water.

At midpoint level, comparison of H2 methods using Water Consumption Potential (WCP) with AWARE method indicates that technologies with a high WCP can cause a high impact on the environment both from a water consumption and overall environmental impact. The water consumption and associated damage impacts are reduced in high efficient technologies which use less or do not require water. The highest contributor to the impacts associated with water scarcity in the majority of pathways is electricity consumption (Figure B.1). Consequently, the mix of technologies deployed to produce fuels and electricity determines the associated burden on regional water resources. As competition and conflicts among agriculture, industry, and cities for limited water supplies are already escalating further analysis would consider the particular water resources used and investigate the sustainability of using the water. Because water is consumed throughout the production supply chain and various production processes are heavily interdependent, assessment of water consumption throughout the life cycle of a fuel is necessary to understand water-related impacts.

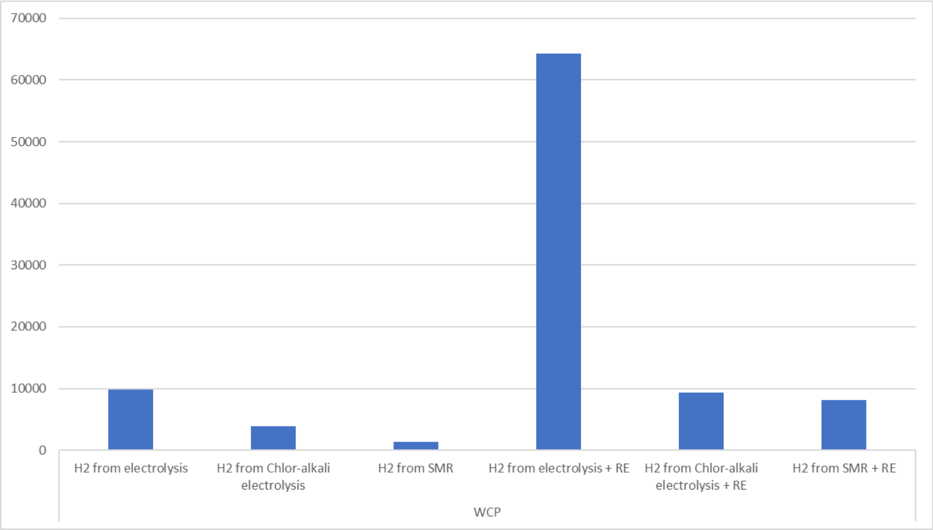

Figure B.2: WCP contribution of processes technologies.

Appendix C

Hydrogen production methods

Electrolysis of water

Water electrolysis is an electrochemical process that splits water into hydrogen and oxygen (see Figure C.1).

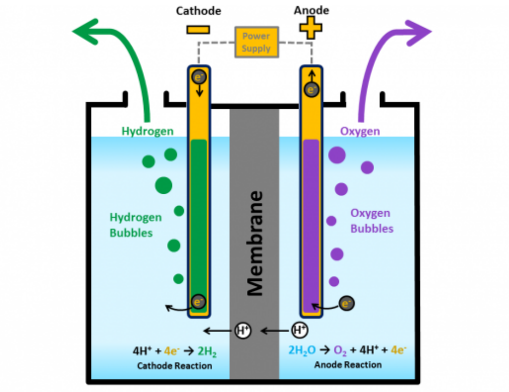

Figure C.1: For details see www.energy.gov ➦.

According to IEA, today less than 0.1% of global dedicated hydrogen production comes from water electrolysis , and the hydrogen produced by this means is mostly used in markets where high-purity hydrogen is necessary (for example, electronics and polysilicon) or in specific areas of the transportation sector. The hydrogen strategy set out in [314], considers **renewable hydrogen**[1] as the most compatible option with EU's climate neutrality and zero pollution goal in the long term and the most coherent with an integrated

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[1] According to EU Communication no. COM(2020) 301 [315], renewable hydrogen: is hydrogen produced through the electrolysis of water and with the electricity stemming from renewable sources.

energy system. Bhandari et al. in [21] evaluated and compared different hydrogen production technologies regarding their environmental impacts and provided also further insight into hydrogen produced by electrolysis using different energy sources. Wind based electrolysis ranked as the best method followed by hydro. GWP values for solar PV, solar thermal and biomass based electrolytic methods were also only slightly higher than the hydro or wind electrolysis. Based on the above, they concluded that electrolytic technologies are competitive with other technologies only if renewable electricity is used. Mehmeti et al. in [220] reviewed different hydrogen production pathways: steam methane reforming (SMR) of natural gas, electrolysis of water, and hydrogen production from biomass resources. The electricity is identified as a major contributor in electrolytic production pathways (more than 90 percent). Irrespective of electrolyser technology, electrolysis is an energy-intensive method of hydrogen production, where the environmental footprint is limited to the electricity supply chain, thus, substantially, confirming Bhandari et al. assessment. Additionally, Wulf et al. in [368] analysed the hydrogen supply chain and divided it in two phases: 'hydrogen production' and 'transport and distribution', including the hydrogen refuelling station (HRS) in the environmental footprint calculation.

Chlor-alkali electrolysis

By-product hydrogen from chlor-alkali processes is another feedstock that could help meet the increasing demand for hydrogen fuel in early fuel cell electric vehicle markets, despite the small volume is around 2% of global production [159]. Such processes separate chlorine (Cl2) from the brine (aqueous sodium chloride - H2O and NaCl) and simultaneously produces sodium hydroxide (NaOH), often referred to as caustic soda, caustic, alkali, or lye) and hydrogen (H2) as by-product (see Figure C.2).

Three different electrolysis techniques are applied: mercury, diaphragm, and membrane cell technology. Up to the end of the 20th century, the mercury cell technique dominated in Europe, while the diaphragm cell technique dominated in the United States and the membrane cell technique in Japan. This pattern has, however, changed during the first decade of the 21st century [32]. According to EUROCHLOR (2016 data) the diaphragm cells account for 13.6% of total capacity, and membrane cells represent most of the remaining 63.5%. The contribution of mercury cells has diminished from 55% in the 2000 to 19.7% in 2016 (see Figure C.3).

The European Commission labels the membrane process as the Best Available Technique (BAT) for the chlor-alkali industry [32]. The membrane

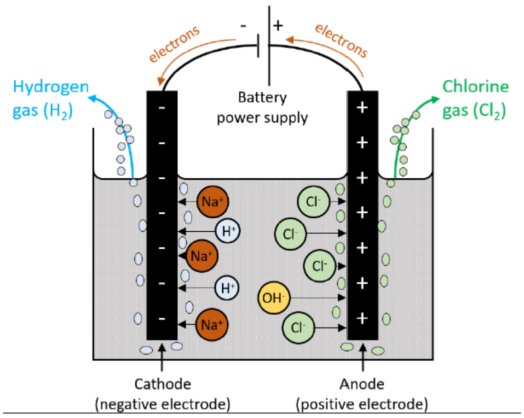

Figure C.2: The principle of electrolysis starting from a brine solution (eurochlor ➦).

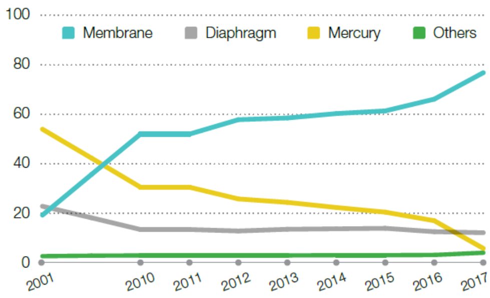

Figure C.3: Share of total installed capacity end of year[54].

cell technology has fewer exhausts to the environment, and it is relatively more efficient in the use of electric power that mercury and diaphragm. As stated in the Minamata Convention [105], production processes in which mercury or mercury compounds are used as a catalyst shall be phased out by 2018. Pursuant to the above, in 2017 the EC amended the communication no. COM(2016) 0039 [337] establishing that by 11 December 2017 mercury based production technology must be ceased, as per Regulation no. 2017/852 [338]. Under the Industrial Emissions Directive 2010/75/EU [331], the BAT conclusions, as required by Article 13(1) of the that Directive, have become legally binding, implying that four years after publication of these BAT conclusions the European chlor-alkali producers using the mercury technology must convert or dismantle these production plants. Margallo et al. in [211] conducted an LCA from cradle to gate taking one ton of chlorine as reference unit, comparing the above-mentioned electrolysis techniques. The conclusions were consistent with previously said: the membrane cell is the most environmentally friendly scenario with a global energy demand lower than the other two. However, according to the authors, the electrolysis system is the most energy intensive production methods and, therefore, the emissions are comparatively higher. Despite no relevant figures were provided, percentage values were used to facilitate the comparison. Lee et al.[189] employed a life-cycle analysis framework to evaluate well-to-gate GHG emissions associated with by-product hydrogen from chlor-alkali processes in comparison with hydrogen from the conventional centralized natural gas steam methane reforming (central SMR) pathway. The analysis is based on U.S. data, but the obtained results are consistent with mainstream LCA results. As claimed by Sørensen et al. in [286], the real case for fuel cell vehicles is therefore strongly dependent on the long-term requirement for a transition to non-fossil fuels. This includes, according to them, the use of hydrogen produced from fossil fuel in demonstration projects during a midterm period, where the infrastructure for sustainable hydrogen production is not yet available. However, as mentioned before, natural gas still plays a significant role as feedstock for hydrogen production and a complete switch to a non-hydrocarbon-based feedstock seems at the moment difficult to predict.

Thermochemical production methods

Hydrogen is made thermochemically by processing hydrocarbons (such as natural gas, coal, biomass, or wastes) in high-temperature chemical reactors to make a synthetic gas or 'syngas', composed of H2, CO, CO2, H2O, and CH4. The syngas is further processed to increase the hydrogen content, and hydrogen is separated out of the mixture at the desired purity [237] (see Figure C.4).

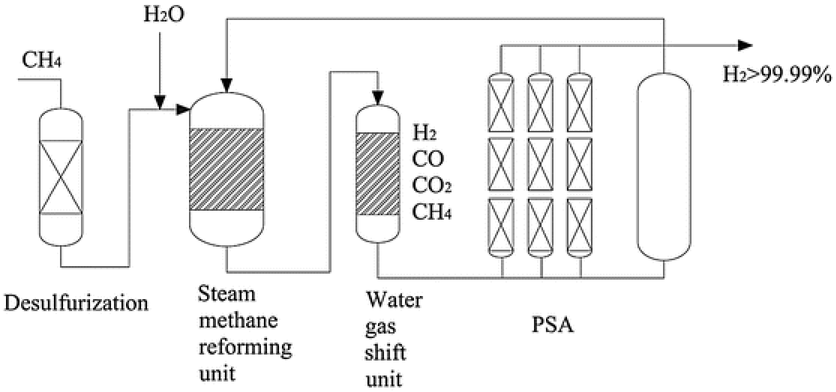

Figure C.4: A diagram of a typical SMR process [52]. The SMR process is characterized by multiple-step and harsh reaction conditions. Typically, four steps are necessary, namely, (1) desulfurization, (2) steam reforming, (3) water–gas shift (WGS), and (4) H2 purification, pressure swing adsorption (PSA).

Steam reforming of natural gas (SMR) offers an efficient, economical, and widely deployed method of hydrogen production, and provides near- and mid-term energy security and environmental benefits. According to IEA recent report on hydrogen future [159] , around 70Mt of dedicated hydrogen are produced today, 76% from natural gas (196 Mtoe) and almost all the rest (23%) from coal. This accounts for about 6% of global natural gas use [35]. Pamela L. Spath performed a dedicated LCA to examine the net emissions of greenhouse gases of a SMR plant, as well as other major environmental consequences. They found that carbon dioxide was the dominant gas, accounting for about 99 percent of the total. The carbon dioxide emitted also accounted for 89 percent of the overall global warming contribution, with the other 10 percent coming from methane emissions, which are lost to the atmosphere during the production and distribution of hydrogen. Operation of the hydrogen plant itself was the source of the majority of the greenhouse gas emissions (almost 75 percent) with the remaining emissions coming from the plant's construction, from natural gas production, and transport. Ramsden et al. in [256] and Edwards et al. in [86] covered 'upstream emissions', which are the emissions generated from processes before the hydrogen production process: principally input fuel extraction and processing.

Coal can also be reformed to produce hydrogen, through gasification. This is a commercial procedure as well, but one that is only competitive with methane reforming where the natural gas is expensive Dufour et al. Hydrogen can also be extracted from oil, gasoline, and methanol through reforming. This partial oxidation process, parallels that of a refinery, is a commercial process as well. However, it also requires the use of pure oxygen and, as with coal gasification, is less efficient and emits more carbon dioxide than steam methane reforming [230].

Carbon capture and sequestration (CCS) from hydrogen production involves removing the carbon by-product from the atmosphere - or from the exhaust gases from a coal gasifier or steam methane reformer - and storing it underground in depleted oil or gas fields, deep coal beds, deep saline aquifers, or the deep ocean. Combing multiple techno-economic studies, the capture rate can range between 50% and 90% [158]. In contrast, although CCS is claimed as being vital to climate change mitigation, it is has not yet deployed on scale commensurate with the intended ambitions [39]. As argued by Krebs, '[i]n terms of scale, carbon dioxide is emitted on a multigigaton scale annually whereas our current capacity for handling carbon dioxide is more than an order of magnitude lower'. Previous reviews, [205] and [24], still confirm that all of the individual components of the CCS chain, from capture all the way through to (and including) storage, have been demonstrated at or close to industrial scale. As recently reported by the European Environmental Bureau (EEB), the European Commission plans to invest heavily in expensive carbon capture and storage (CCS) and in a very early-stage process known as pyrolysis[2]. Hydrogen from biomass processing is gaining interest since a great quantity of biomass waste is generated by different industrial and agricultural activities, offering a great potential for energy generation [220].

Hydrogen Infrastructure deployment

With suitable governance and funding schemes in place, local authorities would be well positioned to invest in infrastructure that supports sustainable transportation. As recognized by Kennedy et al., strategic investments in public transit infrastructure represent one of the four pillars of sustainable urban transportation[3]. In focusing on public transportation, less attention is given to private vehicle-based travel or goods movement, but provision and maintenance of supporting infrastructure (ports, new refuelling stations, rail transfer stations, bus terminals,...) is clearly the essential to the vitality of cities.

In that view, the EU Directive 2014/94/EU [332] on the deployment of alternative fuels infrastructure (the Alternative Fuels Infrastructure Directive - AFID) introduces for the first time, requirements around the provision, accessibility, and design standards of infrastructure. According to AFID, the EU member states are required to develop national frameworks to create the required infrastructure for alternative fuels. In that, AFID put in place an overarching strategy with investment friendly regulatory framework to support alternative transport fuels in the EU. The AFID builds on substantial work with industry, public authorities and civil society, public consultation, and, above all, demonstration projects for alternative fuels. In CUTE project, refuelling stations were constructed and operated in each of the project cities, incorporating on-site renewable production of hydrogen and achieving station availability of 80%. Within CHIC project, hydrogen refuelling stations have demonstrated the improved capability to reliably (around 97%) and safely supply current fuel cell bus fleets with hydrogen fuel. Additionally, CHIC project provided solid ground for gaining lessons and recommendations derived from infrastructure planning, procurement, permitting, and

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[2] Pyrolysis is a well-known route for hydrogen production, in which hydrogen-containing compounds such as hydrocarbons are the only reactants. In fact, these compounds are decomposed by heating in the absence of oxygen [195], which can mitigate the carbon emissions resulting from the production of hydrogen made from fossil gas [195]

[3] The authors argued that the process of achieving more sustainable transportation requires the establishment of four pillars: effective governance of land use and transportation; fair, efficient, stable funding; strategic infrastructure investments; and attention to neighbourhood design.

operation. In order to facilitate a smooth integration of H2FC buses, High V.LO-city project established and enhanced four hydrogen production and refuelling facilities, linked to economical and sustainable hydrogen production plants, reducing the life cycle costs of hydrogen provision and transport. The station's availability was almost close to 100%, thus contributing to the standardisation of authorization protocols for hydrogen refuelling infrastructure, through the analysis of existing experiences and existing barriers of national and regional regulatory frameworks in Europe.

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