Life Cycle Assessment of Conventional and Alternative Fuels for Vehicles

By

HUSEYIN KARASU

A Thesis Submitted in Partial Fulfilment

of the Requirements for the degree of

Master of Applied Science

in

Mechanical Engineering

Faculty of Engineering and Applied Science

University of Ontario Institute of Technology

Oshawa, Ontario, Canada

August 2018

Abstract

For the near future, it is important that vehicles are run by alternative fuels. Before we can go ahead with the new alternatives, it is crucial that a comprehensive life cycle analysis is carried out for fuels. In this thesis study, a cradle-to-grave life cycle assessment of conventional and alternative fuels for vehicle technologies is performed, and the results are presented comparatively. The aim of the study is to investigate the environmental impact of different fuels for vehicles. A large variety of fueling options, such as diesel, electric, ethanol, gasoline, hybrid, hydrogen, methane, methanol and natural gas are considered for life cycle assessment of vehicles. The study results are shown in abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and human toxicity potential using three different impact assessment methods. The analyses show that hydrogen vehicle is found to have the lowest environmental impacts with ozone layer depletion of 8.14×10^{-10} kg CFC-11-eq/km and the human toxicity potential of 0.0017 kg (1,4 DB)-eq/km respectively. On the other hand, the gasoline-powered vehicle shows a poor performance in all categories with the global warming potential of 0.20 kg CO_2-eq/km.

Keywords: Life cycle assessment; Vehicles; Fuels; Hydrogen; Electric vehicles; natural gas; Ethanol; Methanol.

Acknowledgments

First and foremost, I would like to express my sincere gratefulness and gratitude to my supervisor, Prof. Dr. Ibrahim Dincer, for his limitless support and precise guidance throughout my master's study. Dr. Dincer has provided me excellent supervision and guidance in a tremendously smart manner during my research at UOIT. This master thesis would not be possible without his true supervision, support and patience.

While it is not possible to state all the names here I would like to acknowledge my colleagues at UOIT from Dr. Dincer's research team for their assistance and support during the preparation of this thesis, especially Dr. Yusuf Bicer, Dr Kemal Ozdemir, Dr. Hasan Ozcan, Murat Emre Demir, Burak Yuzer, Eren Sevinchan, Dr. Farrukh Khalid, Dr. Abdullah Al-Zahrani, Haris Ishaq, Osamah Siddiqui and Maan Al-Zareer. I also would like to thank Mr. Nuri Kurt for his financial support.

Last but not the least, I would like to thank my respected mother who always prays for me, and special thanks go to my wife for her whole-hearted support, my lovely kids and siblings who have provided me their support with their encouragement, prayers, love, and understanding.

I dedicate this work to the memory of my loved father, Omer Karasu, who passed away during the preparation of my thesis.

Table of Contents

List of Figures

List of Tables

Acronyms

ADF	Abiotic Depletion Factor
ADP	Abiotic resource depletion potential
AECL	Atomic Energy of Canada Limited
AP	Acidification Potential
BEV	Battery electric vehicle
BG	Biomass Gasification
CACs	Criteria air contaminants
CAFE	Corporate Average Fuel Economy
CERL	Clean Energy Research Lab
CG	Coal Gasification
CI	Compression ignition
CML	Institute of Environmental Sciences, Leiden University
CNG	Compressed natural gas
DALY	Disability-Adjusted Life Year
EIA	Energy Information Administration
EP	Eutrophication Potential
EPD	Environmental product declaration
EVs	Electric vehicles
FCV	Fuel cell vehicle
FFVs	Fuel flexible vehicles
GHGs	Greenhouse Gases
GREET	Greenhouse gases Regulated Emissions and Energy in Transportation
GWP	Global Warming Potential
HEVs	Hybrid electric vehicles
HHV	Higher Heating Value
HPC	Hydrogen Production Capacity
Hrp	Heat recovery percentage
HTP	Human Toxicity Potentials
ICE	Internal Combustion Engine
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied natural gas
MSWI	Municipal waste incineration
NREL	National Renewable Energy Laboratory
ODP	Ozone Depletion Potential

OPM	Open Pit Mining
PHEVs	Plug-in hybrid electric vehicles
PM	Particulate Matter
RAD	Radioactive Radiation
RAINS	Regional Air Pollution Information and Simulation
REPA	Resource and Environmental Profile Analysis
SOEC	Nuclear solid oxide electrolysis cell
TLS	Total Lifetime of the System
UCTE	Union for the Co-ordination of Transmission of Electricity
VOCs	Volatile Organic Compounds
WMO	World Meteorological Organization
WTW	Well-to-Wheel

CHAPTER 1 : INTRODUCTION

1.1. Transportation Sector and the Environment

Globally, the transportation sector is confronted with significant environmental concerns in consequence of the use of fossil fuel based fuels to power vehicles, which is the main reason for greenhouse gas (GHG) and pollutant emissions. Vehicle global registrations jumped from 980 million units in 2009 to 1.015 billion in 2010 described in a study, which is based on government-reported registrations and past vehicle-population trends [1]. In last six decades, the worldwide passenger vehicle fleet has annually increased by about 5% and consuming more than 20 million barrels of crude oil per day. This fleet is anticipated to upsurge up to 1.7 billion vehicles in 2035 [2]. Present passenger cars are mainly fueled by crude-oil-based fuels and thus a considerable source of CO_2 emissions. Furthermore, these cars are important sources of air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x),) and particulate matter (PM), which are progressively subsidizing to human health impacts. Moreover, security of future oil resources and stability in its prices are uncertain [2–4].

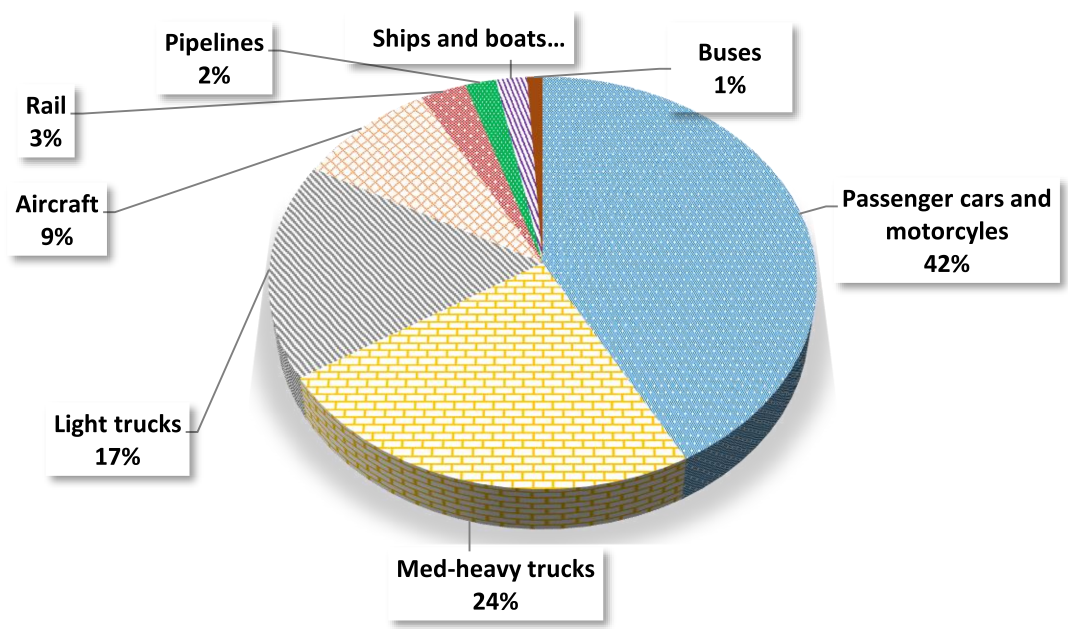

Figure 1.1 Proportion of greenhouse gas emissions from various U.S transportation sectors (data from [5]).

1.2. Energy Consumption in the Transportation Sector and Environmental Pollution

Energy is a key resource in wealth and economic growth of countries, and the population is rapidly increasing worldwide. Energy demand and availability are the two key factors, which play an important part in bringing economic development [6,7]. The International Energy Agency (IEA) conducted a wide range study on transportation that focuses on finding solutions for sustainable transportation. Improving fuel efficiency, implementing advanced technologies, transport modes, and switching to lower-carbon fuels were the policy advice given to governments by International Energy Agency [8].

The transportation sector consumes a substantial part of the U.S energy. According to a report from U.S. Energy Information Administration [9], 29% of the total share of energy usage is utilized in transportation sector, while remaining 71% is used in all the remaining sectors. Figure 1.2 exhibits the graphical representation of energy consumption by the transportation, industrial, residential, agriculture etc.

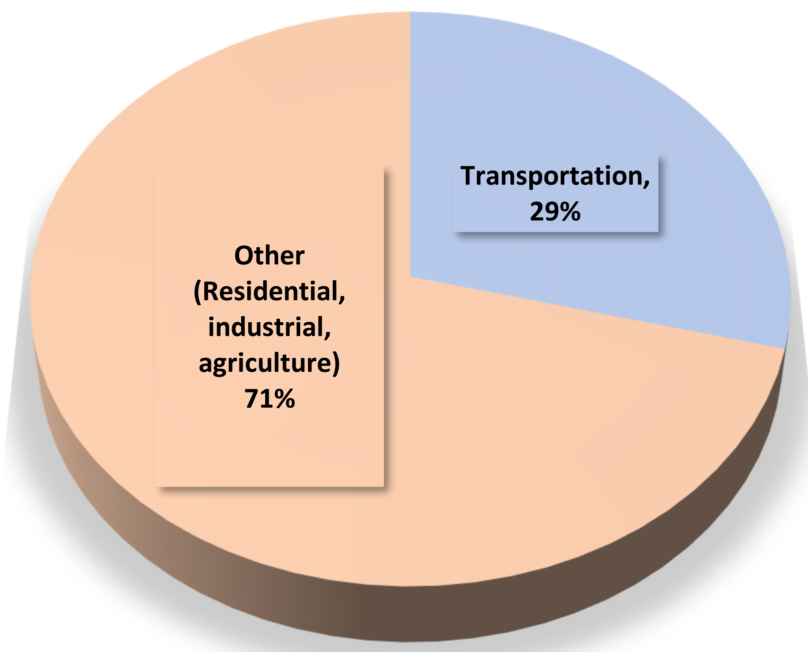

Figure 1.2 Share of total U.S. energy consumption for transportation sector in 2017 (data from [8]).

1.3. Life Cycle Assessment (LCA) and Transportation Fuels

A report was conducted by natural resources Canada [9] based on the greenhouse gas emissions in total end-use sectors. Natural resources Canada presented the database of greenhouse gas emissions produced by the major economic sectors like; residential, commercial/institutional, agriculture, transportation, and industrial sector on past 25 years. The database was presented from 1990 to 2015. Figure 1.3 shows the total end-use sector greenhouse gas emissions for different years through key sectors like commercial/institutional, transportation, residential, industrial, and agriculture. The transportation sector was the largest GHG emitter in Canada followed by industrial sector.

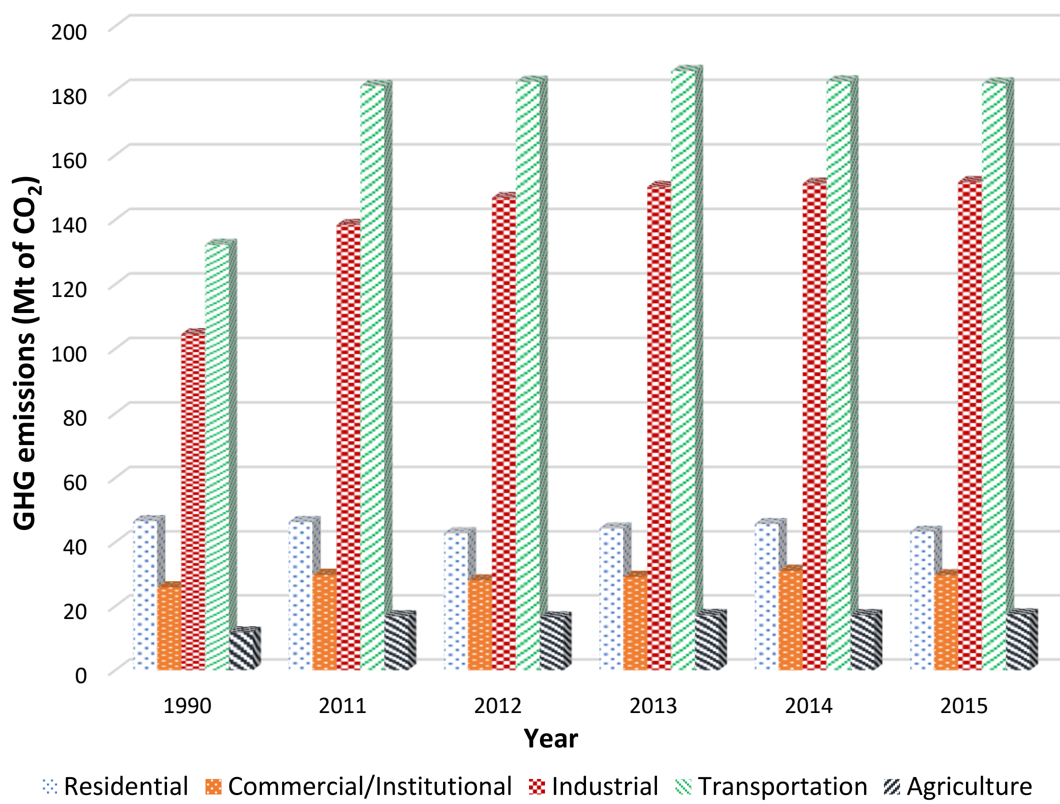

Figure 1.3 Total end-use sector greenhouse gas emissions for different years by key sectors [9].

In a report presented include by U.S Energy Information Administration (EIA), 92% of petroleum products were accounted from the total energy usage of U.S. transportation sector while biofuels contributed 5% of the remaining energy usage and natural gas contributed 3%. Electricity provided less than 1% of the transportation sector energy usage.

The U.S. leading transportation fuel is gasoline, then it comes to diesel and jet fuels. Gasoline is further classified in aviation and motor gasoline. Petroleum and ethanol fuel are considered under motor gasoline category. Figure 1.4 displays the U.S. transportations energy fuels/sources. The total gasoline components except ethanol are evaluated as 55% of total transportation energy usage in U.S. in 2017. It is followed by diesel with 22%, then it comes to kerosene (jet fuel), which occupies 12% of the transportations energy fuel, and 3% other includes, residual fuel oil, lubricants, hydrocarbon gas liquids and electricity.

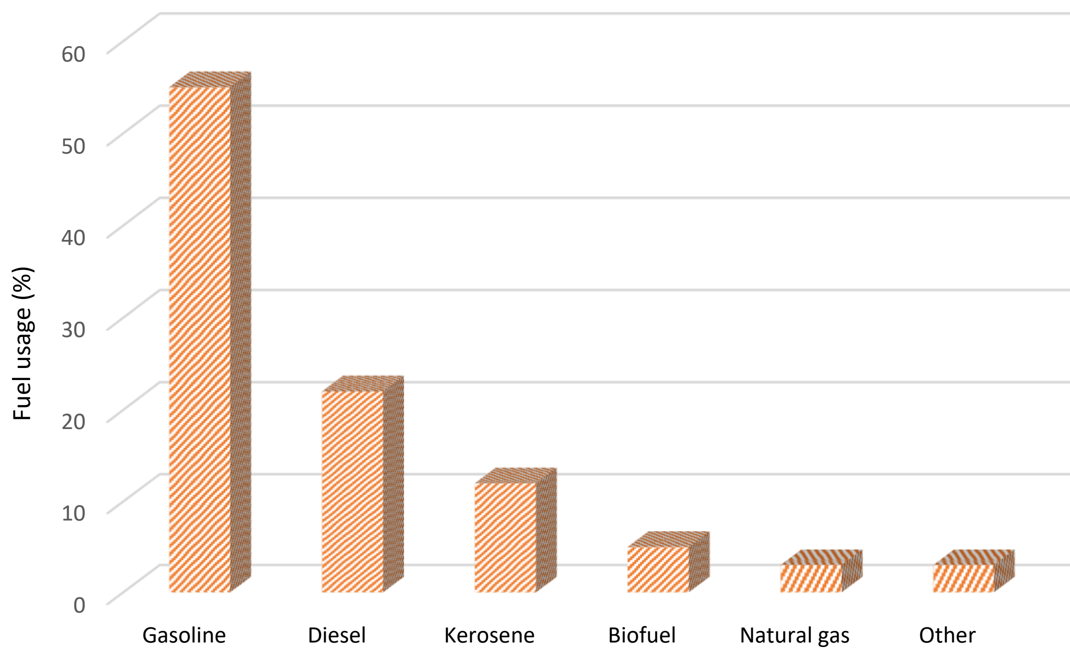

Figure 1.4 U.S transportation energy sources/fuels 2017 [10].

Automakers have proceeded with the advancement and execution of several fuel efficiency technologies like hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs). Furthermore, alternative vehicle fuels like hydrogen and biofuels are being developed. It is important to reduce environmental impact of passenger cars with new fuel-efficient vehicle technologies. Major issues impacting sustainability in passenger vehicles need to be tackled.

Life cycle assessment (LCA) is one of the inclusive methods for analyzing environmental impact of a product, process or service throughout its entire lifetime. The significant purpose of administrating Life cycle analysis includes various applications.

Cradle to grave LCA is the approach that signifies an organized set of processes for investigating the materials and energy inputs and outputs [11]. The life cycle is interlinked with the natural resources extraction to their final disposal. During a life cycle assessment, the environmental impacts, mass flows, and energy flow linked with the plant operation, construction, and dismantling stages are considered. Some assumptions and simplifications are usually set up to help LCA to determine all input and output flows.

A typical life cycle of a vehicle technology includes a cradle to grave LCA including not only the fuel cycle but also the vehicle cycle. Fuel cycle contains all the step from digging out the fuel to the fuel consumption in the vehicles and its environmental impacts while vehicle cycle comprises of all the steps related to vehicle production like material extraction, manufacturing, assembly, production and then the recycling and life end processing of the vehicles. Diesel, electric, ethanol, gasoline, hybrid, hydrogen, methane, methanol, and natural gas vehicles are considered for LCA study

The focus of this thesis is on numerous types of passenger vehicles based on conventional and alternative fuels. Well-to-wheel (WTW) analyses are largely used in the literature for comparison of vehicle technologies. Only fuel production, electricity, and the tail-pipe emissions are the focus of a WTW assessment. This produces a bias to zero-tailpipe emissions as environmental effects linked with the component production of batteries as well. The results of a reliable LCA reflects the full life of a product system and is not only restricted to the fuel production and usage. It should include the mining of raw materials, the manufacturing of automobile components, its assembly, the use phase and the end-of-life (EoL) scenarios [11,12].

The GREET model has turned out to be the standard for performing LCA of transportation fuels. Firstly, it implements the life cycle assessments on fuel production, then it performs the life cycle assessments on materials production for vehicles, and then it combines the two assessments with the intention of estimating the cradle-to-grave impact of different transportation technologies. The WTW analysis denotes hence a subset of the cradle to the grave assessment as WTW does not account the energy and emissions linked with the manufacturing and recycling of the vehicles [13].

1.4. Vehicle Powering Options

Numerous types of vehicle powering options are available worldwide regarding conventional and alternative fuels. All types of gasoline and diesel fuels are included in conventional fuels category while all other vehicle types like electric, ethanol, methane, natural gas, methanol, hydrogen and liquefied natural gas are counted in alternative fuels category. Figure 1.5 shows all the fuel powering categories like conventional fuels, carbon-free fuels, pneumatic options, renewable fuels and electric options. Vehicle powering can be delivered through the following options:

- Conventional fuels represented in natural gas and petroleum fuels.
- Carbon-free fuels represented in ammonia and hydrogen.
- Renewable fuels such as solar energy and biofuels.
- Electric options characterized in batteries and fuel cells.

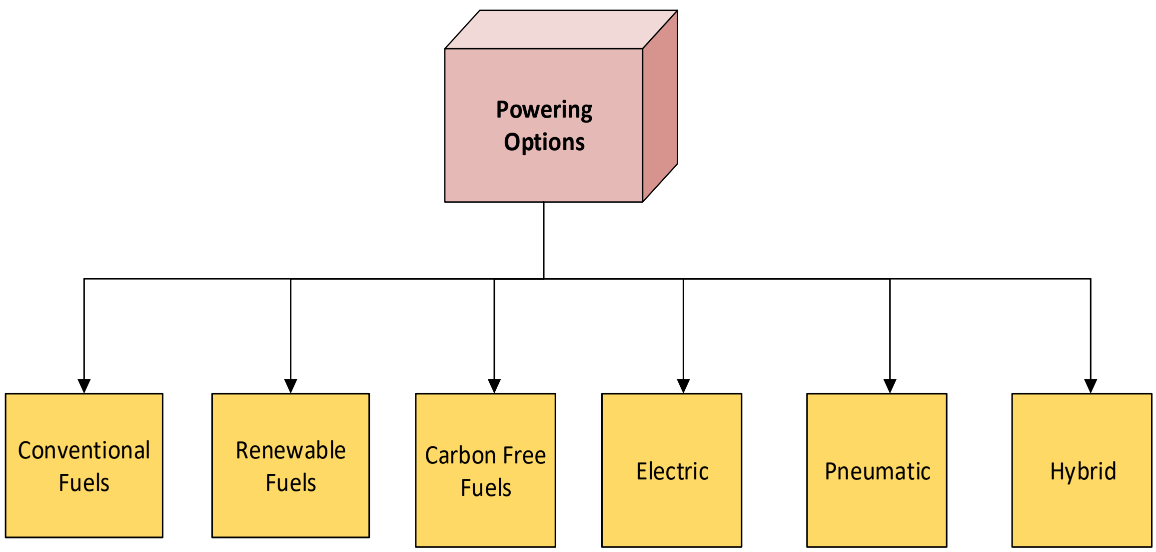

Figure 1.5 Vehicle powering options based on fuel type

1.5. Motivation

Transportation is the second largest source of air pollution and greenhouse gas emissions in Canada. Moreover, it carries substantial unfavorable effects on the natural environment and on living beings' lives. It also contributes significantly to global warming. Considering these reasons, transportation will be unsustainable without mitigation in emissions released by passenger cars. Sustainable transportation's environmental characteristics are concerned with noise and atmospheric pollution, resource use, land use, human health, flora and fauna, waste disposal etc. Use of passenger cars cause the leading environmental impacts, but the construction and development of infrastructure, manufacture of vehicles, manufacture of car batteries and other components, the disposal of vehicles and roads have a large share in the pie as well.

Accomplishing sustainability in transportation sector would lower greenhouse gas emissions, and it will lessen the dependency on the fossil fuels. Researchers recommend numerous solutions, such as using solar energy, renewable fuels, hydrogen fuel cell vehicles, battery electric vehicles (BEVs) and hybrid options. This thesis investigates the utmost wide-ranging environmental impacts of transportation fuels for vehicles and identifies the hot spots in supply chain in order to help accomplishing sustainable transportation.

1.6. Objectives

The goal of this study is to analyze the environmental impacts of conventional and alternative fueled vehicles and to form an unbiased image of the environmental impact of vehicles with conventional and alternative fuels. The results of this study determines the environmental burdens of traveling one kilometer with a specific chosen vehicle, and the underlying reasons for these impacts.

The analyses in this research provide a comprehensive vehicle LCA covering numerous transportation fuels that presented comparatively in six impact categories. Furthermore, three different LCA methodologies are employed to determine the environmental impact of vehicles. The performed LCA is process-based. The results of this study can be used by the academic researcher in the LCA field and can be used by the auto manufacturer for decision making on critical environmental issues. This study also aims to inform transportation policymakers and helping them in designing transportation policies that have a better understanding of the environmental impacts of the transportation sector. The specific objectives of this thesis study are summarized as follows:

- To perform comprehensive LCA studies of diesel, electric, ethanol, gasoline, hybrid, hydrogen, methane, methanol and natural gas vehicles, and present the results comparatively for assessment and evaluation.
- To determine environmental impacts of these vehicles in terms of abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and human toxicity potential impact categories.
- To carry out LCA studies on fuel production (i.e., fuel cycle) and materials production for vehicles (i.e., vehicle cycle), and then to combine the two assessments to study the cradle-to-grave impacts of various vehicle powering and fueling options
- To define the vehicle powering and fueling options with the highest and lowest environmental impacts and their consequences.
- To analyze the environmental impacts at each life cycle stage, namely operation of vehicle, manufacturing of vehicle, maintenance of vehicle, construction of roads, operation and maintenance of roads, recycle and disposal of vehicle, disposal of roads, and to identify the hot spots in supply chain of the vehicle life cycle stages.
- To utilize mid-point oriented impact assessment methodology through CML 2001, end-point oriented methodology through Eco-indicator 99 and a combination of mid-point and end-point oriented methodology through IMPACT 2002+.

CHAPTER 2 : LITERATURE REVIEW

In this chapter, the most recent LCA studies that conducted on vehicle fuels are discussed. Furthermore, the LCA studies that carried out on conventional and alternative fuels for vehicles are reviewed and described. Effect of using different impact assessment methods on LCA results is discussed as well. Main gaps in the literature are determined and described.

2.1. Life Cycle Assessment Methodology

LCA is an extensive method for evaluating the environmental impact of a product, service, and activity over its entire life cycle. The aim of performing LCA studies varies according to the goal of the application. Different applications utilize LCA for different intentions. Primarily, the main objective of using LCA is to lessen the environmental impact of products by guiding companies or organizations to reach decisions towards more sustainable systems and solutions. Life Cycle Impact Assessment (LCIA) is the utmost sensitive phase in a LCA where the life cycle inventory (LCI) outcomes for a specific product are transformed into comprehensible impact classes that characterize the environment impact [14,15,24,25,16–23]. Numerous LCIA methodologies consider different approaches for dealing with modeling the environmental emissions effects.

2.2. Life Cycle Assessment and Vehicles

Sharma and Strezov [26] presented a study on the sustainability assessment of powertrain technologies and substitute transport fuels. The significant focus of this research was on the alternative transport fuels for evaluating the economic and environmental life cycle impacts and its comparison with conventional fuels. The assessment of sustainability was executed for particular fuels, containing gasoline, bio-diesel, diesel, liquefied petroleum gas, hydrogen, ethanol, electricity, and fuel cell using SimaPro 8.05 software. This study concluded ethanol flexi fuel has the highest environmental impacts. The highest total economic costs on per km basis are revealed for BEVs. The collective economic and environmental impacts discovered hydrogen fuel cell as the best suitable option.

A comparison was conducted for different vehicle technologies on the basis of environmental performance [27]. Considering only tailpipe emissions included emissions during fuel production. Limiting to tailpipe and emissions fuel production is not even enough as components production and end life process treatment also includes much emissions and should be taken into consideration. Thus, complete life cycle assessment is suggested in this study for any vehicle to avoid problems in shifting stages. The article presents full LCA of fuel cell electric, petrol, compressed natural gas, diesel, electric battery, liquefied petroleum gas, hybrid electric, bio-ethanol, and bio-diesel vehicles. Numerous vehicle technologies impact on the environment was the major objective of the manuscript. Different vehicle technologies are studied, and their results regarding mineral extraction damage, climate change, acidification and respiratory effects are presented. By this study, it is established that influence of the vehicle is important to be considered in the life cycle assessment.

Cavalett and Chagas [22] presented an article on the comparative LCA of ethanol and gasoline utilizing LCIA methods. The core objective of this article is to examine how environmental performance get affected by using different LCIA methods. Some of the LCIA methods considered during the study are CML 2001, Eco-indicator 99, ReCiPe, Impact 2002+, Ecological Scarcity 2006 EDIP 2003 and TRACI 2. It was revealed that considering single-core indicators, different LCIA methods provide with the different results and restrict the interpretability at the endpoint.

2.3. Environmental Impacts of Conventional and Alternative Fueled Vehicles

Various studies are conducted on the comparative study based on the conventional fuel vehicles [28–37]. Owsianiak et al. [21] in his article, discussed a case study based comparison using ReCiPe 2008, ILCD's and IMPACT 2002+. At this point, the ILCD 2009 is compared with ReCiPe 2008 and IMPACT 2002+ and focusing on midpoint characterization aiming at four-window design options in a residential building.

Cherubini et al. [23] presented a paper on the uncertainty in life cycle assessment. Uncertainty can be found in many forms but in this study, more focus was on methodological choices variability having LCA outcomes and conducting sensitivity analysis is a common practice. A case study based on swine production was used for methodological choices. The multi-functional processes utilizing the swine production substitution methods presented the best results for all categories excluding freshwater eco-toxicity. The uncertainty analysis provides us with less uncertain decision-making to some extent by indicating the uncertainties.

A LCA was conducted in Belgium based on the conventional and passenger vehicles [38]. This paper examines the conventional and new passenger vehicle technologies concerning their environmental effects and how environmentally friendly they are. The paper includes a WTW LCA emission analysis based on the fuel production and distribution and cradle-to-grave emissions analysis as well based on vehicle production, maintenance, transportation and end life processing. The impact categories considered for this paper are air acidification, greenhouse effect, human health, and eutrophication. The petrol vehicle has the highest impact on human health, and the major factors of these effects are SO_X, particulate matter, and NO_X emissions.

Onat et al. [39] considered hybrid, plug-in hybrid and conventional vehicles in this paper. HEVs, PHEVs and electric vehicles (EVs), are better options for comparing energy consumption and greenhouse gas emissions with internal combustion vehicles. Though, selecting among these mentioned vehicle options is a tough decision due to many factors like regional driving patterns and sources of electricity. Vehicles from 50 states were compared in this study considering electricity generation and state-specific average mixes, battery manufacturing impacts vehicle, and regional driving patterns.

Bicer and Dincer [40] carried out an LCA study based on hydrogen, methanol and EVs considering WTW approach to examine the alternative vehicles impacts on human health and environment. For each base case, all the processes from materials extraction for electricity, methanol, and hydrogen to vehicles disposal are analyzed. Global warming, ozone layer depletion, and human toxicity are the three different categories considered to observe diverse effects of vehicles. This study came up with the conclusion that EVs cause higher human toxicity comparatively. The hydrogen-based engine is more environmentally friendly as compared to the methanol concerning ozone layer depletion and global warming because of the high energy density of hydrogen.

Rose et al. [41] conducted a LCA for diesel and natural gas-powered vehicles. Consumers, investors and worldwide organizations are looking to decrease greenhouse emissions and their environmental impact by searching for conventional diesel and gasoline vehicles containing low-carbon alternatives. A LCA of compressed natural gas and diesel-powered heavy-duty vehicles refuse is conducted in this paper. This study concluded compressed natural gas (CNG) as the better suitable option regarding reducing climate impacts and cost-saving method.

Bauer et al. [2] presented a paper on the LCA for current and future technologies for passenger vehicles. This paper comprises a comprehensive number of mid-sized current and future passenger vehicles and their environmental performance. A novel simulation framework for an integrated vehicle is presented in this paper, which considers future technological methods. Both conventional and hybrid natural gas, diesel, gasoline, fuel cell electric and battery vehicles are analyzed. This study resulted that significant mitigation of change in climate can be achieved by using electric passenger vehicles. Many more studies are conducted on the comparative study based on the alternative fuel vehicles [42–50].

Ahmadi and Kjeang [51] proposed an inclusive LCA based on the hydrogen fuel cell vehicles (FCVs) considering four Canadian provinces. Three hydrogen production methods considered in this study are; thermochemical water splitting, electrolysis, and natural gas and compared with the base case of conventional gasoline vehicles. Significant decreases are projected in greenhouse gases (GHGs) from all three methods considered for hydrogen production excluding electrolysis in Alberta because a major part of electricity is produced through fossil fuels. Hydrogen production through the thermochemical process is concluded as the best option because of renewable waste heat usage. Natural gas based hydrogen produced is resulted in the lowest fuel costs.

Messagie et al. [12] conducted a LCA of the various vehicle technologies, their fuels and environmental impacts. This study considered all the steps like; tailpipe emissions, combine fuel production, specific components production and end life process treatment, which can have the possibility of containing emissions

A thesis based comparative study was conducted on the hydrogen production for vehicles through numerous methods [52]. A comparative environmental assessment was conducted in this thesis by various energy sources for hydrogen production methods like fossil fuels and renewable energy sources. Natural gas steam methane reforming method was considered for hydrogen production through fossil fuels. Electrolysis utilizing sodium chlorine cycle is examined for hydrogen production through renewable energy sources. This thesis came up with the conclusion that natural gas-based steam methane reforming carries maximum environmental impacts and carries three-time energy consumption as compared to hydrogen vehicles. Many more studies are conducted on the comparative study of the hydrogen production methods for vehicles.

Ozbilen [53] undertook LCA of nuclear-based hydrogen production through thermochemical copper-chlorine (Cu-Cl) cycle. Three, four and five steps based thermochemical copper-chlorine (Cu-Cl) cycles and some other hydrogen production processes were considered in this thesis. An investigative tool of LCA is utilized in this thesis study for identifying environmental effects of the systems. The LCA conduct during this study came up with the conclusion that four-step thermochemical copper-chlorine (Cu-Cl) has the least environmental impacts due to lesser thermal energy requirement as compared to three and five-step copper-chlorine cycles. Moreover, the parametric studies illustrate that nuclear-based four-step thermochemical copper-chlorine (Cu-Cl) cycles are found as the most environmentally benign methods compared to other methods.

Creutzig et al. [54] presented a paper on the environmental and economic evaluation of the vehicles based on compressed air. Technological innovations are required in the transport sector, and the major reasons are energy security and climate change. Compressed air car is one of the suggested environment-friendly vehicle using energy stored in compressed air. In this study, pneumatic engine based compressed air car is considered and compared with potential energy chemical storage. The results of this study revealed that car based on compressed air is less efficient and produces more emissions as compared with battery electric vehicle while a hybrid pneumatic combustion vehicle can compete with HEVs regarding being inexpensive and technologically feasible.

Granovskii et al. [55] presented an exergetic LCA on renewables-based hydrogen production. This exergetic LCA helped in evaluating exergy efficiency, environmental impact and economic effectiveness of renewables (wind and solar) based hydrogen production systems and the final product of these systems (hydrogen) is a replacement of gasoline in fuel cell vehicles. Numerous processes like; natural gas reforming and crude oil distillation, electrolysis and gasoline based hydrogen production, natural gas and crude oil pipeline transportation, hydrogen distribution, and electricity generation through solar and wind renewable energy sources are considered in this study for examining environmental impacts and exergy efficiencies. This study came up with the result that hydrogen based on renewable energy is a long-term solution for numerous environmental problems.

Suleman et al. [56] conducted a comparative LCA for different hydrogen production methods. Both fossil fuel and renewables energy sources are considered in this study. Natural gas steam methane reforming and electrolysis using sodium chloride (NaCl) cycle is characterized by the fossil fuels and renewables-based hydrogen production. Hydrogen production based on electrolyte is also compared utilizing diaphragm cell, membrane cell, and mercury cell. An investigative tool of LCA is utilized in this paper for identifying environmental effects of the systems. The LCA results established that natural gas-based steam methane reforming carries maximum environmental impacts and carries three-time energy consumption as compared to hydrogen vehicles.

Granovskii et al. [57] presented a LCA study based on gasoline and hydrogen vehicles containing production and utilization of fuel in vehicles to examine the environmental impacts and efficiencies. Numerous processes like; natural gas reforming and crude oil distillation, electrolysis and gasoline based hydrogen production, natural gas and crude oil pipeline transportation, hydrogen distribution, and electricity generation through solar and wind renewable energy sources are considered in this study for examining environmental impacts and exergy efficiencies. Hydrogen production through electrolysis using electricity generated by wind energy source and its usage in proton exchange membrane fuel cell has at least energy consumption and greenhouse gas emissions.

Offer et al. [58] presented an analysis based on the sustainability of hydrogen fuel cell, battery electric and hybrid vehicles. In this paper, BEVs are compared with hydrogen fuel cell based plug-in hybrid vehicles and EVs. After going through the comprehensive analysis, this study came up with the result that fuel cell electric vehicles can accomplish lifecycle cost in 2030 with conventional gasoline vehicles. The vital conclusion of this study is that fuel cell PHEVs are the best pathway for future advancement.

Lombardi et al. [59] conducted the LCA of the hybrid, electric, fuel cell and conventional powertrains. Comparing the environmental impacts of a pure electric vehicle, plug-in hybrid fuel cell-battery vehicle, a conventional gasoline vehicle and a plug-in hybrid gasoline-electric vehicles in the main focus of this paper.

Yan and Crookes [60] presented a paper on the greenhouse emissions and energy usage in China for transportation fuels. An investigative tool of LCA is utilized in this thesis study for identifying environmental effects of the systems. This paper conducted a review on the recently published data on the life cycle studies and put some efforts to recognize the best reliable option regarding petroleum usage, fossil fuel usage and greenhouse gas emissions in China. Fuels studied during this paper contains conventional diesel, soybean-derived biodiesel, cassava-derived ethanol, compressed natural gas, conventional gasoline, sugarcane-derived ethanol, wheat-derived ethanol, liquefied petroleum gas, corn-derived ethanol and rapeseed-derived biodiesel and some recommendations were made for future work.

Paulino et al. [61] conducted an LCA based on the alternative options for passenger transport, and Europe was taken into consideration. Passenger transport shares a reasonable amount of pollutants emission and energy consumption in any country. Numerous efforts and researches are being done for the sake of reducing environmental impacts. An LCA methodology was applied in 27 European countries on passenger transport considering three major stages of production, use and end life processing. The use of more recent vehicles technology or diesel vehicles shows substantial reductions in, respectively, five and eight impact categories (out of 15), justifying their adoption in the European fleet. This study concluded that biofuels, compressed natural gas or EVs undergo the extreme drop in climate change up to 46%.

Baptista et al. [62] performed the LCA for fuel cell hybrid taxi. This study presented an LCA for fuel cell hybrid vehicles to observe environmental impacts and energy consumption and comparing the impacts with substitute vehicle technologies and both

Tank-to-Wheel and Well-to-Tank analysis are considered for fuel life cycle, and Cradle-to-grave analysis was considered for vehicle materials. A diesel taxi based on internal combustion engine was set as a current source of reference vehicle technology for comparison with fuel cell and battery vehicles. Consequently, the diesel, hydrogen, and electricity are the energy pathways utilized in this paper. Public Carriage Office- Centre for Excellence for low carbon and fuel cell technologies (PCO-CENEX) drive cycle was used for analysis, and it was proved that configurations of the vehicles powered by fuel cell undergo less energy consumption as compared to diesel and BEVs.

Hooftman et al. [63] proposed an environmental analysis based on the diesel, petrol and electric passenger vehicles and country of consideration was Belgian. The combustion of fossil fuels in the transport sector leads to an aggravation of the air quality along city roads and highways. Urban air pollution is becoming severe with the enhancement of the number of vehicles on a yearly basis. This paper focuses on the relation of non-exhaust emissions considering conventional including diesel and petrol or electric EVs by environmental impacts and air quality. An environmental LCA was conducted during this study considering real-world emission by fuel refinery and passenger vehicles data. The results depict that as being more environmentally friendly transportation means, EVs can be the best suitable substitute solution. The results concluded from this study highlighted policymakers to maintain some objective policies and regulations and EVs offered an effective solution for this issue.

Hawkins et al. [64] studied a LCA on the electric and hybrid vehicles. A literature study was conducted to observe the environmental impact assessment of electric and hybrid vehicles regarding life cycle assessment. The results achieved from this research work were combined to compare EVs and hybrid vehicles base on internal combustion engine by global warming potential. Numerous method was defined to observe life cycle stages, impact categories, environmental impacts, emission categories and resource use and 51 environmental assessments were considered for electric and hybrid vehicles. The results achieved by environmental impact assessment for life cycle inventories are considered in term of global warming pollutants and emissions caused by other pollutants. Global warming pollutants results achieved through key parameters and life cycle stage are extracted, and these results are further utilized for performing a meta-analysis.

Karaaslan et al. [65] conducted a LCA study for sport utility vehicles utilizing distinctive fuel options. Sport utility vehicles usually contain low fuel economy because of the payload capacities, curb, and their environmental impacts. A cradle-to-grave LCA is conducted in this paper to evaluate the environmental impacts of sports vehicles from manufacturing to end life processing. A combination of economic input-output and LCA technology is utilized in this study to evaluate the energy consumption, greenhouse gas emissions, and water withdrawal. This LCA analysis is accompanied by sensitivity analysis utilizing Monte Carlo simulation to evaluate the fuel economy and operation mileage ranges. Socio-economic impacts studies and electricity generation regional differences are recommended in this paper.

Mansour and Haddad [66] proposed a WTW study based on low carbon fuel vehicles for road transport. Rapid advancements in road transportation are carried out as more viable substitute fuel vehicle as an efficient mean of climate change dealing. Numerous studies are conducted based on WTW methodology in the developed countries to evaluate the environmental impacts and conduct a comparison with conventional fuel vehicles. In this study, a WTW assessment considering Lebanon and some other fuel importing countries where transportation infrastructure and energy are underdeveloped. This paper examines criteria pollutant emissions, the energy use, economic costs and GHGs for both conventional and alternative fuel vehicles. Results of this paper concluded that EVs are most beneficial and suitable for a lifelong period as they need much expensive clean electricity mix and charging infrastructure. Sensitivity analysis displayed that vehicles based on natural gas are competitive regarding high mileage.

Wallington et al. [67] considered oil production trend for comparing the substitute fuel vehicles for life cycle assessment. Unconventional reserves are making a huge contribution for petroleum products to fuel supply transportation, but the only disadvantage is costly and more environmental burdens than conventional sources. Gasoline-fueled conventional internal combustion engine vehicles are considered as the reference for alternative fuel vehicles. Disposition of alternative fuel-vehicle on large-scale will reduce petroleum demand, and it will result is declined production. Existing modeling approaches are undervalued if borderline petroleum resources impact more than average petroleum resources.

Batista et al. [68] presented an overview based on the light-duty vehicles, their environmental rating methodologies and their applications worldwide. Numerous methodologies for environmental ratings are accessible globally to compare and estimate the vehicles environmental performance, and these methodologies are useful for organizations and consumer decisions of fewer pollutant technologies and fuels. Green Score (US), EcoTest (Europe), Green Car Rating (UK) and Eco score (Belgium) adopted the life cycle standpoint while Eco vehicles rating (Mexico), VCD (Germany), and Green Vehicle (Australia) considered fuel in-use. Ecoscore and Green Score varies concerning the impact categories if comprehensive life cycle methodologies are considered. For this characteristics variability, a set consisting of seven actual vehicles was designated consisting of alternative vehicles and internal combustions engines considering biodiesel and hydrogen as alternative fuels. The applications of these techniques presented that commercial vehicles ranking differs for both methodologies. This study concluded that electric vehicle marks the less environmental impact as compared to the internal combustion engine.

Nordelof et al. [69] proposed an environmental impact assessment based review on the battery electric, hybrid and plug-in hybrid vehicles. This review article considered 79 papers to examine the practicality of numerous LCA types. Additionally, it was discussed in this study that with the advancement and research in EVs technologies, the manufacturing and material processing of parts is being ignored regarding future perspective. It was proposed that EVs can result in justifying global warming potential if low emissions are carried out by charging electricity because this is a cause of environmental impacts. Practitioners studying LCA of electric and hybrid vehicles are highly recommended to deliver scope formulation and clear and comprehensive goal.

Singh et al. [70] delivered a LCA based on forest biomass for fuel cell and EVs. Biomass-based hydrogen and electricity usage in substitute transport can deliver sustainable transport choices. A LCA was performed based on the fuel cell and EVs driven by bio-hydrogen and bioelectricity. The results demonstration that bio-hydrogen and bioelectricity powered vehicles undergo 30% less amount on global warming.

Ma et al. [71] conducted a comparison between internal combustion and electric battery vehicles regarding greenhouse gas emission through life cycle assessment. EVs have become the focus of interest internationally especially BEVs and the main reason is that it can be a sustainable long-term solution. Though, to observe how much these vehicles can contribute to reducing the environmental impacts (greenhouse gas emissions) can be observed by analyzing LCA and comparing the results with internal combustion vehicles. This study shows an analysis of alternative vehicle technologies considered; real-world effects, greenhouse gas emissions, and manufacturing and end life processing of vehicles.

Abdul-Manan [4] presented a study considering the gasoline based electric and conventional vehicles regarding the uncertainty and greenhouse gas emissions difference. A huge difference in uncertainty and greenhouse gas emissions is possible considering transport electrification. The distinctive LCA provided with the modeling pathway methodology to evaluate the greenhouse gas emissions (GHG) and emissions estimation comparison for electric and internal combustion engine vehicles within the range from 10% to 60%. Monte Carlo simulation methodology is used in this paper to evaluate the GHG emission uncertainty in electric and internal combustion engine vehicles by considering all probable variations, which can affect GHG emissions lifecycle. This study proposed a stance by proposing transport electrification as low carbon future mobility to all the policymakers globally.

Onat et al. [72] studied a life cycle sustainability considering alternative passenger vehicles. Mobility and sustainable transportations are significant components and fundamentals of sustainable development. The main focus of this study is to show the macro-level economic, social and environmental impacts considering the United States alternative vehicle technologies. The vehicle technologies considered during this research paper are conventional hybrid including four electric ranges, gasoline, plug-in hybrid and battery EVs. As a whole, a bunch of 19 sustainability indicators is scenario quantified, which charges EVs through present U.S. power grid and another scenario of charging EVs by solar charging stations.

LCA is carried out considering the material manufacturing, extraction, operation and processing phases up to end life processing. The results revealed that most influential phase of socio-economic impacts is manufacturing phase while in environmental impacts, operation phase leads among others. Electric battery vehicles carry fewer human health impacts and air pollution to conventional gasoline vehicles. This study concluded that BEVs have at least greenhouse gas emissions.

Hawkins et al. [73] presented LCA based on the electric and conventional vehicles. Low-carbon electricity sources coupled with EVs have the possibility of decreasing greenhouse gas emissions. It is significant to debate on problem shifting concerns to consider these benefits. Additionally, while many types of research have targeted use phase in transportation options comparison meanwhile vehicle production also has a significant role while comparing electric and conventional vehicles. An inventory is developed in this study based on the transparent life cycle considering electric and conventional vehicles and this inventory can be applied to assess electric and conventional vehicles in specified impact range categories. To improve the environmental profile of EVs, clean electricity sources promotions are necessary regarding electricity infrastructure.

2.4. Main Gaps in the Literature

From the literature survey that conducted, it is found that no cradle-to-grave LCA studies conducted on hybrid (LNG and electric), bio-methane, and ethanol fuel vehicles. Furthermore, there is no comprehensive LCA studies have been conducted yet, which take into account the various possible environmental impacts that from the several life cycle stages involved. Moreover, very few studies have considered comparing the environmental impact assessment results from different types of impact assessment methodologies. Utilizing and comparing the results obtained through different methodologies enhances the reliability of the results. Hence, in the present study, three different types of impact assessment methodologies are utilized, and the results are compared for evaluation purposes

CHAPTER 3 : LIFE CYCLE ASSESSMENT

In this chapter, a detailed discussion of a LCA methodology is provided. The different life cycle stages that involved are explained comprehensively in accordance with the ISO standards. A detailed description of the various environmental impact categories and their significances is also provided.

3.1. Description of Life Cycle Assessment

LCA is considered one of the inclusive environmental impact assessment methods for a product over its entire life cycle. The objective of conducting LCA study differs among numerous applications. Various applications utilize LCA for diverse purposes. In common, the major focus of utilizing LCA technique is on reducing the environmental impact of specific products under consideration for more sustainable solutions through decision-making process [74–76].

The most crucial stage during a LCA study is LCIA, which the results of LCI of the specific substances associated with the certain system study are altered into comprehensible impact classifications, which represent the environmental impact. Numerous LCIA methods have been developed considering diverse approaches to deal with emissions effects modeling on the environment.

3.2. Why LCA?

The core requirement for founding LCA studies arisen from the necessity to measure the product environmental releases to classify possible room of improvement by lower resources consumption and reduced environmental impacts in the entire life cycle. LCA can be utilized for numerous purposes and each derived purposed may need a separate set of details concerning the collection of data. The data highly depends upon the application and purpose for which LCA tool is utilized, and data is most likely to be very simplified or detailed [77]. Some significant LCA goals are explained in the following sections.

3.2.1. Product Development

Product development utilizing LCA is considered as ecological process design. Usually, there are numerous options for the resources and materials choice during the design phase of any specified product. Employing LCA during the product development is crucial, and the reason is any decision related to the resources and materials affects the subsequent life cycle phases [78]. Thus, the prior LCA is utilized proficiently in the design phase; the lesser will be the environmental impact. In such scenario, the LCA methodology may require wide data collection and this data collection can be time-consuming. Though, making LCA simpler in this scenario can be valuable [79], such that, the focus, analysis, and investigation will be on the resources and materials that possibly have the high impact on the environment, and then before moving towards development process, try to find substitute preliminary design solutions.

3.2.2. Product Improvement

Improvement in an existing process or product can be accessible concerning data collection. It is significant to concentrate on the resources and the materials solely, which affect the product considerably when LCA is utilized as a tool for the product improvement. In this way, various products become comparable with each other via an environmental viewpoint, where the environmental impact of each specified product is calculated and compared with some other case from the same classification. Substitute solutions for the resources or materials, which creates a higher environmental impact during life cycle stages (manufacturing, operation, and disposal) are then combined and assembled for the reassessment of the whole solution [80].

3.2.3. Marketing

Marketing is the method of collaborating the specific features of the product as per the customer expectations and requirements for certain quality requirements. With the increase in environmental consciousness level, some environmental properties of services and goods are getting more attention from the consumer. For utilizing LCA technique for the environmental marketing purpose, environmental labeling (Eco-labelling) is well known as the most relevant type [81]. To confirm if the specified product is environmentally friendly, environmental labeling is taken as a proof. When a defined product goes along with Eco-labelling standards, it gets an Eco-label, and this is the reason why it is attractive for marketing intension and environmentally friendly products are more attractive to the consumer. As per Eco-label regulation EU, LCA is considered as the major requirement for the Eco-label criteria advancement. The EU Ecolabelling structure has so far caused in criteria for definite product classifications like paints and varnishes, washing machines, laundry detergents, soil improvers, toilet paper, kitchen towels, copying papers, water heaters, T-shirts and bed linen, light bulbs, dishwashers, ovens, refrigerators and freezers, air conditioning, cars and televisions [82–84]. Environmental product declaration (EPD) is another marketing purpose type of alike Eco label scheme. According to the ISO 14025 standard and based on LCA, EPD comprises a range of information related to the environmental characteristics and components of a defined product [85,86]. The overall impression of EPD is to give the graphical presentation to a product of a current environmental impacts number like using a bar diagram. Graphical presentation can be easily understood by environmentally conscious consumers and professional buyers, but still, it might not be very clear to wide-ranging consumers. In permitting conversant decisions in its place of conferring judgments, though it appears that EPD is better as compared to Eco-labeling the detail level required for the establishment of EPD is high as compared with the Eco-labelling scheme, that is a difficulty towards its implementation and operation process [81,87].

3.3. General LCA Framework

Some general related terminologies and definitions to the LCA process are discussed in this section. By the ISO 14040 standards [88], defined framework is specified to employ an LCA process. The scope, the considered boundaries, and the detail level of an LCA study is totally depend on subject and intended use of the work. The complexity and extensiveness of LCA studies can vary significantly depending on the goal of a specific LCA study. All LCA studies should follow ISO standards in order to present accurate results for direct applications. All the standards and recommendations can be briefed in these four core steps:

- definition of goal and scope
- inventory analysis
- impact assessment, and
- interpretation of the results.

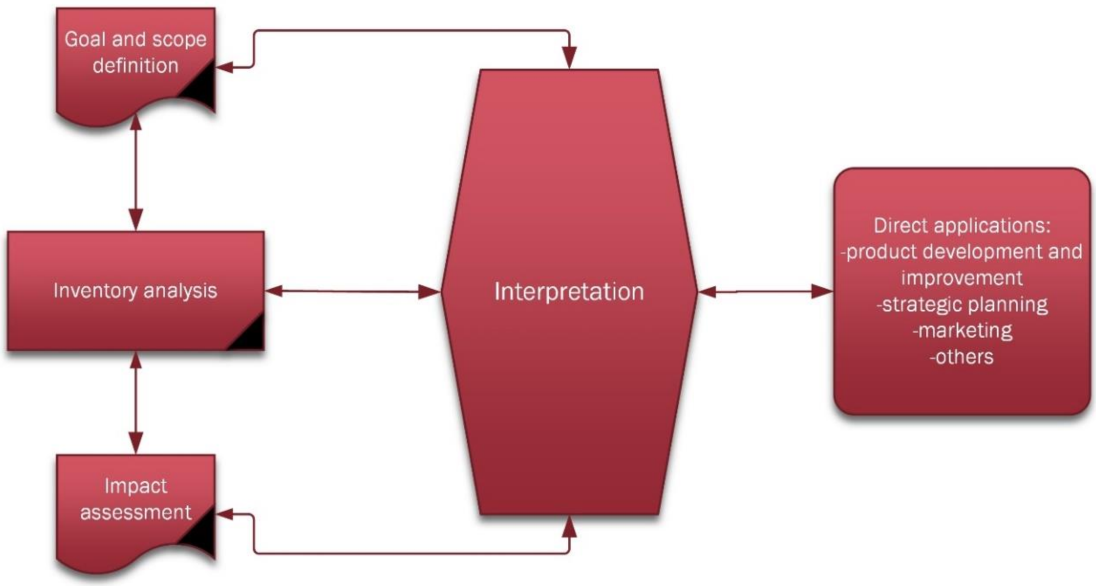

Figure 3.1 LCA framework according to ISO 14040 standard

Figure 3.1 exhibits these all major steps. The arrows in the Figure among the stages indicate the iterative and cooperative nature of LCA. For a scenario during the impact assessment, someone may come up with the result that specific information is vague or missing and this result shows that the inventory analysis needs improvement. In another scenario when throughout the interpretation stage, the results interpreted may be unclear or inadequate to overcome the application requirements, which presents that the definitions of the scope and goal may need improvement and modification [81]. These four steps are required to conduct an LCA assessment efficiently are provided in the ISO standard [21,88–90] and are debated in the subsequent subsections.

3.3.1. Goal and Scope Definition

Definition of goal and scope is the initial stage in an LCA analysis, which the product is specified and the assessment context is to be made. This stage is quite important in the LCA process. This phase influences the impact assessment stage in identifying numerous parameters such as the purpose of the study, time and resources desired, the intended application, the assessment methodology, the system boundaries, and the wide-range limitations and assumptions. Thus, goal and scope definition will lead the whole LCA process to make sure that utmost appropriate results are attained [91]. Though, because of the LCA iterative nature, variations may take place through the study of goal and scope definitions.

3.3.2. Inventory Analysis

The inventory analysis results are arranged in the form of the list, which contains the materials quantities and energy consumed during the various life cycle stages of a defined product. Thus, during the inventory analysis stage, the associated materials and energy flow based on the specific product are described to signify the product and the overall inputs and outputs to and from the corresponding natural environment [92]. The LCI analysis highly depends on the quantities and types of numerous natural resources like water, energy, etc., the transportation methods, the production materials, usage of the defined product during its lifespan, and the final disposal of the product. The deliberation and special effects of the described factors can vary among different regions. For various scenarios like a region, which does not have sufficient resources for certain product production, or some other region contains various technologies for the certain materials production, or it might further depend upon the fossil fuels or renewable energy resources, and these variances may disturb the LCA assumptions and limitations.

3.3.3. Impact Assessment

Compiled LCI list containing the related product studies based on the consumed energy quantities and corresponding materials is interpreted and converted into comprehensible impact indicators in this step of impact assessment. The described indicators present the severity of the impact categories contribution to the environmental load. ISO standards 14042 have recommended a series of stages to conclude the indicators [88], some steps among the defined steps are mandatory while remaining are optional. The mandatory steps are impact categories definition and classification, and characterization while optional steps are listed as normalization and weighting.

3.3.4. Interpretation of the Results

The impact assessment results achieved through the whole assessment are illustrated, and conclusions are established in this step for the guidance in decision-making process. Environmental issues which are considered and the importance of specific processes or product components relative contribution to the environmental load is documented. Results verification can be prepared depending upon the study requirement via data check according to three standpoints described [93] as follows:

i) Completeness check

Make sure about the comprehensiveness of the study like some substantial environmental issues identified previously present the data attained by the different LCA stages sufficiently according to the defined goal and scope.

ii) Sensitivity check

Check if the uncertainties included in data effects the ultimate outcomes and conclusions or the designated calculation methods. Therefore, the major focus of the sensitivity and uncertainty check is to achieve the confidence in the study results related to its general goal. This described sensitivity check is generally used for assumptions test throughout the study. The sensitivity and uncertainty check can be achieved by considering a scenario of "what if", which the values representing the different input parameters can be altered systematically. This is also achievable by using Monte Carlo simulations.

iii) Consistency check

This step included evaluating the methods consistency, treatment, and procedures of data being utilized during the study and coherency check with the goal and scope. Some of the items considered during the consistency check are data accuracy, data source, geographical representation, assumptions and system boundaries.

3.4. ISO Standards for LCA

Environmental organizations put some pressure to standardize LCA methodology and this pressure results in the LCA standards development in the International Standards of Organization (ISO) 14000 series [75,88,94], which are recorded in Table 3.1

i) ISO 14040:2006

ISO 14040:2006 defines the framework and principles for LCA counting: the goal and scope definition in LCA, the LCIA stage, the LCI analysis stage, the life cycle interpretation stage, limitations of the LCA, reporting and crucial review of LCA, the relation amongst the LCA stages and optional elements conditions. ISO 14040:2006 occupies LCA studies as well as LCI. It does not emphasize the LCA technique and does not specify individual phase methodologies for the LCA. The proposed application of LCA or LCI findings are considered throughout the goal and scope definition but itself the application is not included within this International Standard scope.

ii) ISO 14044:2006

ISO 14044:2006 indicates necessities and delivers guidelines for LCA. LCA comprising: the goal and scope definition for LCA, the LCI analysis (LCI) stage, reporting and crucial review for LCA, the LCIA stage, the life cycle interpretation stage, relationship between the LCA stages, boundaries of the LCA and situations for optional elements utilization.

Table 3.1 ISO standard series for a life cycle assessment

Number & Year	Title	Explanation of the standard
ISO 14040:2006	Environmental management -- LCA -- Principles and framework	This standardized document provides with an overall description and framework of LCA. This item describes a summary of the practice, applications, and boundaries of LCA.
ISO 14044:2006	Environmental management -- LCA -- Requirements and guidelines	This item describes the requirement and guidance for the impact assessment and also provides with the nature and quality of collected data.

Source: [74,88,94]

3.5. Life Cycle Impact Assessment (LCIA) Methods

LCIA step is considered as the most crucial step within an LCA study, and the reason is that it treats with comprehensive data quantity that is exhibited in the results achieved by inventory analysis. These inventory analysis results are then altered into easily understandable impact indicators coinciding within the impact categories afterward passing by the compound environmental modeling focused on the normalization and characterization of the environmental and natural science and acknowledged the social, political and ethical issues. Because of the reason for this complication in the LCIA step, approaches were established to make simpler and improve the LCIA process. LCIA approaches are acknowledged as the tools established to link the LCI findings to the accompanying environmental impacts in which the LCI findings are categorized within impact classifications containing a category indicator. Through this, the LCIA methodologies development expedites the trade-off and dissimilarities among various alternative products, make the process simpler for LCA practitioners as well as facilitate benchmarking. Two characterization approaches midpoint and endpoint approaches, inside of the LCIA phase can exist beside the impact indicator pathway. Indicator situated at someplace besides the methodology mechanism is used for categorizing midpoint level models nevertheless earlier to the endpoint classifications; endpoint level characterization requires modeling throughout the endpoint categories designated by the protection areas (In utmost methodologies, the key protection areas used are: Eco system quality, human health, and resources). Thus, the possible location of the category indicators will be in-between the LCI outcomes and the category endpoints in the effect chain cause.

3.5.1. CML 2001 Method

A group of scientists proposed a midpoint oriented method known as CML being led by, Institute of Environmental Sciences at Leiden University containing an impact categories group and the impact assessment stage characterization methods in 2001 [93,95]. Standardization is delivered, but it does not contain weighting or addition. The provincial impact categories legitimacy of the CML approach is universal excluding acidification and photo-oxidant formation. CML 2001 method is most widely used in LCA studies because it is a problem focused approach. Result of this study is mainly reported in CML 2001, due to its suitability for this study. The impact categories selected for this study are explained in following subsections. Table 3.2 shows impact categories selected for this study, their units and definitions.

i) Acidification Potential (AP)

Acidification potential (AP) is associated with the acid testimony of acidifying impurities on groundwater, soil, surface water, ecosystems, biological organisms, and substances. Key acidifying contaminants are SO_2, NOx, and NHx. Natural environment, human health, the human-made environment and natural resources are the protection zones. Acidifying constituents motives an extensive influences collection on groundwater, soil, surface water, ecosystems, organisms, and constituents. The Regional Air Pollution Information and Simulation 10 (RAINS) model is utilized to determine the AP for air releases, and describe the deposition and fate of acidifying constituents [96]. Equivalents/kg of SO_2 (kg Sb-eq) emission is used to express the AP [97].

Table 3.2 CML 2001 impact categories and their units

Impact category	**Definition of the unit**
Abiotic depletion potential (ADP) (kg Sb-eq)	Kilogram of Antimony equivalent
Acidification potential (AP) (kg SO_2-eq)	Kilogram of Sulphur dioxide equivalent
Eutrophication potential (EP) (kg PO_4-eq)	Kilogram of Phosphate equivalent
Global warming potential (GWP) (kg CO_2-eq)	Kilogram of Carbon dioxide equivalent
Ozone layer depletion (OLP) (kg CFC-11-eq)	Kilogram of Trichlorofluoromethane equivalent
Human toxicity potential (HTP) (kg (1,4-DB)-eq)	Kilogram of 1,4-dichlorobenzene equivalent

ii) Eutrophication Potential (EP)

Nutrient upgrading can object an undesirable change in the composition of the species and raised up biomass production in both terrestrial and aquatic ecosystems. All probable influences of enormously high environmental concentrations of macronutrients predominantly nitrogen and phosphorus are included in Eutrophication. All emissions containing the same effects are similarly considered within the “eutrophication” impact class. The Nutrification potential (NP) is highly based on the Heijungs stoichiometric procedure, which is stated as the ratio of kg PO_4 equivalents and kg emission while the geographical scale fluctuates between continental and local scale. Exposure and fate are not contained [98].

iii) Abiotic Depletion Potential (ADP)

Abiotic resources are natural substances, which are non-living like crude oil, copper ore and might comprise some energy resources like wind energy. Abiotic depletion potential (ADP) is among one of the best generally deliberated impact classes and to this category, there is a widespread procedures variety available to describe contributions. Non-renewable raw materials extraction is mostly considered. The kg antimony (Sb) equivalent is the unit indicator utilized for such impact category. The most important focus of described category is the ecosystem and human health, which gets affected by the minerals and fossil fuels extraction as system inputs. The abiotic depletion factor (ADF) is evaluated for each mineral and fossil fuels extraction. The described indicator consumed globe scale and based on de-accumulation rate and concentration reserves [98].

iv) Global Warming Potential (GWP)

Global warming potential (GWP) represents the emissions influence on some radiative forcing of the atmosphere like heat radiation absorption. Global warming influences the ecology and human health, which ultimately results in climate change. Majority of such releases increase radiative forcing and this improvement causes the increase in temperature at the earth's surface, which is generally indicated as 'greenhouse effect". The GHGs associated with air effects the climate change. This climate change can result in adverse effects on the ecosystem, human health, and substantial welfare. The Intergovernmental Panel on Climate Change (IPCC) established the categorization model, which is carefully chosen for the characterization factors advancement. Global Warming Potential (GWP) is expressed by a kg emission/kg carbon dioxide for 500 years (GWP500) time horizon [99].

v) Ozone Depletion Potential (ODP)

The stratospheric ozone layer is getting thinner as a result of previously described releases and these phenomena can be labeled as stratospheric ozone depletion. The thinning sources a solar UV-B radiation superior portion to range the earth's surface and it has potentially destructive effects on ecology, human health, aquatic and terrestrial ecologies, animal health, materials and biochemical cycles [98]. This classification is output-associated at the global scale. World Meteorological Organization (WMO) developed the description model, which expresses different gasses by their ozone depletion potential (kg CFC-11 equivalent/ kg emission). The geographical scope of this described indicator is presented at the global scale with the infinite time span.

vi) Human Toxicity Potential (HTP)

Toxic constituents on the ecology, which harms human health environment are considered as the core focus of this category. The human health risks in the operational atmosphere are not incorporated in the discussed category. Human Toxicity Potentials (HTP) and categorization factors are evaluated by USES-LCA, exposure, describing fate and toxic substances effects for an unlimited time limit. 1,4-dichlorobenzene equivalents/kg emissions expresses each toxic material [98].

3.5.2. Eco-Indicator 99 Method

PRe consultants first developed the Eco-indicator method in 1995, which is an endpoint oriented method during the Dutch NOH program [98,100]. Regarding scores and numbers, the Eco-indicator method identifies the environmental impact. By containing the weighting method, it makes simpler the clarification of LCA. it supports to provide each of the process or product with a single score after weighting, which is evaluated by comparative environmental impact. The score is presented on a point scale, which a point is denoted the yearly environmental load of a regular citizen. Eco-Indicator 99 uses average European load, and it uses three broad categories to express the environment damage as explained in following sections [101].

i) Human Health

This category comprises the duration and number of diseases and life years' loss because of the permanent deaths instigated by environmental degradation. The described effects are contained primarily by climate change, carcinogenic effects, ozone layer depletion, ionization and respiratory effects at global scale.

ii) Ecosystem Quality

Species diversity, ecotoxicity, acidification, land-use and eutrophication impact is included in this category at regional scale.

iii) Resources

Depletion of energy resources and raw materials is included in this category. It is calculated concerning the excess future energy required for extracting the lower quality of minerals and energy at global scale. The depletion based on the agricultural resource is considered under the land use category.

3.5.3. IMPACT 2002+ Method

IMPACT 2002+ is considered as a mid- and end-point oriented method. Federal Polytechnic school of Lausanne (EPFL)-France and Swiss Federal Institute of Technology developed this method [98]. IMPACT 2002+ can be described as four methods combination: IMPACT 2002, CML, Eco-indicator 99 and IPCC.

The described methodology includes the subsequent midpoint impact classifications: human toxicity, ionizing radiation, respiratory effects, photochemical oxidant formation, ozone depletion, terrestrial ecotoxicity, global warming, aquatic ecotoxicity, mineral extraction, terrestrial eutrophication and acidification, aquatic eutrophication, land occupation and non-renewable energy. Inventory results are associated with four damage categories based on endpoint via midpoint categories, which are also the environmental protection areas: human health, climate change, Ecosystem quality, and resources. Categorization factors are amended by four other methodologies: Impact 2002, CML, Eco-indicator 99 and IPCC.

CHAPTER 4: TYPES OF VEHICLES AND FUELS CONSIDERED

4.1. Life Cycle of Vehicles

In this chapter, the vehicle life cycle model utilized is discussed. The life cycle model has been adapted from "Greenhouse gases, Regulated Emissions and Energy in Transportation" (GREET). The various life cycle stages involved are described comprehensively. Furthermore, a detailed description of the various selected fuels and vehicles and their life cycle stages involved is provided. Moreover, a discussion about the air contaminants and greenhouse gas emissions is included.

4.1.1. GREET Vehicle Life Cycle Model

The Greenhouse gases, Regulated Emissions and Energy in Transportation (GREET) has become an ideal model for the accomplishment of transportation fuels life cycle analyses. GREET is widely accessible database model established at Argonne National Laboratory (ANL) that is accessible and can run through a user's computer. GREET emissions models consider transportation fuels utilize all three most severe traditional GHGs containing CH_4, CO_2 and N_2O and the principal pollutants in the United States. Global warming potential (GWP) standards are employed to cumulate all three major greenhouse gas (GHG) emissions into a form of single carbon dioxide (CO_2e) equivalent result collectively. Carbon monoxide (CO) and volatile organic compounds (VOC) count up in the completely oxidized methods as CO_2 [102].

Figure 4.1 symbolizes the idea behind GREET: The GREET model has turned out to be the standard for performing LCA of transportation fuels. Firstly, it Implements the life cycle assessments on fuel production, then it performs the life cycle assessments on materials production for vehicles, and then it combines the two assessments with the intention of estimating the cradle to the grave impact of different transportation technologies. The WTW analysis denotes hence a subset of the cradle to grave assessment as WTW does not account for the energy and emissions linked with the manufacturing and recycling of the vehicles [13]. A vehicle life cycle can be categorized into two key cycles: the fuel cycle and the vehicle cycle. Each cycle is explained in following sections.

4.1.2. Fuel Cycle

The fuel cycle reflects processes for the raw materials production and vehicles fuel consumption. This stage considers the energy associated with intake and gas emissions extracted in mining. In the fuel cycle, the related input of energy to extract crude oil, natural gas and the emissions output related to the extraction are included. As for diesel and gasoline, the extraction of crude petroleum is considered. Feedstock transportation is taken into account as well. Natural gas and oil are transported via pipelines. Oil pipelines are the most frequently used method of oil transportation. Pipelines are characteristically utilized to transfer crude oil through the wellhead to processing facilities and assembly and then towards refineries and tanker loading amenities.

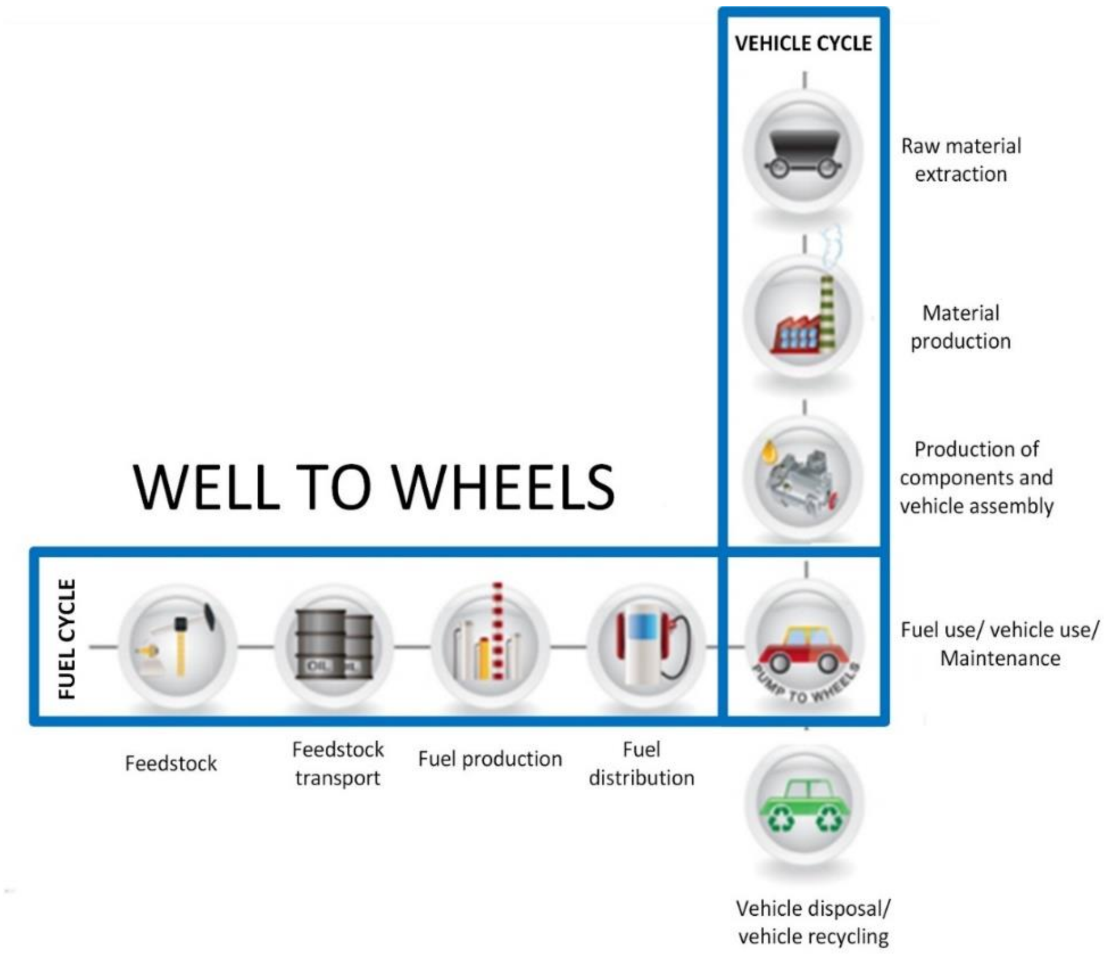

Figure 4.1 Typical life cycle of a vehicle technology [14].

Pipelines need considerably less operational energy as compared to rail or trucks and contains a less carbon footprint. Crude oil feedstock conversion to applied fuels is a fuel cycle energy intensive step, which generates significant emissions amounts. Though, purification of natural gas results in considerably less energy usage and lower emissions. In conclusion, the fuel requires to be transported to be accessible by the vehicle for usage. Energy usage and emissions linked with fueling trucks are consequently accounted in the fuel distribution phase. In this life cycle assessment, the fuel cycle contains similar inputs and outputs at the fuel usage phase by the vehicle cycle shown in figure 4.1 above.

4.1.3. Vehicle Cycle

The production and operation both are required to be accounted for the vehicle life cycle assessment. The materials required for vehicle production are extracted from the earth and accounted in the ‘‘Vehicle Material Production’’ phase. In the fuel storage systems and internal combustion engines, steel and aluminum are required for production. The specified materials for vehicle production can either be achieved through the recycling of vehicles or extracted from the ground. The LCA contains the energy requirement for the specified operations and emissions generated as well. These materials are transported to plants assembly in the next stage where energy is production requirement associated with the emissions linking with production. Additional energy is required, and emissions are produced for the transportation of the vehicles to the end users and recycling or disposal at the lifetime end. A LCA for the vehicle technology can be comparatively laborious and data and time intensive. As it can be perceived since observing the fuel corridor from the vehicle production stages and resource extraction through raw materials, ample time can be consumed in assembling the inventory data. Therefore, it might be beneficial to practice established tools, which can access the essential data from databases and assist according to the analysis.

4.1.4. Modeling in SimaPro Software

An LCA can be conducted by either doing the calculation by hand or using current LCA software on the market, which is developed by different companies or organizations. In this study, the life cycle analysis is conducted following the ISO 14040 standardized LCA procedure with the Simapro software version 7.3, which is developed by PRe Consulting Group. SimaPro comprises the newest in science-based methods and databases. The data collection for this study relies on the GREET life cycle model inventory database, Eco-Invent database, which produced by the Swiss center for life cycle inventories. The secondary data is collected from different government reports, websites and literature. Environmental life cycle impacts are evaluated mainly with CML 2001 method and investigate the environmental impacts of the selected vehicles in two different LCIA methods additionally, namely these methods are Eco-indicator 99 and Impact 2002+ methods. The following impact categories are selected for this study:

- Abiotic resource depletion potential (ADP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Global Warming Potential (GWP)
- Ozone Depletion Potential (ODP)
- Human Toxicity Potential (HTP)

4.2. Vehicle Fuels and Power Systems

Majority of all passenger vehicles today are either gasoline-powered or diesel-powered vehicles. Both of the described fuels are petroleum derivatives, which is a non-renewable resource. There are some alternate fuel sources as a substitute for petroleum. These alternative fuels are significant as they can replace petroleum fuels based vehicles through some of these sources contain a minor petroleum amount in the mixture. The usage of alternate fuels also accompanies numerous benefits. Vehicles burning gasoline is dominating the automobiles quantity at present. The significant alternative fuels take in alcohol, compressed natural gas, liquefied petroleum gas, electricity, and hydrogen.

4.2.1. Conventional Fuels

Conventional fuels like diesel or gasoline are manufactured from crude oil in oil refineries whose compositions are specified in Table 4.1. Crude oil is not much to be used in transportation sector directly, so it passes through refining processes in the oil refinery to obtain diesel or gasoline.

i) Gasoline

Gasoline is considered as one of the utmost extensively used possessions in the world. Gasoline is a separated as a by-product from numerous petroleum industries and is utilized predominantly to fuel cars. Petro-gasoline, petroleum spirit (petrol) or gasoline (gas) is a liquid mixture derived from petroleum mostly consists of aliphatic hydrocarbons, boosted with aromatic hydrocarbons benzene and toluene or iso-octane to enhance the octane rating. It is first and foremost utilized in internal combustion engines as a fuel. Gasoline is manufactured in oil refineries. Distillation is the technique used for its separation from crude oil. As gasoline discharges prodigious energy deal when burnt, it became the favored automobile fuel [103].

Table 4.1 Composition of a typical gasoline fuel

Composition	**Values (%)**
Carbon	84
Hydrogen	14
Metals (nickel, vanadium, iron, arsenic, copper)	<1
Oxygen (found in organic compounds like carbon dioxide, ketones, phenols and carboxylic acids)	<1
Nitrogen (amine group basic compound)	<1
Sulfur, containing hydrogen sulfide, disulfides, sulfides and elemental sulfur	<1
Salts (magnesium chloride, sodium chloride and calcium chloride)	<1

The significant amount of gasoline manufactured via oil plants is directed to the gas stations through pipelines. Pipelines are the utmost proficient mean for liquid transportation that evaporates rapidly while a part of gasoline might get mixed with supplementary products. Moreover, from different refineries, numerous brands containing different additives are usually joint while transportation of gasoline via pipelines. The pipeline end from where trucks are loaded with gasoline to supply it to gas stations typically is storage terminal nearby consumer areas. Consumers can purchase gasoline finally at gas stations to power their vehicles.

Gasoline that is utilized in cars is frequently advanced by adding small quantities of lubricants like anti-icing agents and anti-rust agents. Nearly entire gasoline holds an oxygenating agent in the form of ethanol United States. Regular, midgrade and premium are the three grades of gasoline available at stations. These described grades differ in octane levels, which subsequently results in price variance. Regardless of its extensive usage, gasoline has raised up numerous environmental anxieties for the reason that it produces

GHGs. Gasoline likewise carries a health risk due to its carcinogenic elements. Numerous consumers and organizations are considering to replace gasoline with other alternative or substitute energy sources as energy demand continues to expand worldwide even regarding global warming. However, such alternate energy sources are not present in large-scale use, which makes gasoline the undeniable transport fuels king.

ii) Diesel

Diesel is a hydrocarbons blend gained by crude oil distillation. In compression ignition (CI) engine, diesel is powered as principal fuel. As CI engine generally operates at the higher compression ratio of 16:1 to 22:1, thus, it offers better fuel economy as compared to spark ignition engine [104]. To increase emission reduction and engine performance, the diesel fuel quality is desired to be improved. Diesel fuel is utilized in diesel engines established in utmost cargo trucks, buses, trains, farm, boats and construction vehicles and small trucks and some cars as well.

4.2.2. Alternative Fuels

An alternative or substitute fuel is generally defined as any powering fuel except the traditional diesel and gasoline selections, which is labored to yield power or energy. The energy output and emissions impact generated by alternative fuels differ from one source to another. Alternative fuels examples include biodiesel, electricity, ethanol, compressed natural gas, hydrogen, and propane. The alternative fuels currently being utilized are d0 escribed briefly in the next section.

i) Biodiesel

Biodiesel, a renewable alternative is a clean burning fuel, which can be manufactured from wide-ranging animal fats and vegetable oils. Biodiesel does not contain petroleum while it can be merged with petroleum diesel at any level to produce a biodiesel blend. This biodiesel is usable in diesel-based compression-ignition engines by way of slight or no modifications.

ii) Ethanol

Ethanol, an alternative renewable biofuel prepared from numerous plant materials. Ethanol can be merged with gasoline in different quantities such as high spark-ignited gasoline-engines operates fine with 10 percent ethanol (E10) mixtures., An 85 percent ethanol (E85) mixture and 15 percent unleaded gasoline is used as alternative fuel in flexible fuel vehicles (FFVs) [105].

iii) Electricity

Electricity grid provides the electricity, which is stored in the batteries of vehicles and utilized to power vehicles. Vehicles that operate on electricity does not transmit tailpipe emissions. Electricity based vehicles are not available by major auto manufacturers at present while mostly being converted by amateur mechanics.

iv) Propane

Propane, a crude oil refining, and natural gas processing by-product, which is also named as liquefied petroleum gas. Propane is less toxic as compared to other fuels. Propane exhibits exceptional characteristics designed for spark-ignited internal-combustion engines and a high octane rating. According to the current U.S. survey, less than 2 percent consumption of propane is employed for transportation though interest is developing because of its high energy density, domestic accessibility, and clean-burning qualities.

v) Compressed Natural Gas (CNG)

Compressed Natural Gas (CNG) represents from its name, a natural gas stored in compressed form, which is extracted from wells. Compressed natural gas comprises of fossil fuel majorly of methane, which is cleaner burning as compared to diesel or gasoline fuel. Vehicles based on natural gas are established to yield fewer greenhouse gas emissions as compared to gasoline vehicles, but a small portion of natural gas is being consumed currently for transportation fuel.

vi) Hydrogen

Hydrogen (H_2) is an alternative renewable fuel produced domestically, which can be utilized to produce electricity. Hydrogen and oxygen react chemically to produce the electric power. When the pure hydrogen is used as fuel in transportation, the water vapor is the only resulting emission. For emission-free transportation, hydrogen fuel can be a good option dependent on the energy source, which causes the chemical reaction. Hydrogen source is not extensively used currently, but industrial research and development and existing government are inspecting economical and safe hydrogen production for hydrogen vehicles.

4.3. Vehicles Selected for the Study

Diesel, electric, ethanol, gasoline, hybrid (LNG and electric), hydrogen, methane, methanol, and natural gas powered vehicles are comparatively analyzed and assessed, to evaluate the environmental impacts of different types of fuels,

Each vehicle's specific information used for modeling in SimaPro software is explained in following sections. For each vehicle, Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal, and disposal of roads have been allocated based on the Gross tonne kilometer performance. Expenditures due to the operation of the road infrastructure, as well as land use, have been allocated based on the yearly vehicle kilometer performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 239,000 person-km/vehicle has been assumed. The chosen unit person-km can be stated as transporting one person within one-kilometer distance.

4.4. Process-based LCA

The inputs like energy resources and materials and the outputs like environmental wastes and emissions are specified for a certain step in product production in a process-based LCA. Consequently, considering a simple product like a disposable drinking cup paper, an individual may list the materials like paper and glue while natural gas or electricity to operate the machinery for cup manufacturing, and some may list paper material achieved from scrap, low-quality cups and waste glue, which become surplus for the outputs.

Nevertheless, for a broad view of the life cycle, the same job is essential to be done during the whole materials life cycle for the cup and their usage. Thus, the inputs must be identified like pulp, dyes and water for paper making, the machinery and trees for pulp making and harvesting and growing trees for forestry practices. Likewise, the inputs and outputs cup packaging also need to be specified for the store shipment, the store trip for cup purchasing, and the outcome after wasting the cup in the garbage and ultimately being incinerated or landfilled. Process-based LCA technique can rapidly be twisted including an overwhelming inputs and outputs number considering a straightforward product. Now, implementing the same methodology of process-based LCA on a specified product like an automobile, which has more than 20,000 distinct parts or some other process like electricity generation [106].

Process-based LCA gives rise to the two main issues. First is defining analysis boundary. The primary step of this methodology is outlining the things contained in the analysis and the things, which will be ignored and excluded. Some may be selected to exclude the steel making impacts and processing equipment manufacturing, which makes the cups for paper cup example. Boundary establishment limits the project scope and consequently the effort and time required to gather the inputs and outputs information. However, compulsory to generate a convenient LCA project, boundary defining for the analysis spontaneously confines the consequences and generates the true life cycle underestimate impacts.

Another major concern with process-based LCA techniques is circularity effects. In the current time, making new stuff is highly based upon the same stuff. Thus, the steel machinery is required to manufacture the paper cup. However, to manufacture steel machinery, other tools and machinery are required, which are prepared from steel. Moreover, machinery is required to manufacture steel, yes, prepared from steel. A completed LCA for all the processes and materials included should be conducted effectively before LCA of any process or material is completed. Numerous decisions and assumptions are required to complete a comprehensive, vigorous LCA that sort LCA as a time consuming and complex endeavor [106].

4.5. Methods

In this thesis, a comprehensive LCA of conventional and alternative fueled vehicles is performed. In conjunction with the WTW emissions (Fuel production, Fuel distribution, and transportation, fuel use in the vehicle), the LCA also comprises cradle-to-grave emissions (Directly and indirectly emissions from the vehicle manufacture, vehicle use, maintenance, and end-of-life treatment of the vehicle). In this study, the combination of the following light duty passenger vehicle powering options and fuel types are considered:

a) Internal combustion engine vehicle (ICEV) technology for gasoline, diesel, methanol, biogas, methane, LNG, and CNG fuel.

b) Flexi fuel vehicle technology for ethanol fuel

c) Fuel cell vehicle (FCV) for hydrogen fuel;

d) Battery electric vehicle (BEV) for electricity.

e) Hybrid electric vehicle (HEV) for a combination of an internal combustion engine (ICE) and an electric motor.

In this study, inventory data for LCA is obtained by utilizing a combination of following listed LCA databases. (a) Eco-invent 2.2 database, which was issued by the eco-invent center [97]; (b) Argonne GREET model version 2017; (c) literature review of current peer-reviewed papers, government reports (d) online available sources.

In the current thesis, a process based LCA is conducted. The results of the LCA are reported according to the framework of the ISO 14040/44 standards [89,94]. There are numerous LCIA methods were developed over the time, however; the results presented in this study are produced with three calculation methods namely; CML 2001, Eco-indicator 99 and Impact 2002+. The results are mainly shown in midpoint approach, but endpoint approach is used in the study as well.

4.6. Goal and Scope Definition

The goal of this study is to analyze the environmental impacts of conventional and alternative fueled vehicles and to form an unbiased image of the environmental impact of vehicles with conventional and alternative fuels. The results are presumed to answer the following question. What are the environmental burdens of traveling one kilometer with a particular vehicle today? Moreover, what causes these impacts? The performed LCA is attributional and process-based. The results of this study can be used by the academic researcher in the LCA field and can be used by the auto manufacturer for decision making on critical environmental issues.

4.6.1. Functional Unit

The functional unit is a quantified performance of a product system for use as a reference unit according to ISO 14040. It helps to compare two or more product systems by a mutual provided service. In this study, the functional unit is chosen as ‘transport one person on one km with a small passenger car.' The functional unit takes all life cycle phases of a small passenger car into account and assumes a total life mileage of 239,000 km.

4.6.2. Assumptions

Inventory represents the all-inclusive transport life cycle. Environmental and expenditures interventions because of the renewal, disposal and roads construction have been allotted by the performance Gross tonne kilometer for road infrastructure. Expenses linked with the road infrastructure operation and land usage have been allotted by the vehicle kilometer yearly performance. The outcomes of environmental impact categories and GHG emissions for individual automobile type are stated per km distance. An automobile life time performance has been assumed as 239,000-person km/vehicle for the acknowledgment of vehicle transport performance share. Generally, the average vehicle usage element is assumed as 1.59 passengers per automobile. The inventory for road infrastructure and vehicle operation represents Swiss circumstances. Vehicle maintenance and manufacturing inventory denote generic European statistics. Vehicle disposal data represents the Swiss situation.

4.6.3. Data Collection and Quality

Any LCA requires the collection of reliable data. The quality of data has a large impact on the quality of the results calculated or estimated by an LCA tool. In this study, the life cycle analysis is conducted according to the ISO 14040 standardized LCA procedure with the Simapro software version 7.3, which is developed by PRe Consulting Group. SimaPro comprises the newest in science-based methods and databases. The data collection for this study relies on the GREET life cycle model inventory database, Eco-Invent database, which produced by the Swiss center for life cycle inventories. The secondary data is collected from different government reports, websites and literature. A difference in data can be observed depending on geographic region, climate and energy sources.

4.7. Life Cycle Boundaries and Stages

LCA boundaries of a vehicle technology are illustrated in Figure 4.1 at the beginning of this chapter. These boundaries can be categorized as follows: a) Material production and transportation, b) Vehicle manufacturing and maintenance, c) Vehicle operation, d) Construction, operation, and maintenance of roads, e) End of life stage (Disposal/Recycle)

4.7.1. Vehicle Manufacturing and Maintenance

The inventory catalog comprises methods for the use of water, energy, and material in the manufacturing of passenger car. Road and rail materials transport is accounted for. Plant foundation is elaborated collected with the subjects like land use, road, building, and parking construction. A modern vehicle is represented by the material consumption. Vehicle production inventory is demonstrative for manufacturing locations through environmental administration system. Consequently, the subsequent data possibly will be an underestimation of an ordinary vehicle fleet concerning environmental impacts. Electricity originates by UCTE mixture (Union for the Co-ordination of Transmission of Electricity) countries. The UCTE works in continental Europe based on the transmission association system, which around 450 million individuals are provided with electricity. In the process of electricity usage, direct sulfur hexafluoride (SF_6) emissions and transmission network are involved. The high-medium voltage conversion along with medium voltage electricity transmission is considered.

The electric vehicle (EV) operation differs from conventional vehicles in more or fewer features such as the operational energy source is the first difference in which electricity is applied instead of diesel or petrol. Hereafter, no tail-pipe emissions exist there. Subsequently, it is expected a significant portion of emissions are limited to brake wear, tire and surface road abrasion. For electric automobiles, steel required amount is lesser concerning conventional vehicles ever since their car does not contain internal combustion engine (ICE). Lithium-ion batteries and electric motor production are contained within the EVs. At present, existing EV batteries varies from 100 kg and 400 kg depending upon the range and size of the vehicle. The lithium-ion battery and electric motor regular masses are supposed as 104 kg and 312 kg, respectively [107]. The automobiles maintenance inventory comprises resources utilized for energy consumption and alteration parts of vehicles. Road and rail transport of materials is accounted for. Throughout the vehicle lifetime of EVs, single battery change is expected. Hereafter, the replacement of lithium-ion battery and disposal procedures are also considered in the maintenance stage.

4.7.2. Operation of Vehicle

The vehicles operation process is considered as one of the most significant units of life cycle analyses. Fuel consumption is included in this phase. Direct flying emissions of particulate matters, gaseous materials, and heavy metals are assumed. Particulate emissions occupy abrasions and exhaust emissions. Evaporation is contained by hydrocarbon emissions. Heavyweight metal emissions to water and soil created by abrasion of the tire are also assumed. The standards are founded upon the average vehicle operation. For hydrogen vehicle, nuclear solid oxide electrolysis cell (SOEC) method is used for manufacturing hydrogen. For EVs, transmission and production of electricity are measured as UCTE Mix. Vehicle electricity consumption is involved in this study. Particulate emissions consist of abrasions and exhaust emissions. Heavy metal emissions to water and soil produced by abrasion of the tire are also assumed. In the usage of electricity process, the transmission network, electricity production mix, and direct SF6-emissions are accounted.

4.7.3. Vehicle Disposal (End of life stage)

The vehicle disposal inventory encloses disposal procedures for bulk materials. A cut-off portion is functioned for the tires disposal. Furthermore, the tires transportation to the cement works is also considered. For the aluminum, steel, tires and copper disposal, a cut off factor is functional. Specific waste water included with air emissions as of supplementary resource depletion and incineration of the scrubbing of flue gas are also accounted. River water short-term releases as well as groundwater long-term emissions as of slag segment and residual landfill material are well-thought-out with the energy loads process municipal waste incineration plant (MSWI). Processes involved in the vehicle disposal contain; plastics disposal in a blend with 15.3% water to municipal incineration of 65 kg, glass disposal to municipal incineration of 30.1 kg, emulsion paint remains disposal to HWI of 100 kg, and zinc disposal in the car shredder leftovers (remaining) to MSWI of 5.89 kg.

Lithium-ion batteries are reprocessed for various purposes. The utmost conspicuous is the repossession of esteemed materials and ecological laws survey. Frequent approaches are existing for lithium-ion batteries recycling with miscellaneous environmental consequences. Generally, battery recycling processes can be presented in three major categories; pyro-metallurgical, mechanical, and hydrometallurgical processes. Hydrometallurgical procedures are estimated to necessitate significantly minor energy requirements likened with pyro-metallurgical processes. Hydrometallurgical process for batteries disposal is nominated by a 57.5% of ordinary efficiency and 140 kWh/tonne of energy use in this study [108].

4.8. Vehicle Emissions

Vehicles yield emissions that impact on the environment and human health. A complex blend of gases is emitted as exhaust when a vehicle burns fuel like diesel or gasoline. The ejected tailpipe emissions are categorized as:

4.8.1. Criteria Air Contaminants

Criteria air contaminants (CACs) contain carbon monoxide (CO), volatile organic compounds (VOC), ammonia (NH_3), nitrogen oxides (NO_X), sulfur oxides (SO_X) and particulate matter (PM) [109].

4.8.2. Greenhouse Gases

GHGs include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). CO_2 is the principal GHG. Vehicle GHGs are measured in Canada to lessen GHGs from the transportation sector. Light-duty vehicles yield around 12% of Canada's GHG emissions. The catalytic converter can reduce the N_2O and CH_4 produced by the engine. GHGs contribute to climate change by trapping heat in the atmosphere. Drivers can decrease GHG emissions by selecting more fuel-efficient vehicles, by applying fuel-efficient techniques for driving and by driving less. CO_2 produced by the engine cannot be reduced by a catalytic converter. Vehicle emissions can be categorized into five main classes [110]

i) **Carbon Dioxide (CO_2),** which is an unavoidable produced by burning of a fuel that comprises carbon like other petroleum products. CO_2 needs to be reduced as it is a major contributor to global warming, but it does not spoil the air we inhale. The solution is to either use less or no carbon containing fuels or by manufacturing more efficient vehicles and their engines.

ii) **Carbon Monoxide (CO),** produced while the incomplete burning of carbon-based fuel. It is poisonous in high concentrations and should be controlled. This carbon monoxide can be decreased either by using high efficient engine combustion, in this way CO_2 is created instead of CO or in a catalytic converter, it can be further reduced after combustion by oxidizing [$2xCO + O_2 = 2xCO_2$].

iii) **Hydrocarbons (CH),** well-known as “Volatile Organic Compounds (VOC) are unburned fuel. These compounds can cause a problem for individuals having breathing problems and contributes to producing “Photochemical Smog” in specific climatic conditions. They can be decreased by using high efficient engine combustion and further in a catalytic converter by decreased oxidizing after combustion [$4HxCy + (x+4y) O_2 = 2xH_2O + 4yCO_2$].

iv) **Oxides of Nitrogen (NO_x)** are produced when the air is heated in an engine. Air mainly comprises oxygen and nitrogen mixture. Oxides of nitrogen are a contributor to both Acid Rain and Photochemical Smog and might able to be lungs irritant. Having contrast with CO and HC, NO_x cannot be removed by oxidation. The opposite process, oxygen removal recognized as the reduction is compulsory to reformulate oxygen and nitrogen.

v) **Particulate Matter (PM)** comprises of very tiny particles mostly of unburnt carbon. PM can be liquid or solid particles in the atmosphere. Smoke or dust is the major effect of particles, which are dark or large enough to stay visible.

CHAPTER 5: RESULTS AND DISCUSSION

In this chapter, the results are obtained through modeling a comprehensive LCA study of conventional and alternative fueled small passenger vehicles in SimaPro software. For this study, ten different vehicle technologies are selected from conventional and alternative vehicle segments, and the results are presented and assessed comparatively. Firstly, Section 5.1 presents result of LCIA methods used in this study. Section 5.1.1 carries out the environmental impacts of ten different passenger vehicles regarding impact categories defined by CML 2001 method. Secondly, Section 5.1.2 and Section 5.1.3 investigates the environmental impacts of the selected vehicles in two different LCIA methods additionally, namely these methods are Eco-indicator 99 and IMPACT 2002+. Thirdly, section 5.2 compares the environmental impact assessment results of CML 2001, Eco-indicator 99, and IMPACT 2002+ methods used in the study. After that, section 5.3 shows LCA results of vehicles selected for the study. Fourth, Section 5.4 reports results for six impact categories selected for this study. Finally, Section 5.5 provides validation and comparison of the results with literature data.

5.1. Results of LCIA Methods

SimaPro software's background database the Ecoinvent and GREET database are used to calculate LCI data for materials, fuel production, manufacturing processes of the vehicle and its parts, energy production, distribution and transportation involved in the life cycles of both conventional fueled and alternative fueled vehicles.

The results of a performed LCA should be interpreted in the context of the used LCIA methods. The results presented in this chapter, are produced with three calculation methods namely; CML 2001, Eco-indicator 99 and Impact 2002+. The results are mainly shown in midpoint approach, but endpoint approach is used in the study as well. The main difference between midpoint and endpoint methods is they look at different stages in the cause-effect chain to calculate the impacts. Endpoint results typically show the impact on human health, ecosystem quality and resource depletion. On the other hand, midpoint approach results can be more difficult to interpret because they consider a large number of impacts categories, but they offer more detail in return. Midpoint approach results give us the chance to make a well-grounded decision either way. Endpoint results would show a high impact on ecosystem quality and human health, lacking indicating the source. For this reason, the results are presented in term of impact categories defined in midpoint approaches. Only the contaminants involved in the utilized LCIA methods were taken into account concerning the characterization factor attributed to each impact category. The following six impact categories are considered as the most important today. For this reason, the obtained results will be shown in following categories in depth.

- Abiotic resource depletion potential (ADP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Global Warming Potential (GWP)
- Ozone Depletion Potential (ODP)
- Human Toxicity Potential (HTP)

5.1.1. Results of CML 2001 Method

Impact assessment results and comparison of various vehicle technologies on selected six big impact categories is illustrated in Figure 5.1. The results in this section are produced by using CML 2001 impact assessment methodology. Except for acidification, the regional validity of the CML 2001 method is global regarding impact categories. As being observed that each vehicle has a different impact on various impact category due to their supply chain in fuel and material production. Each vehicle and impact category will be shown, in detail, on with their level of contribution to the life cycle in the following sections.

LCIA results of both conventional and alternative fuelled vehicles per impact category and per one (1) km traveled by a passenger car is shown in Table 5.1. Each categories results are shown in different units. As observed from Figure 5.1 as well as from Table 5.1 and Table 5.2 in abiotic depletion impact category, the worst performing vehicle is natural gas vehicle with 0.001423 kg Sb eq/km, followed by gasoline vehicle (petrol, fleet average), hybrid vehicle, ethanol vehicle, gasoline vehicle (petrol, EURO5), diesel vehicle, hydrogen fuel cell vehicle, methane vehicle, methanol vehicle and electric vehicle. The best performing vehicle is an electric vehicle in this category with 0.000434 kg Sb eq/km.

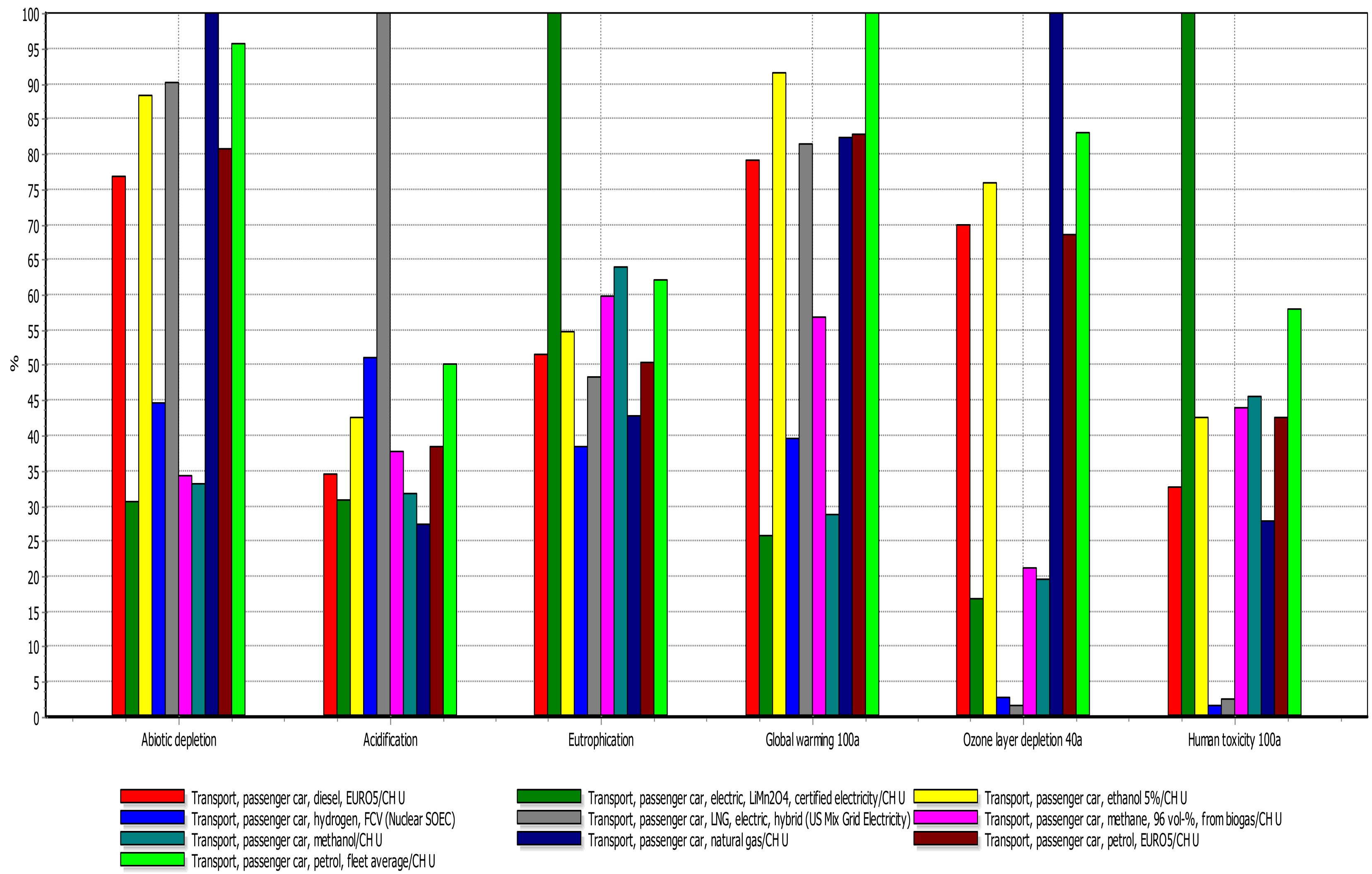

Figure 5.1 Comparison of various vehicle technologies on selected 6 big impact categories. (Method: CML 2001)

Table 5.1 Impact assessment results for various vehicle technologies on selected six big impact categories per one (1) km traveled (Method: CML 2001)

Impact Category	Unit	Diesel	Electric	Ethanol	Hydrogen	Hybrid
Abiotic depletion	kg Sb eq	0.00109	0.00043	0.0013	0.00063	0.0012
Acidification	kg SO_2 eq	0.000412	0.00037	0.00051	0.00061	0.0012
Eutrophication	kg PO_4 eq	0.000122	0.00024	0.00013	9.10E-05	0.00011
dataGlobal warming 100a	kg CO_2 eq	0.159	0.052	0.18	0.079	0.16
Ozone layer depletion 40a	kg CFC-11 eq	2.02E-08	4.81E-09	2.19E-08	8.14E-10	4.74E-10
Human toxicity 100a	kg 1,4-DB eq	0.0347	0.10	0.045	0.0017	0.0027

Table 5.2 Impact assessment results for various vehicle technologies on selected six big impact categories per 1 km traveled (continued) (Method: CML 2001)

Impact category	Unit	Methane	Methanol	Natural gas	Gasoline 1	Gasoline 2
Abiotic depletion	kg Sb eq	0.00048	0.00047	0.0014	0.0011	0.0014
Acidification	kg SO_2 eq	0.000451	0.00038	0.00033	0.00046	0.0006
Eutrophication	kg PO_4 eq	0.00014	0.00015	0.00010	0.00012	0.00015
Global warming 100a	kg CO_2 eq	0.11	0.058	0.17	0.17	0.20
Ozone layer depletion 40a	kg CFC-11 eq	6.10E-09	5.62E-09	2.89E-08	1.98E-08	2.40E-08
Human toxicity 100a	kg 1,4-DB eq	0.047	0.048	0.029	0.045	0.062

Gasoline 1; EURO5, gasoline 2; fleet average

The winner in abiotic depletion category is alternative fueled vehicles. Conventional fueled vehicles are not performed as well as expected. As observed from Figure 5.1 as well as from Table 5.1 and Table 5.2 in acidification category highest environmental impacts comes from Hybrid (LNG and electric) vehicle with 0.001193 kg SO_2 eq/km, followed by hydrogen, gasoline (fleet average), ethanol, gasoline (EURO5), methane, diesel, methanol, electric and natural gas. It is interesting that natural gas vehicle is performing best in acidification while it performs worst in abiotic depletion category. Alternative fueled vehicles are not ideal options for acidification category.

In eutrophication category, highest impacts obtained from EVs corresponding to 0.000238 kg PO_4 eq/km and lowest impacts comes from hydrogen vehicle and followed by the natural gas vehicle. In this category, both categories give close results, but the most environmental benign option is hydrogen car.

In global warming category with 100 years' time horizon, highest impacts obtained from gasoline vehicles followed by ethanol, natural gas, hybrid (LNG and electric), diesel, methane, hydrogen, methanol, electric. Based on the observation from LCIA results conventional fueled vehicles are worst in global warming as they burn fossil fuels, which is the key human sources of greenhouse gas emissions. To mitigate global warming use of alternative fueled vehicles should be encouraged.

In ozone layer depletion category with 40 years' time horizon, best-performing cars are hybrid, and hydrogen vehicles, emissions they produced per km is respectively 4.74E-10 kg CFC-11 eq/km, 8.14E-10 kg CFC-11 eq/km. On the other hand, natural gas and gasoline vehicle contribute most to this category.

In human toxicity category, electrics car contributes significantly due to the emissions from the manufacture of batteries in the course of the vehicle production stage, which represent an important share of the environmental impacts in electric car manufacturing. Most environmentally friendly car in his category is hydrogen vehicle.

To summarize the results obtained with CML 2001 method, the electric car performs very well almost in all categories, except in eutrophication and human toxicity followed by methanol car. Hydrogen and hybrid cars perform exceptionally well in ozone layer depletion and human toxicity impact categories. On the other hand, gasoline and diesel vehicles show a poor performance nearly in all categories. Hence, alternative fueled vehicles are environmentally more benign options for drivers worldwide.

5.1.2. Results of Eco-indicator 99 Method

The results in this section are produced by using Eco-indicator 99 LCIA methodology. Eco-indicator is an endpoint oriented method. LCIA results of both conventional and alternative fuelled vehicles per impact category and per 1 kilometer traveled by a passenger car is shown in Table 5.3 and 5.4. Each categories results are shown in different units. As observed from Figure 5.2 as well as from Table 5.3 and Table 5.4 in climate change impact category, the highest impacts seen in gasoline vehicle (average fleet) with 4.21E-08 DALY (disability adjusted life years)/km followed by ethanol, gasoline (EURO5), natural gas, hybrid, diesel, methane, hydrogen, methanol and electric vehicle, which correspond to 1.08E-08 DALY/km. The results are slightly different then CML 2001, but this difference can be neglected. For example, both methods best performing vehicles are electric, and methanol and worst performing vehicles are gasoline, natural gas, and ethanol. In ozone layer depletion category, highest environmental impacts come from gasoline, ethanol, followed by diesel, gasoline (EURO5), natural gas, methanol, methane, electric, hydrogen and hybrid car respectively. Eco-indicator 99 results are similar to CML 2001 methods' results. In the eco-toxicity category, least environmental impacts observed in hydrogen and hybrid vehicles and highest environmental results observed in electric and methane vehicles as it is shown in Figure 5.2 and tabulated in Table 5.3. The results for hydrogen, hybrid car, and electric car are similar to one in CML 2001. However, conventional fueled vehicles' results are different from CML 2001 here. For acidification/eutrophication category, highest impacts observed for gasoline (average fleet) vehicle, lowest impacts are seen in hydrogen and electric car, the remaining vehicles give very close numbers in PDF*m^{2}yr/km. For fossil fuels depletion, the highest resource depletion impact per kilometer obtained for gasoline and natural gas and lowest for electric and methanol vehicles. Although there are slight differences in CML 2001 and eco-indicators results, both methods' results match. Hence, the LCA results' reliability is high in this study.

Table 5.3 Impact assessment results for various vehicle technologies on selected six big impact categories per 1 km traveled (Method: Eco-indicator 99)

Impact category	**Unit**	**Diesel**	**Electric**	**Ethanol**	**Hydrogen**	**Hybrid**
Climate change	DALY	3.33E-08	1.08E-08	3.85E-08	1.66E-08	3.39E-08
Ozone layer	DALY	2.36E-11	5.46E-12	2.56E-11	9.44E-13	5.49E-13
Ecotoxicity	PAF*m^{2}yr	0.045	0.11	0.089	0.005	0.0055
Acidification/ Eutrophication	PDF*m^{2}yr	0.0019	0.0011	0.0018	0.0011	0.0019
Fossil fuels	MJ surplus	0.18	0.059	0.21	0.082	0.18

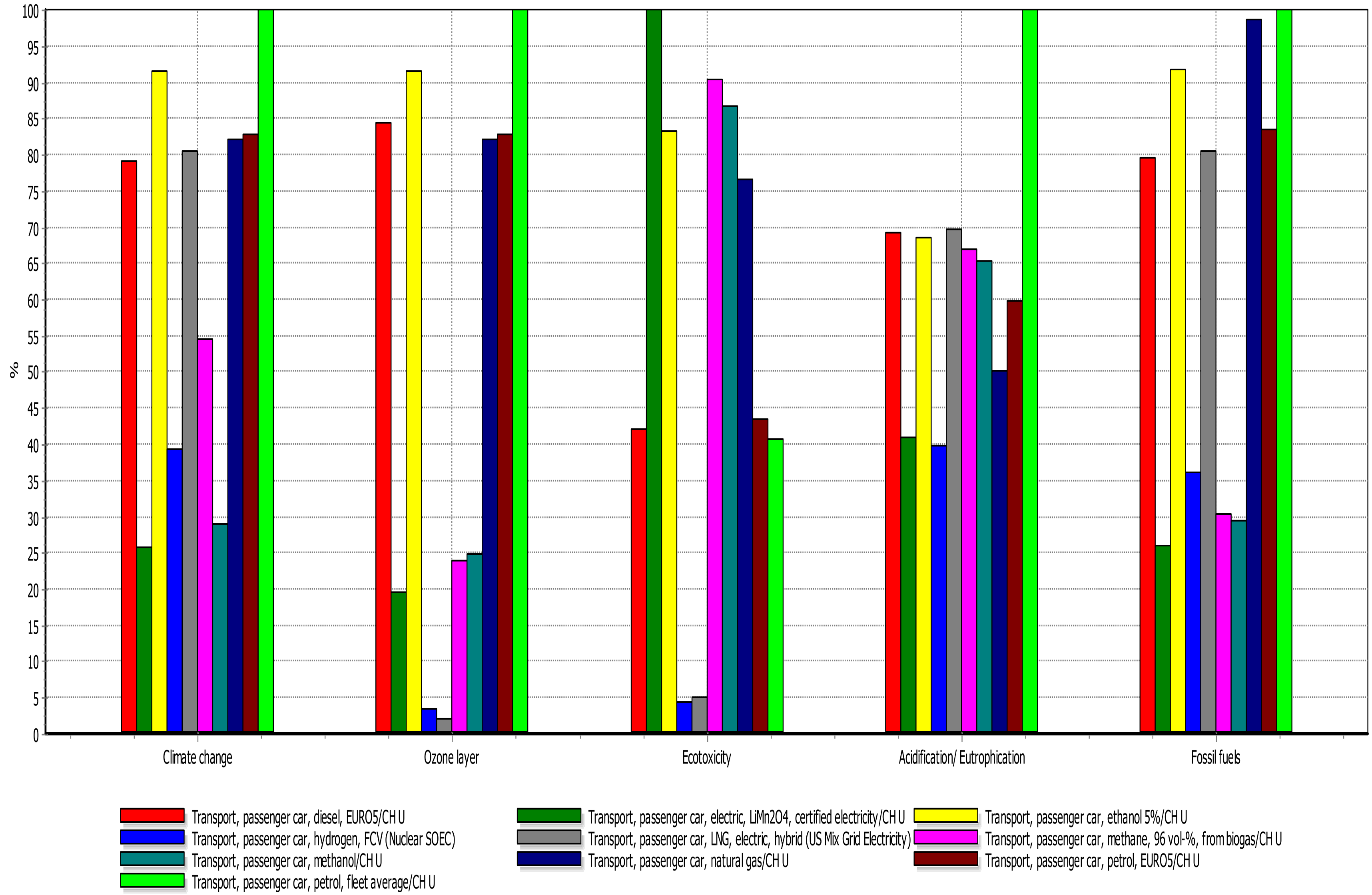

Figure 5.2 Comparison of various vehicle technologies on selected 6 big impact categories. (Method: Eco-indicator 99)

Table 5.4 Impact assessment results for various vehicle technologies on selected six big impact categories per 1 km traveled (Method: Eco-indicator 99) (continued)

Impact category	**Unit**	**Methane**	**Methanol**	**Natural gas**	**Gasoline 1**	**Gasoline 2**
Climate change	DALY	2.30E-08	1.21E-08	3.45E-08	3.48E-08	4.21E-08
Ozone layer	DALY	6.71E-12	6.91E-12	2.30E-11	2.31E-11	2.80E-11
Ecotoxicity	PAF*m^{2}yr	0.096	0.092	0.082	0.046	0.043
Acidification/ Eutrophication	PDF*m^{2}yr	0.0018	0.0018	0.0014	0.0016	0.0027
Fossil fuels	MJ surplus	0.069	0.067	0.23	0.19	0.23

Gasoline 1; EURO5, gasoline 2; fleet average

5.1.3. Results of IMPACT 2002+ Method

IMPACT 2002+ impact assessment method is considered as a mid- and end-point oriented method. Federal Polytechnic school of Lausanne (EPFL)-France and Swiss Federal Institute of Technology developed this method. IMPACT 2002+ can be defined as four methods combination: IMPACT 2002, CML, Eco-indicator 99 and IPCC. LCIA results of both conventional and alternative fuelled vehicles per impact category and per one (1) km traveled with a passenger vehicle is tabulated in Table 5.5 and Table 5.6. Each categories results are shown in different units. Figure 5.3 shows a comparison of all selected vehicles in 6 impact categories. In ozone layer depletion category, highest impacts observed for gasoline vehicle followed by natural gas, ethanol, diesel, gasoline (EURO5), methane, methanol, hydrogen and hybrid vehicles. Most promising vehicles are hybrid and hydrogen vehicles in this category.

The results are very similar to CML 2001 and eco-indicator 99 methods' results. In terrestrial eco-toxicity category, as it can be seen in Figure 5.3 the highest environmental impact result obtained from ethanol vehicle, followed by methanol, methane, natural gas, electric, gasoline vehicles, hybrid and hydrogen vehicles. Unlike CML 2001 and eco-indicator 99, IMPACT 2002+ impact result for electric vehicle obtained low in terrestrial eco-toxicity. However, this can be explained by toxicity focused in different areas.

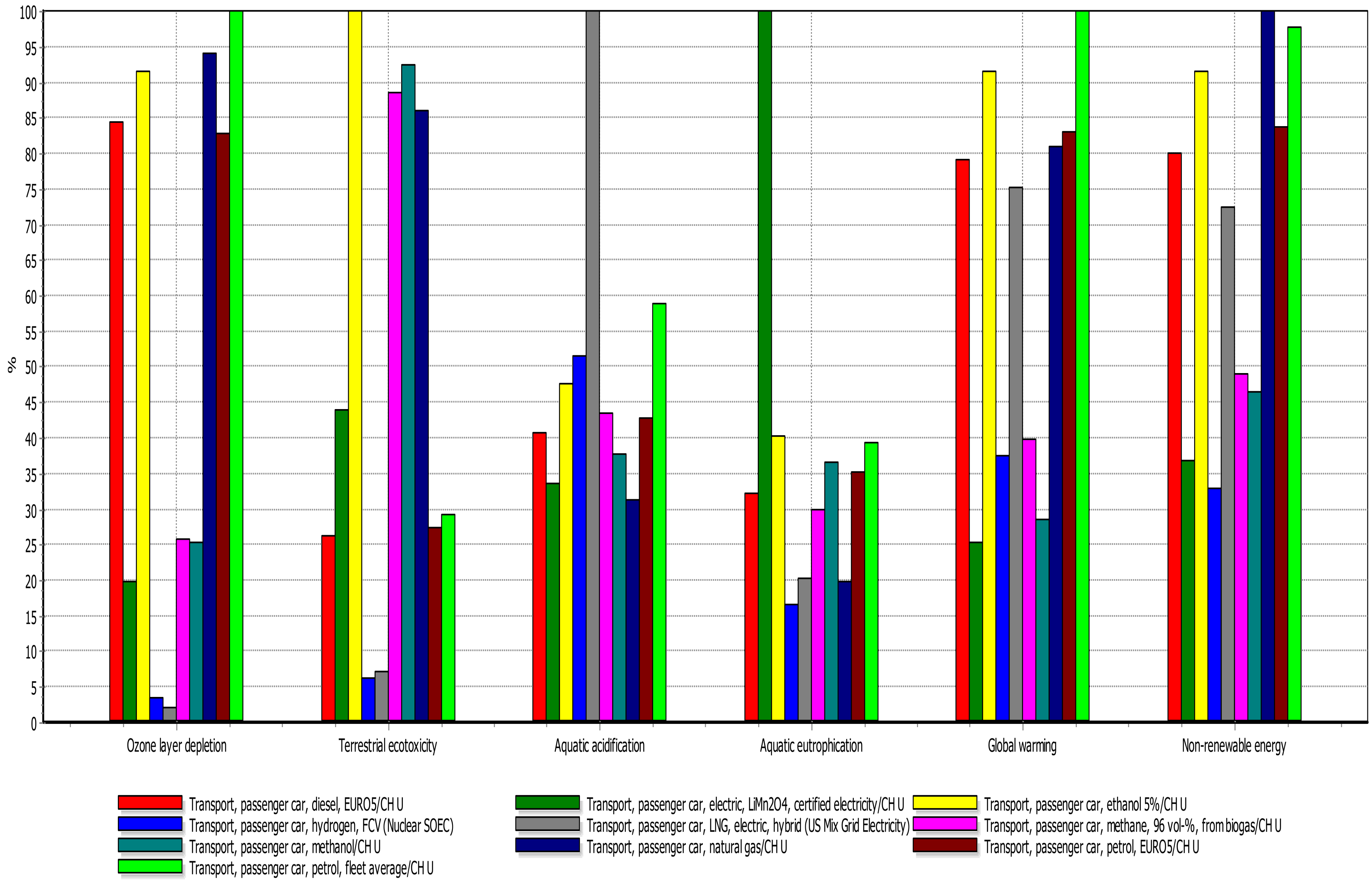

Figure 5.3 Comparison of various vehicle technologies on selected 6 big impact categories. (Method: IMPACT 2002+)

Table 5.5 Impact assessment results for various vehicle technologies on selected six big impact categories per 1 km traveled (Method: IMPACT 2002+)

Impact category	**Unit**	**Diesel**	**Electric**	**Ethanol**	**Hydrogen**	**Hybrid**
Ozone layer depletion	kg CFC-11 eq	2.26E-08	5.29E-09	2.45E-08	9.03E-10	5.26E-10
Terrestrial ecotoxicity	kg TEG soil	3.19	5.34	12.14	0.74	0.86
Aquatic acidification	kg SO_2 eq	0.00042	0.00035	0.00049	0.00054	0.0011
Aquatic eutrophication	kg PO_4 P-lim	1.98E-05	6.14E-05	2.47E-05	1.02E-05	1.25E-05
Global warming	kg CO_2 eq	0.16	0.05	0.18	0.07	0.15
Non-renewable energy	MJ primary	2.73	1.26	3.12	1.12	2.47

In aquatic acidification category, as is it can be seen in Figure 5.3 the worst performing car is a hybrid vehicle, followed by gasoline, hydrogen, ethanol, methane gasoline (EURO5), diesel, methanol, electric and natural gas vehicle. CML 2001 and IMPACT 2002+ results in exactly matches, but small differences observed in comparison with the eco-indicator method.

Table 5.6 Impact assessment results for various vehicle technologies on selected six big impact categories per 1 km traveled (Method: IMPACT 2002+) (continued)

Impact category	**Unit**	**Methane**	**Methanol**	**Natural gas**	**Gasoline 1**	**Gasoline 2**
Ozone layer depletion	kg CFC-11 eq	6.87E-09	6.78E-09	2.52E-08	2.22E-08	2.68E-08
Terrestrial ecotoxicity	kg TEG soil	10.76	11.22	10.44	3.31	3.55
Aquatic acidification	kg SO_2 eq	0.00045	0.00039	0.00033	0.00045	0.00061
Aquatic eutrophication	kg PO_4 P-lim	1.83E-05	2.24E-05	1.21E-05	2.16E-05	2.42E-05
Global warming	kg CO_2 eq	0.078	0.056	0.16	0.16	0.20
Non-renewable energy	MJ primary	1.67	1.593	3.41	2.85	3.33

Gasoline 1; EURO5, gasoline 2; fleet average

In aquatic eutrophication category, lowest impacts come from hydrogen followed by natural gas and hybrid. On the other hand, the electric car has a highest environmental impact for this category. The results match with CML 2001 method, but different than eco-indicator 99 method. Because both CML 2001 and IMPACT 2002+ are mid-point oriented. In global warming category, highest environmental impact observed for gasoline and ethanol, followed by gasoline (EURO5), natural gas, diesel, hybrid, methane, hydrogen, methanol and electric car. The winner in this impact category is an electric car from alternatively fueled vehicle category. The results from all three LCIA methods exactly matches in this impact category. In non-renewable energy impact category, based on Figure 5.3 Table 5.5 and 5.6, it is observed that natural gas, gasoline (fleet) and ethanol vehicles have the highest impact. Hydrogen and electric vehicle have lowest impacts. This tells us that alternative fueled vehicles perform better in this category. The LCA results match with CML 2001 and eco-indicator 99.

5.2. Comparison of LCIA Methods Used in the Study

This section compares the environmental impact assessment results of three different LCIA methods used in the study. The results of a performed LCA should be interpreted in the context of the used LCIA methods. The results presented in this thesis, are produced with three calculation methods namely; CML 2001, Eco-indicator 99 and Impact 2002+.

In ozone layer depletion category, CML 2001 and eco-indicator 99 and IMPACT 2002+ methods' results are very similar. The LCA results are very reliable for this category. In human toxicity, eco-toxicity and terrestrial eco-toxicity category, Unlike CML 2001 and eco-indicator 99, IMPACT 2002+ impact result for electric vehicle obtained low in terrestrial eco-toxicity. However, this can be explained by toxicity focused in different areas. In acidification category, CML 2001 and IMPACT 2002+ results matches closely, but minor differences observed in comparison with the eco-indicator method. In eutrophication category, the results match with CML 2001 method, but different than eco-indicator 99 method. Because both CML 2001 and IMPACT 2002+ are mid-point oriented. In global warming category, the results from all three LCIA methods almost exactly matches in this impact category. In abiotic depletion impact category, all three LCIA methods' results match with each other. It is revealed that the LCIA results from three chosen methods are comparable in most impact categories. However, chosen impact assessment method is important in some cases. For the toxicity related impact categories, different results obtained for IMPACT 2002+.

5.3. Impact Assessment Results for Vehicles Selected for LCA

In this section, the results per kilometer traveled are tabulated for all vehicle selected regarding six impact categories, namely abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and human toxicity. The vehicle has the highest impact on the environment is determined for the sake of discussion in the following section.

5.3.1. Results for Diesel Vehicle

Table 5.7 represents LCIA results for transporting one person per km driving distance with diesel vehicle for all selected impact categories for the LCA study. The diesel vehicle shows high environmental impacts in nearly all categories. However, it contributes less in acidification and human toxicity potentials, in comparison with hybrid and gasoline vehicles. Diesel vehicle is one of the worst performing vehicle in global warming, abiotic depletion and ozone layer depletion potentials categories.

Table 5.7 Impact assessment results for selected categories per 1 km traveled by diesel car.

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.0011
Acidification	kg SO_2 eq	0.00041
Eutrophication	kg PO_4 eq	0.00012
Global warming 100a	kg CO_2 eq	0.16
Ozone layer depletion 40a	kg CFC-11 eq	2.02E-08
Human toxicity 100a	kg 1,4-DB eq	0.035

5.3.2. Results for Gasoline Vehicle (Fleet Average)

Table 5.8 represents LCIA results for transporting one person per km driving distance with gasoline vehicle for all selected impact categories for the LCA study. The gasoline vehicle (fleet average) is the worst performing vehicle in selected vehicles for this study. Especially in global warming, abiotic depletion, ozone layer depletion and human toxicity. Gasoline vehicle is the vehicle that needs immediate improvement in its environmental performance.

An improvement in fuel efficiency, and a change in supply chain at manufacturing stage will make this vehicle better in terms of environmental impacts.

Table 5.8 Impact assessment results for selected categories per 1 km traveled by gasoline vehicle

Impact category	Unit	Total
Abiotic depletion	kg Sb eq	0.0014
Acidification	kg SO_2 eq	0.0006
Eutrophication	kg PO_4 eq	0.00015
Global warming 100a	kg CO_2 eq	0.20
Ozone layer depletion 40a	kg CFC-11 eq	2.40E-08
Human toxicity 100a	kg 1,4-DB eq	0.062

5.3.3. Results for Electric Vehicle

Table 5.9 represents LCIA results for transporting one person per km driving distance with an electric vehicle for all selected impact categories for the LCA study. The electric vehicle is one of the sustainable options in all vehicles selected. However, it shows very high human toxicity potential and eutrophication potential values due to battery production, battery maintenance and disposal. On the other hand, in global warming, and ozone layer depletion potential categories it is one of the most promising vehicle.

Table 5.9 Impact assessment results for selected all impact categories per 1 km traveled by an electric vehicle

Impact category	Unit	Total
Abiotic depletion	kg Sb eq	0.00043
Acidification	kg SO_2 eq	0.00037
Eutrophication	kg PO_4 eq	0.00024
Global warming 100a	kg CO_2 eq	0.052
Ozone layer depletion 40a	kg CFC-11 eq	4.81E-09
Human toxicity 100a	kg 1,4-DB eq	0.11

5.3.4. Results for Ethanol Vehicle

Table 5.10 represents LCIA results for transporting one person per km driving distance with ethanol vehicle for all selected impact categories for the LCA study. The ethanol vehicle shows high environmental impacts in all categories because the fuel combination is 5% ethanol and 95% gasoline here. For this reason, the results are similar with gasoline vehicle in all categories. Specially the results calculated for global warming, abiotic depletion, and ozone layer deletion potential is high as it given in table below. Flexible fuel vehicle can run on up to 85% ethanol, 15% gasoline blend. The ethanol fuel is made from renewable sources like corn and sugarcane, and it is mainly used as a biofuel additive for gasoline. Higher ethanol mixture in gasoline result in better environmental performance.

Table 5.10 Impact assessment results for selected all impact categories per 1 km traveled by ethanol vehicle

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.0013
Acidification	kg SO_2 eq	0.00051
Eutrophication	kg PO_4 eq	0.00013
Global warming 100a	kg CO_2 eq	0.18
Ozone layer depletion 40a	kg CFC-11 eq	2.19E-08
Human toxicity 100a	kg 1,4-DB eq	0.045

5.3.5. Results for Methane Vehicle

Table 5.11 represents LCIA results for transporting one person per km driving distance with methane vehicle for all selected impact categories for the LCA study. Methane vehicle in this study utilize 96% bio-methane. Bio-methane is produced from organic waste, and it is a renewable based fuel. Its properties are similar to natural gas. The result calculated for methane vehicle is much lower then natural gas vehicle because it uses renewable based fuel. However, the results for acidification and eutrophication is high in methane vehicle due to transformation of organic matters like organic waste from industrial sources.

Table 5.11 Impact assessment results for impact categories per 1 km traveled by methane vehicle

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.00049
Acidification	kg SO_2 eq	0.00045
Eutrophication	kg PO_4 eq	0.00014
Global warming 100a	kg CO_2 eq	0.11
Ozone layer depletion 40a	kg CFC-11 eq	6.10E-09
Human toxicity 100a	kg 1,4-DB eq	0.047

5.3.6. Results for Methanol Vehicle

Table 5.12 represents LCIA results for transporting one person per km driving distance with methanol vehicle for all selected impact categories for the LCA study. The methanol can be mixed with gasoline in low-quantities and used in gasoline vehicles. Methanol vehicle shows lower environmental impact in comparison with conventional vehicles and natural gas vehicle. As it can be seen in table below, its calculated results are similar to electric vehicle. However, it shows high impact on human toxicity and eutrophication potential.

Table 5.12 Impact assessment for impact categories per 1 km traveled by methanol vehicle

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.00047
Acidification	kg SO_2 eq	0.000379
Eutrophication	kg PO_4 eq	0.000152
Global warming 100a	kg CO_2 eq	0.057943
Ozone layer depletion 40a	kg CFC-11 eq	5.62E-09
Human toxicity 100a	kg 1,4-DB eq	0.04842

5.3.7. Results for Natural Gas Vehicle

Table 5.13 represents LCIA results for transporting one person per km driving distance with a natural gas vehicle for all selected impact categories for the LCA study. A natural gas vehicle is an alternative fuel vehicle that uses CNG or LNG. The results obtained for natural gas vehicle is better then conventional vehicles like gasoline and diesel. However, natural gas vehicle shows high impact on abiotic depletion and ozone layer depletion potential due to its high impact at vehicle operation and manufacturing phase. Production of fuel tank has noticeable life cycle effects as well.

Table 5.13 Impact assessment for impact categories per 1 km traveled by the natural gas vehicle

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.0014
Acidification	kg SO_2 eq	0.00033
Eutrophication	kg PO_4 eq	0.0001
Global warming 100a	kg CO_2 eq	0.17
Ozone layer depletion 40a	kg CFC-11 eq	2.89E-08
Human toxicity 100a	kg 1,4-DB eq	0.03

5.3.8. Results for Gasoline (EURO5) Vehicle

Table 5.14 represents LCIA results for transporting one person per km driving distance with gasoline (EURO5) vehicle for all selected impact categories for the LCA study. The Euro 5 standards for vehicles restricts emissions of CO, HC, NOx, and PM, which are considered harmful to human health. For this reasons, the gasoline vehicle has EURO5 standards performs much better than an average fleet gasoline vehicle in all impact categories selected for this study. Precaution measurements for vehicle emissions seems working for gasoline vehicles. More restrictions can be implied to make gasoline vehicles perform better, and these restrictions should be applied to all conventional vehicle types.

Table 5.14 Impact assessment results for selected all impact categories per 1 km traveled by gasoline (EURO5) vehicle

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.0012
Acidification	kg SO_2 eq	0.00046
Eutrophication	kg PO_4 eq	0.00012
Global warming 100a	kg CO_2 eq	0.17
Ozone layer depletion 40a	kg CFC-11 eq	1.98E-08
Human toxicity 100a	kg 1,4-DB eq	0.045

5.3.9. Results for Hydrogen Vehicle

Table 5.15 represents LCIA results for transporting one person per km driving distance with a hydrogen vehicle. The results are shown in six impact categories in the table below. This vehicle uses hydrogen gas to power an electric motor, which is called hydrogen fuel cell vehicle. The hydrogen is produced from nuclear SOEC. The hydrogen vehicle shows lowest environmental impacts in comparison with all other selected vehicles. Hydrogen vehicle especially shows very low environmental impact in ozone layer depletion and human toxicity potential impact categories. As it can be seen in table below, the values calculated for hydrogen vehicle is appealing low because hydrogen fuel has high energy density, and it consumes less fuel during vehicle use stage. Hydrogen vehicles development and production should be encouraged and supported by governments due to their low environmental impacts. Therefore, we can have sustainable transportation system in near future by investing more in development of hydrogen vehicles.

Table 5.15 Impact assessment results for selected all impact categories per 1 km traveled by hydrogen vehicle

Impact category	**Unit**	**Total**
Abiotic depletion	kg Sb eq	0.000634
Acidification	kg SO_2 eq	0.000609
Eutrophication	kg PO_4 eq	9.10E-05
Global warming 100a	kg CO_2 eq	0.079617
Ozone layer depletion 40a	kg CFC-11 eq	8.14E-10
Human toxicity 100a	kg 1,4-DB eq	0.001683

5.3.10. Results for the Hybrid Vehicle

Table 5.16 represents LCIA results for transporting one person per km driving distance with hybrid (LNG and electric) vehicle for all selected impact categories for the LCA study. The hybrid vehicle assumed to consume 50% LNG and 50% electricity. The data is taken from U.S sources. The hybrid vehicle shows low impact on ozone layer depletion and human toxicity potential. However, the results indicate high impact on acidification potential.

Table 5.16 Impact assessment results for selected all impact categories per 1 km traveled by the hybrid vehicle

Impact category	Unit	Total
Abiotic depletion	kg Sb eq	0.0013
Acidification	kg SO_2 eq	0.0012
Eutrophication	kg PO_4 eq	0.00012
Global warming 100a	kg CO_2 eq	0.16
Ozone layer depletion 40a	kg CFC-11 eq	4.74E-10
Human toxicity 100a	kg 1,4-DB eq	0.0027

5.3.11. Fossil Fuel Based Electric Vehicles versus Renewable Based Electric Vehicles

BEVs run completely on electrical power that stored in batteries, and EVs are called green vehicles that emitting zero-tailpipe emissions. However; electrical energy used by EVs might involve different levels of life cycle emissions, depending on what type of electricity source is used for charging batteries and for vehicle assembly during production of the vehicle. In fact, EVs swap the tailpipe emissions to production of electricity for charging batteries, and electrical power used for vehicle manufacturing and production of automobile parts. Environmental performance of EVs will further be improved by implementation of clean electricity sources like renewable sources. For the LCIA results, use of grid electricity mix is an important factor for level of emissions. Using an electricity mix based on renewable energies will bring a completely different result than an electricity mix based on fossil fuels. In considerable number of LCA's an electricity mix is utilized, which is totally based on clean energy [111]. The results of renewable based EVs should not be generalized to all EVs as electricity source is the main factor in decision making. To investigate the impact of different electricity sources on electric vehicle's environmental performance, a case study is performed in this section. Figure 5.4 shows LCA results of renewable electricity based an electric vehicle and a consumer grid mix electricity based electric vehicle, which is presented in six impact categories with CML 2001 methodology, respectively.

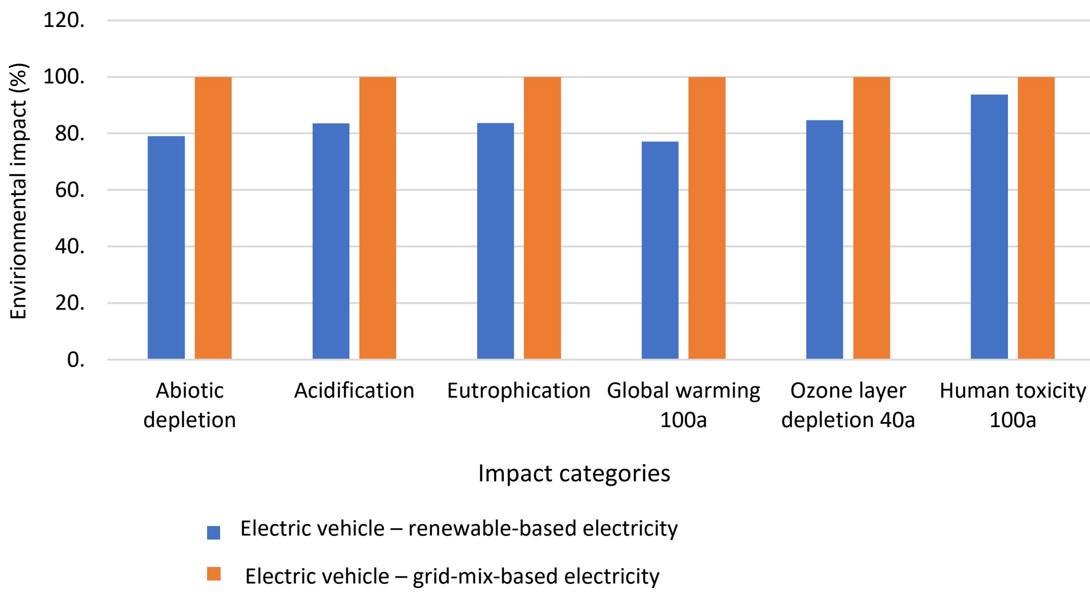

Figure 5.4 Comparison of EVs by energy source

Renewable based electric vehicle use only renewable sources like, wind, solar, hydroelectricity, and tidal energy. On the other hand, consumer mix grid electricity is combination of fossil fuel based and other types of energy sources. In this case study, the renewable based electric vehicle uses a lithium-ion pack charged with Swiss certified electricity. On the other hand, the consumer mix electricity based electric vehicle, which uses a lithium-ion battery pack charged with Swiss consumer mix electricity [112]. The data includes maintenance and disposal of vehicle and road. The data used in the study refers to Swiss conditions. For both vehicles, emissions of particulate matters and heavy metals are accounted. Particulate emissions comprise abrasions emissions only.

The heavy metal emissions to soil and water caused by tyre abrasion are included. Average data for the operation of both selected battery electric vehicle is 20kWh/100km. EVs selected for this study use a $LiMn_2O_4$ graphite battery pack, 100 Wh/kg, actual standard, and 2009 middle class passenger car, which is similar to VW Golf. Both vehicles have battery pack of 312 kg, and an electric motor of 104 kg. The inventory includes processes of material, energy and water use in vehicle manufacturing. Rail and road transport of materials is accounted for. Plant infrastructure is included, addressing issues such as land use, building, road and parking construction are included as well. Additionally, battery and electric motor manufacture is included. The inventory includes materials used for alteration parts and energy consumption of garages. Battery pack replacement and disposal included. The maintenance of the battery electric vehicle is derived from the maintenance of a conventional passenger car. Finally, the battery replacement is included. Life expectancy of battery pack is 100,000 km. As it can be seen in figure 1, the obtained results show that when electricity source changes for an electric vehicle, a change in level of environmental impacts is observed as well. We see an improvement for all impact categories when renewable based electric vehicle is used. However, when consumer mix grid electricity used, approximately there is 23% increase in global warming potential and 21% increase in abiotic depletion potential, 17% increase in acidification potential and eutrophication potential relatively. Hence, source of electricity makes an important difference on environmental performance of electric vehicles.

5.4. Results of LCA Regarding Impact Categories

In the present section, the results are shown in abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and human toxicity impact categories. Environmental impact of selected all vehicles is illustrated per kilometer traveled. Then, the percent contribution of each involved phase is given and compared. Lastly, the flow between all processes is presented with a detailed flow chart to identify important and less important processes involved in the life cycle of vehicles.

5.4.1. Abiotic Depletion Potential

In abiotic depletion impact category as illustrated in Figure 5.5, the worst performing vehicle is natural gas vehicle with 0.001423 kg Sb eq/km, followed by gasoline vehicle (petrol, fleet average), hybrid vehicle, ethanol vehicle, gasoline vehicle (petrol, EURO5), diesel vehicle, hydrogen fuel cell vehicle, methane vehicle, methanol vehicle and electric vehicle. The environmentally best-performing vehicle is an electric vehicle in this category with 0.000434 kg Sb eq/km. The winner in abiotic depletion category is alternative fueled vehicles. However, conventional fueled vehicles did not perform as well as expected. Figure 5.6 shows the contribution of each process during the vehicle's life cycle, 73.4 % all emission comes from vehicle operation stage while 14% of all emissions come from vehicle manufacturing process. Now, if we take a glance at Figure 5.7, we will be able to identify the hotspots in the vehicle's life cycle. The highest impact comes from diesel fuel use in vehicle and production of diesel fuel at the refinery. The impacts on vehicle manufacturing process occur during electricity consumption in each process and reinforcing steel.

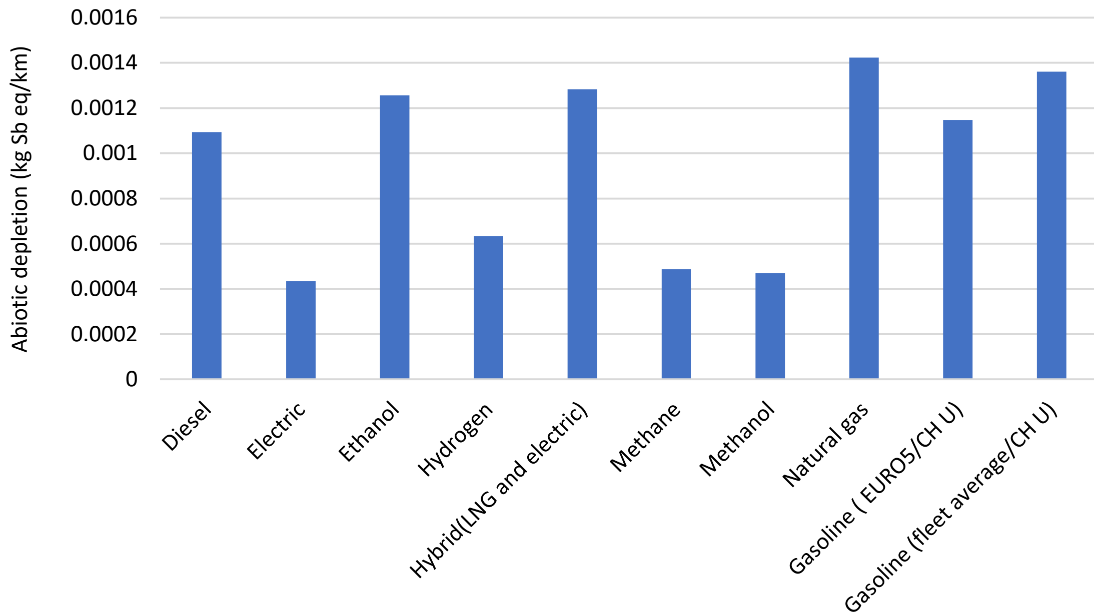

Figure 5.5 Impact assessment results in comparison for various vehicle technologies on abiotic depletion per 1 km traveled.

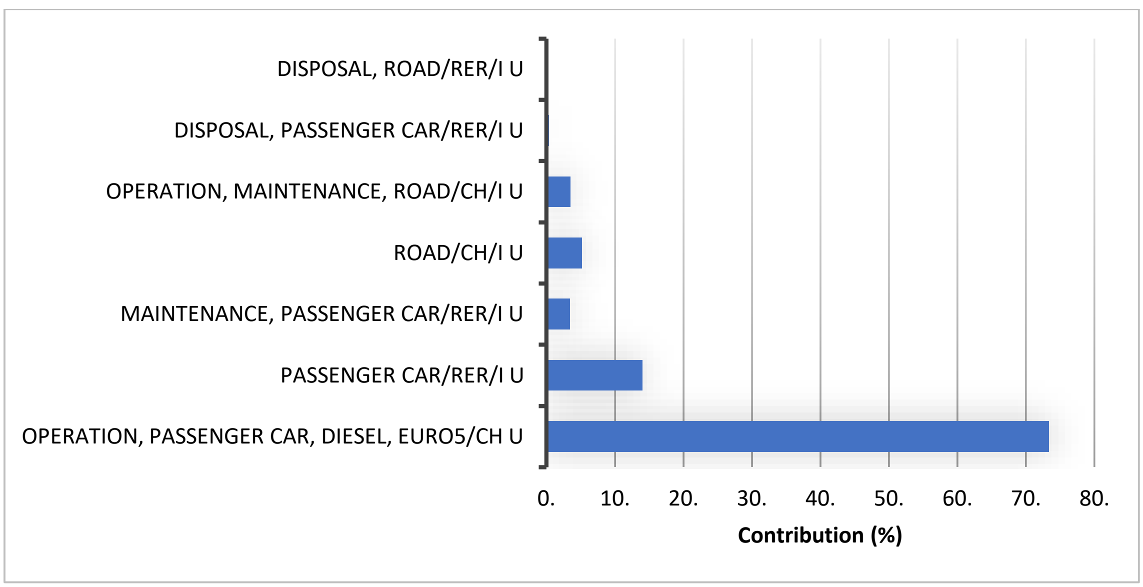

Figure 5.6 Contributions of various LCA processes to abiotic depletion of diesel vehicle

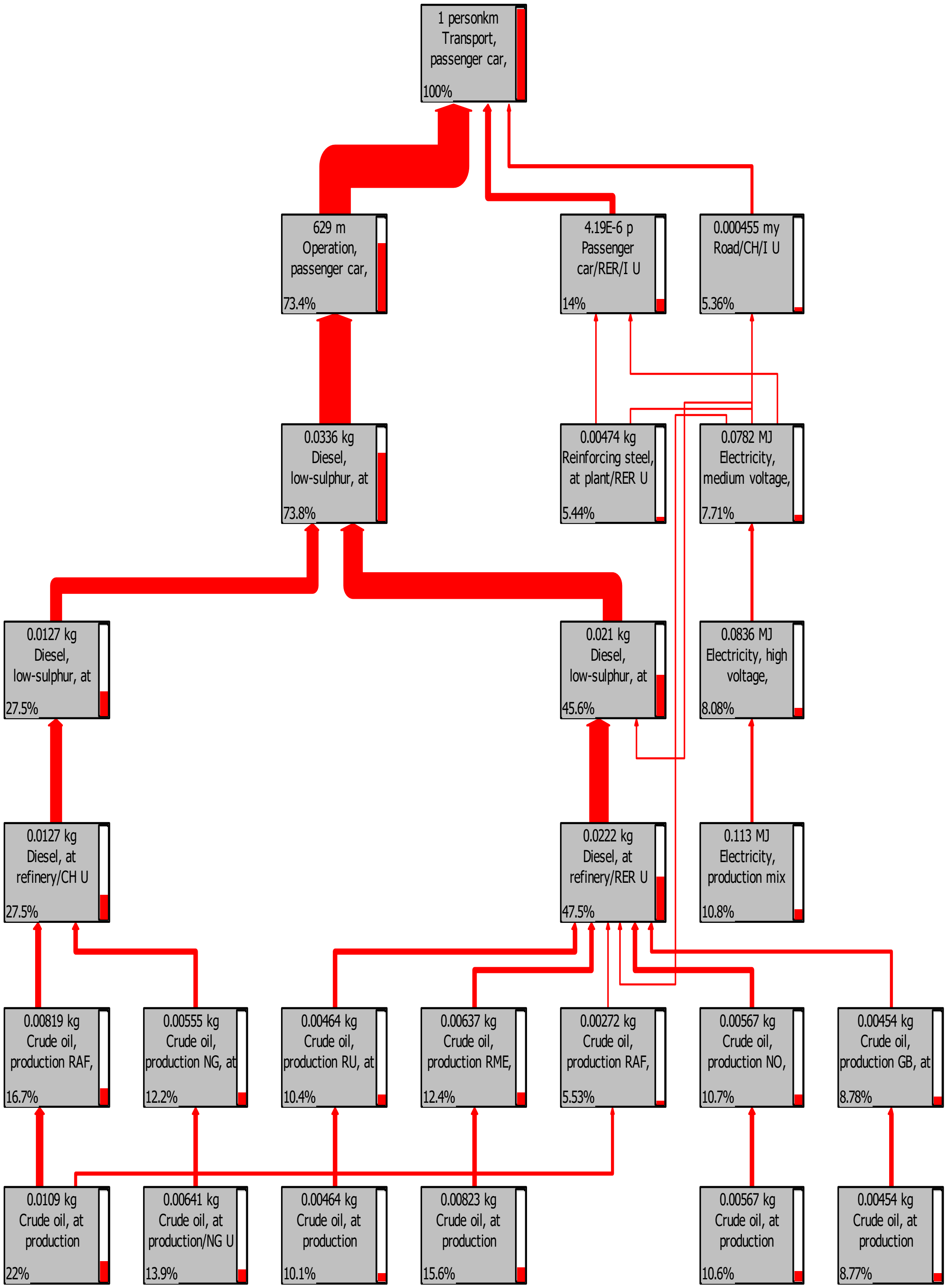

Figure 5.7 LCA process flowchart for abiotic depletion of diesel vehicle (cut-off 5%)

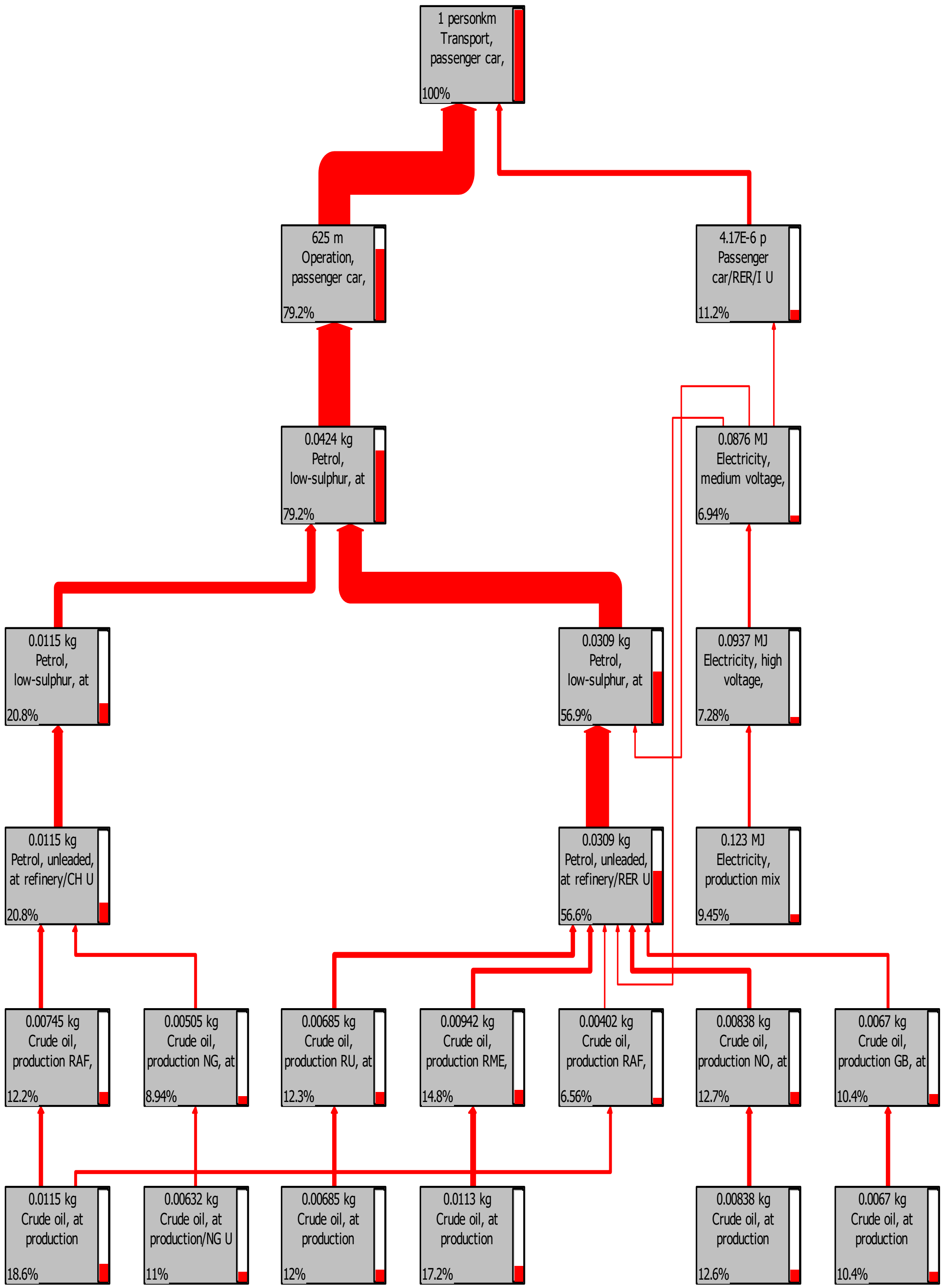

Figure 5.8. LCA process flow chart for abiotic depletion of gasoline vehicle (Petrol, fleet average) (Cut-off 5%)

Figure 5.8 shows contribution between each process for gasoline vehicle life cycle, 79.2 % impacts comes from operation stage of the vehicle and production of fuel. As it can be seen in Figure 5.9 second largest contributor stage is vehicle manufacturing phase with 11.2 %. The disposal stage has the lowest contribution.

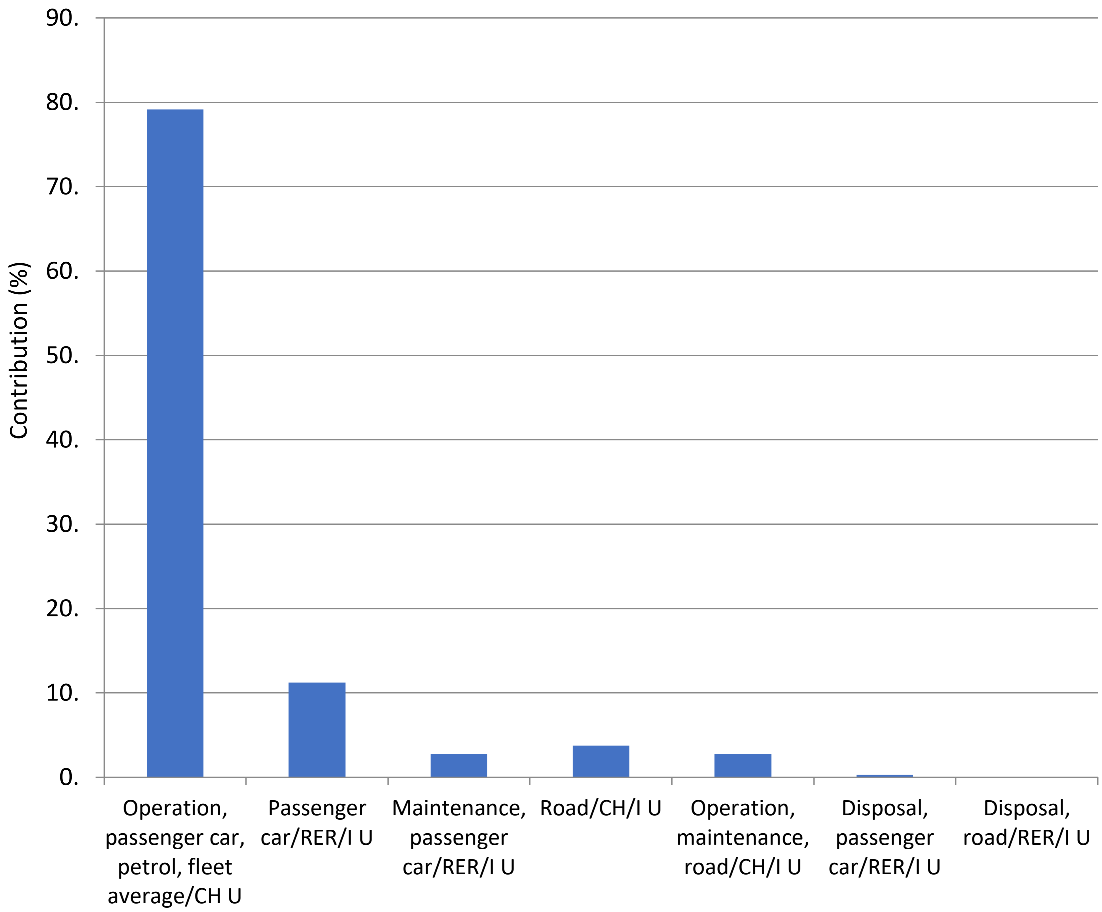

Figure 5.9 Contributions of various LCA processes to abiotic depletion of gasoline vehicle (fleet average)

It is observed that environmental impact of the electric car is very low during operation of the vehicle as shown in Figure 5.10. Hence, if this LCA is only considering wheel-to-well (WTW) emissions, the results would not be reliable, and the results would be biased toward the electric car. Thanks to cradle to grave analyses for taking all materials into consideration, for a full life cycle assessment. Figure 5.11 shows the detailed contribution of each process for an electric vehicle.

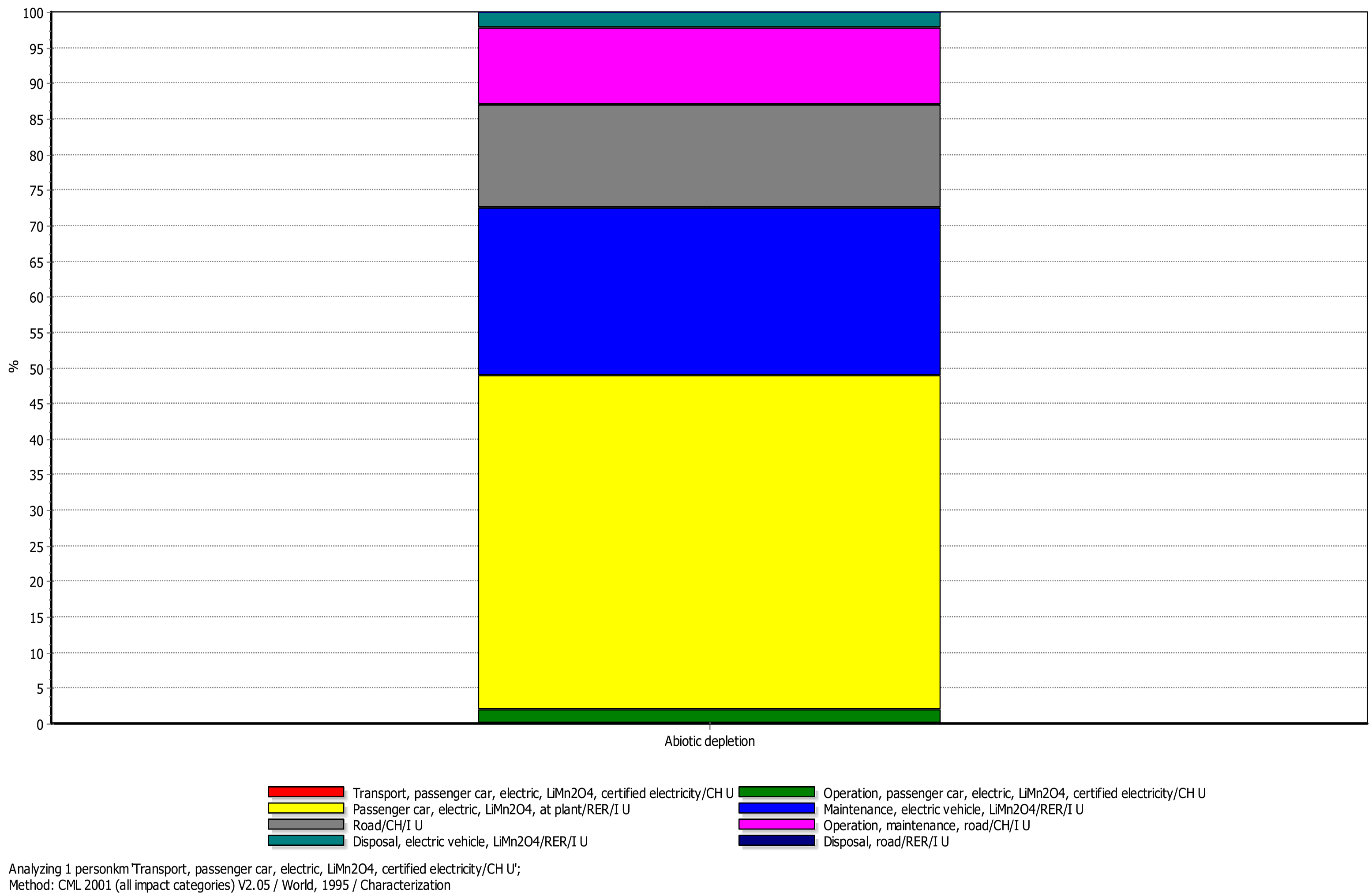

Figure 5.10 Contributions of various LCA processes to Abiotic Depletion of electric vehicle.

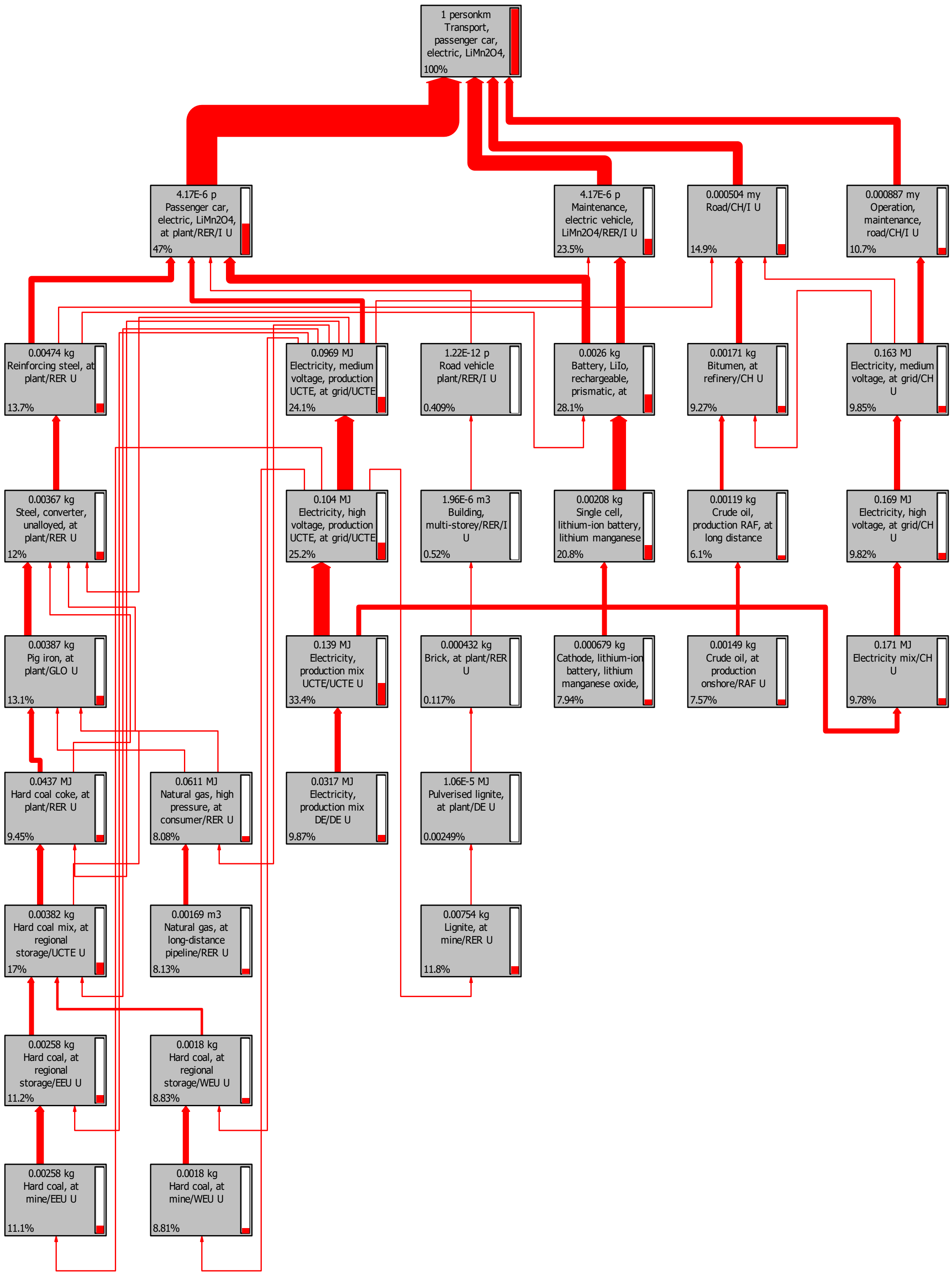

Figure 5.11 LCA process flow chart for abiotic depletion (kg Sb eq) of Electric Vehicle, LiMn2O4, certified electricity/CH U (Cut-off 7 %)

The highest impacts come during electric vehicle manufacturing at the plant, and maintenance of the vehicle has more impact then vehicle use phase.

Figure 5.12 represents the stages are accounted for vehicles life cycle and their level of contribution to abiotic depletion impact category. The impact of vehicle operation (37.5%) and vehicle manufacturing (32.6 %) is pretty close. To see what caused this impacts we need to see Figure 5.13. Production of methanol from biomass and synthetic gas is the main cause of the environmental impact. For vehicle manufacturing stage, UCTE electricity production is the source of impact. A change in the supply chain can mitigate the impacts.

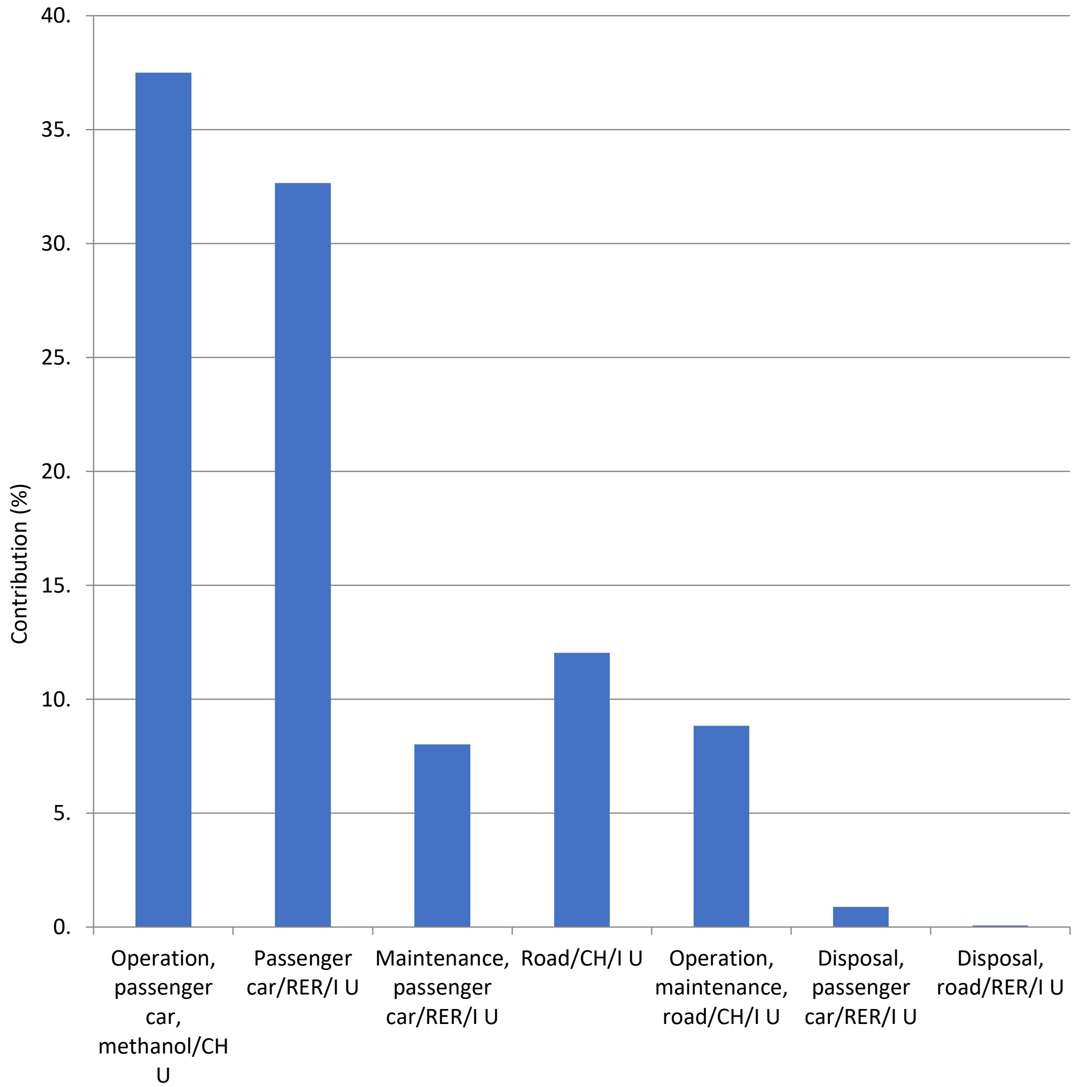

Figure 5.12 Contributions of various LCA processes to Abiotic Depletion of methanol vehicle

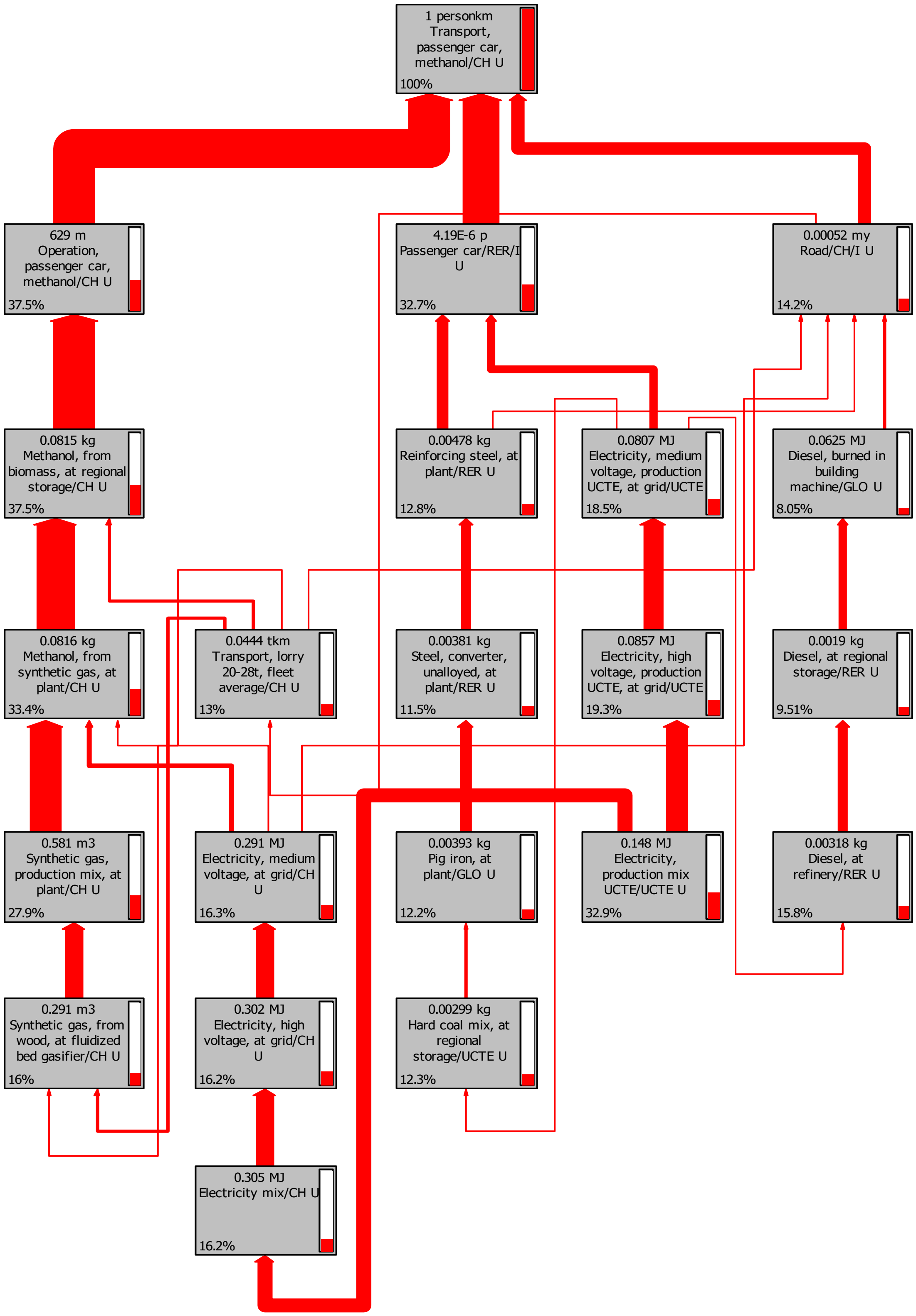

Figure 5.13 LCA process flow chart for abiotic depletion of methanol vehicle (Cut-off 12 %)

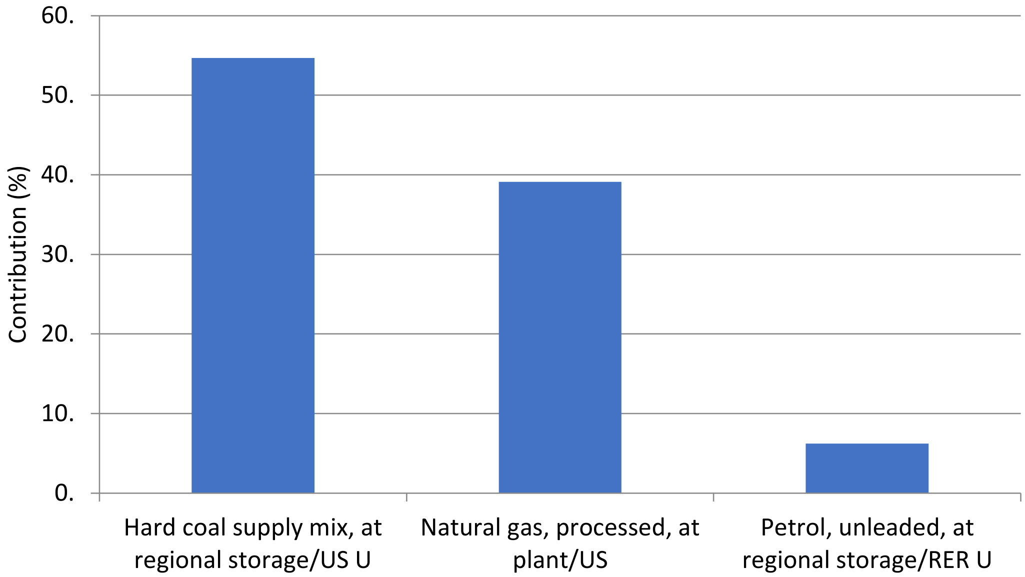

Figure 5.14 Contributions of various LCA processes to Abiotic Depletion of hydrogen vehicle

The hydrogen vehicle is one of the vehicles has a lower effect on abiotic depletion. Figure 5.14 depicts stages has the most effect on abiotic depletion. As shown in Figure 5.15 hard coal supply mix at regional storage and processing natural gas at the plant are the two key factors.

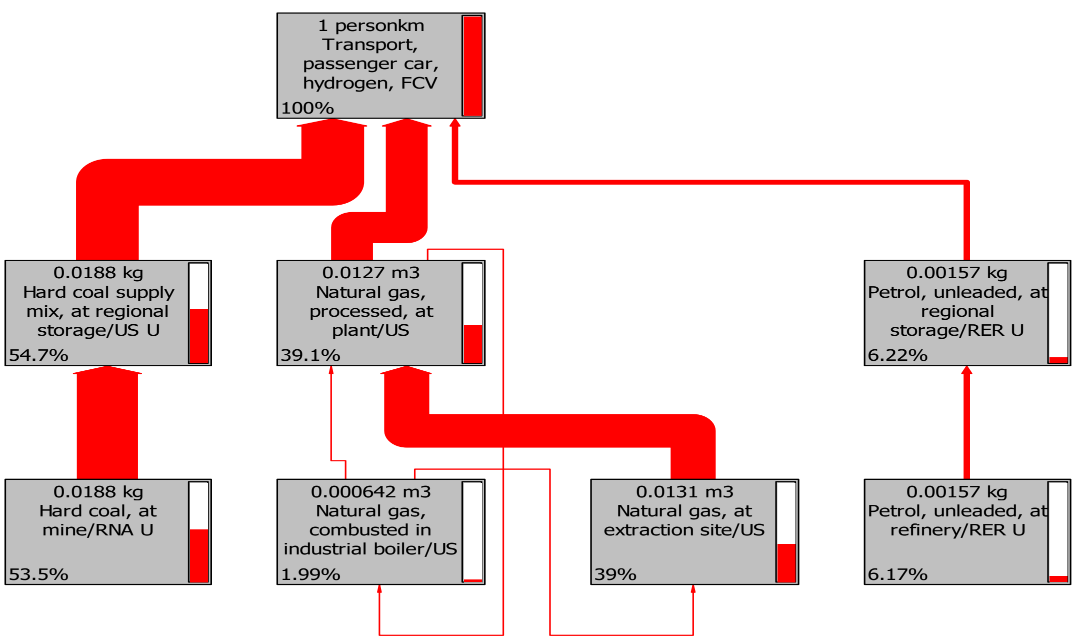

Figure 5.15 LCA process flow chart for abiotic depletion of hydrogen vehicle (Cut-off 1.9 %)

5.4.2. Acidification Potential

As shown in Figure 5.16 the noticeable vehicle is the hybrid vehicle. Highest environmental impacts come from hybrid (LNG and electric) vehicle with 0.001193 kg SO_2 eq/km, followed by hydrogen, gasoline (fleet average), ethanol, gasoline (EURO5), methane, diesel, methanol, electric and natural gas. Natural gas vehicle is performing best in acidification while it performs worst in abiotic depletion category. Alternative fueled vehicles are not ideal options for acidification category.

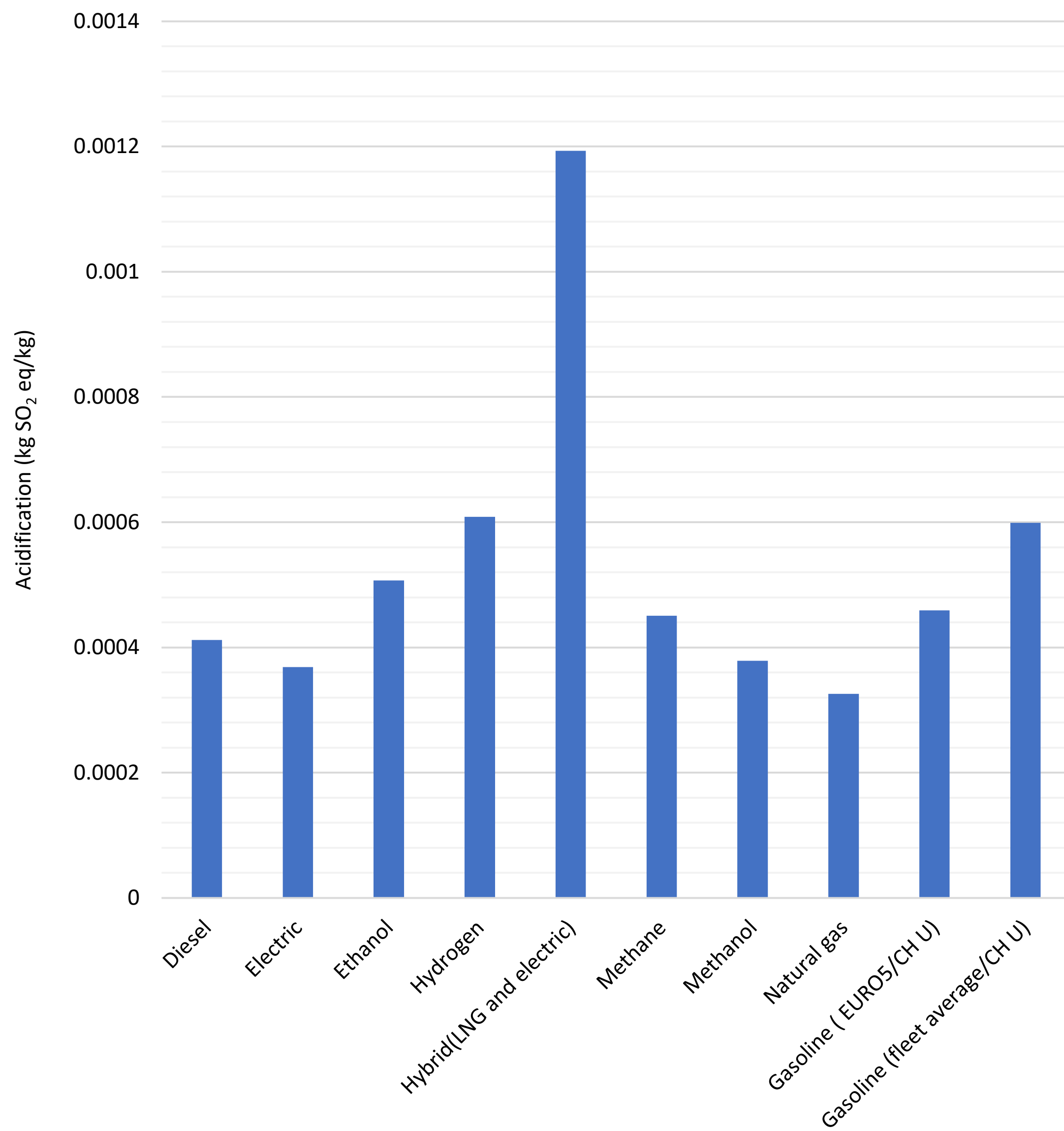

Figure 5.16 Impact assessment results comparison for various vehicle technologies on acidification per 1 km traveled.

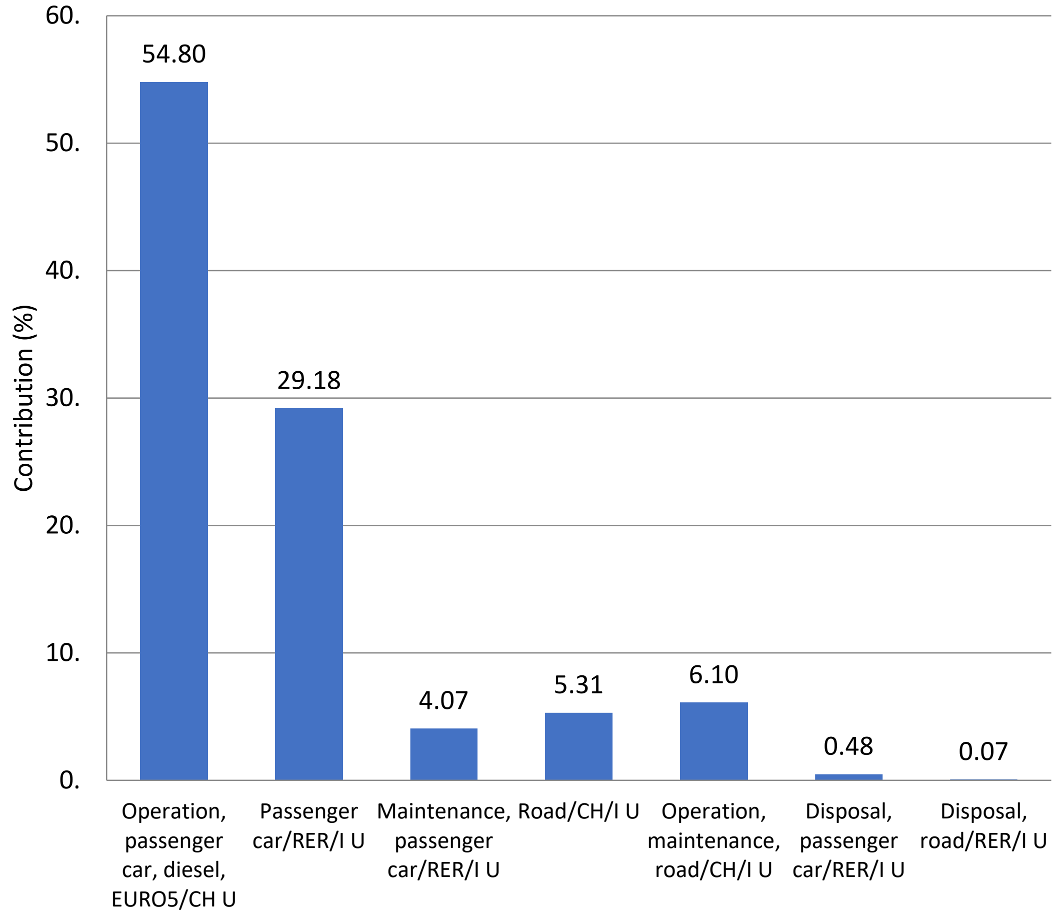

Figure 5.17 Contributions of various LCA processes to acidification of Diesel, EURO/CH U – Vehicle

Operation phase of the diesel vehicle is responsible for more than half of the total emissions with 54.7% as shown in Figure 5.17. The second noticeable stage is the manufacturing of diesel car regarding acidification emissions. In Figure 5.18 the thick red lines show which process contributes most in acidification impact category of the diesel car. That being said, crude oil extraction and diesel production at the refinery are key factors of acidification emissions for diesel car’s life cycle.

As shown in Figure 5.19 and Figure 5.20, it is very obvious that operation phase of gasoline vehicle has a tremendous impact on this category because fossil fuel based gasoline use in a vehicle, and production of the gasoline at the refinery. 69.5 % of all emission is attributed to operation stage.

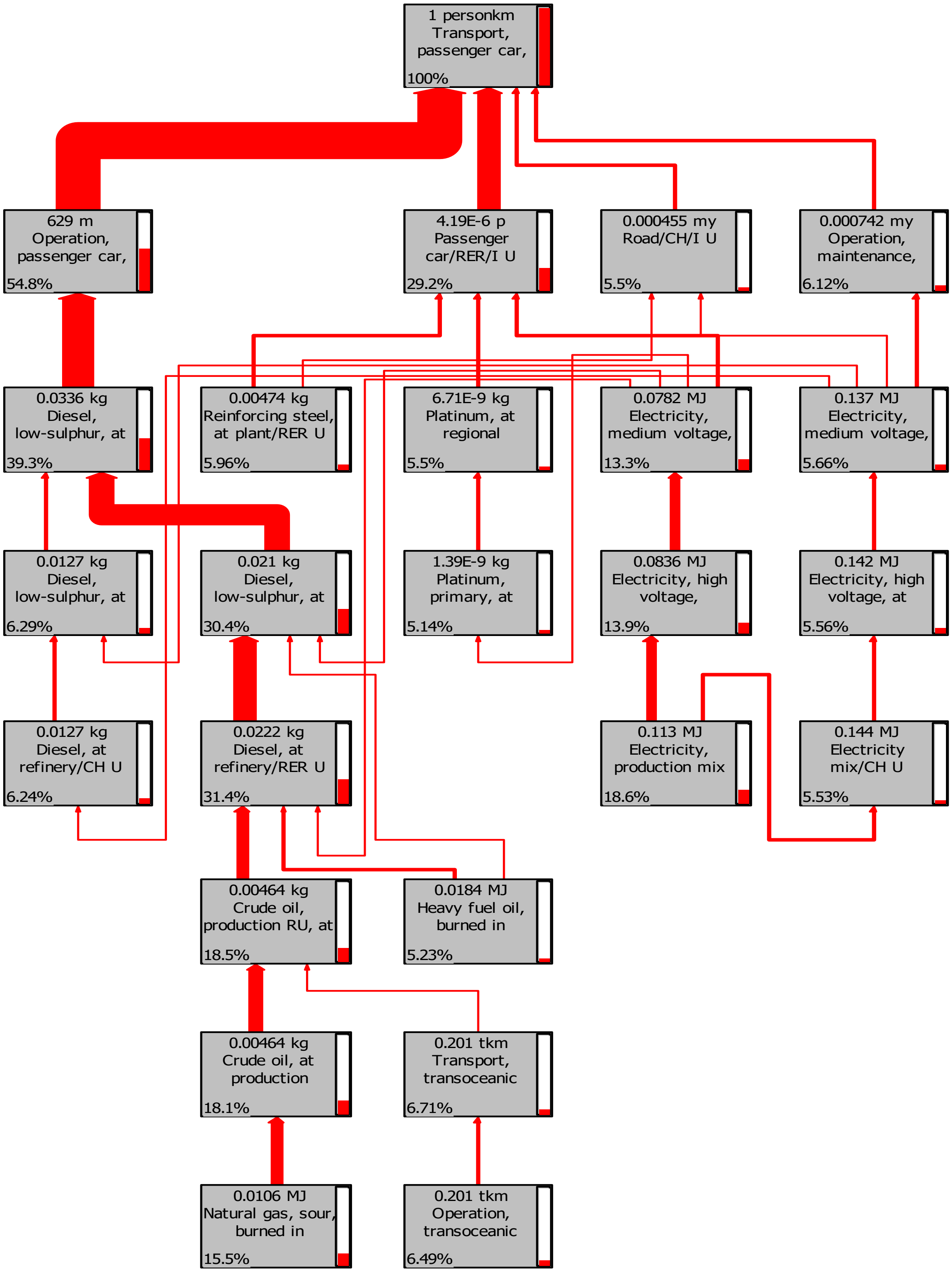

Figure 5.18 LCA process flow chart for Acidification of Diesel, EURO/CH U –Vehicle

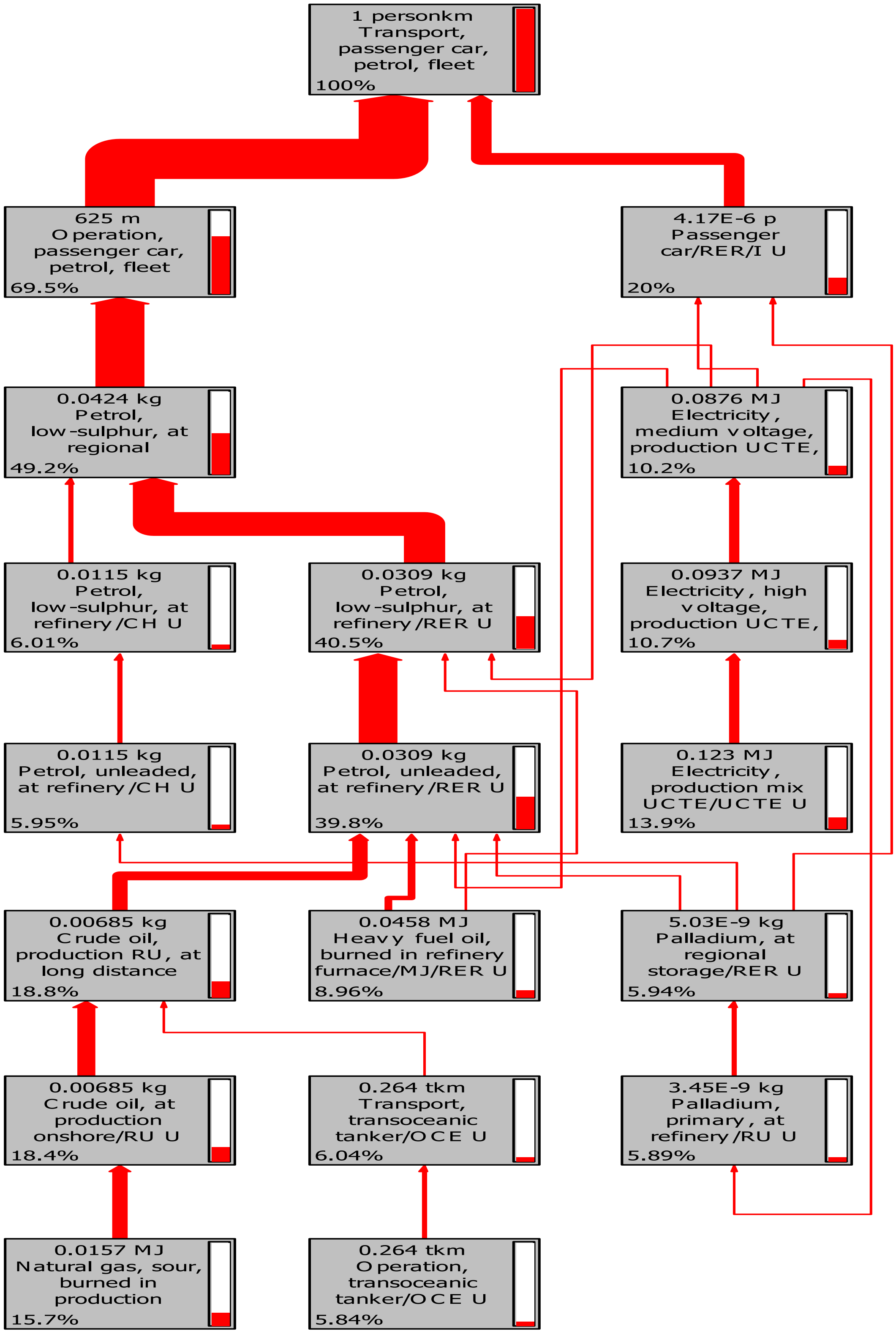

Figure 5.19 LCA process flow chart for acidification of gasoline vehicle (fleet average)(cut-off 5%)

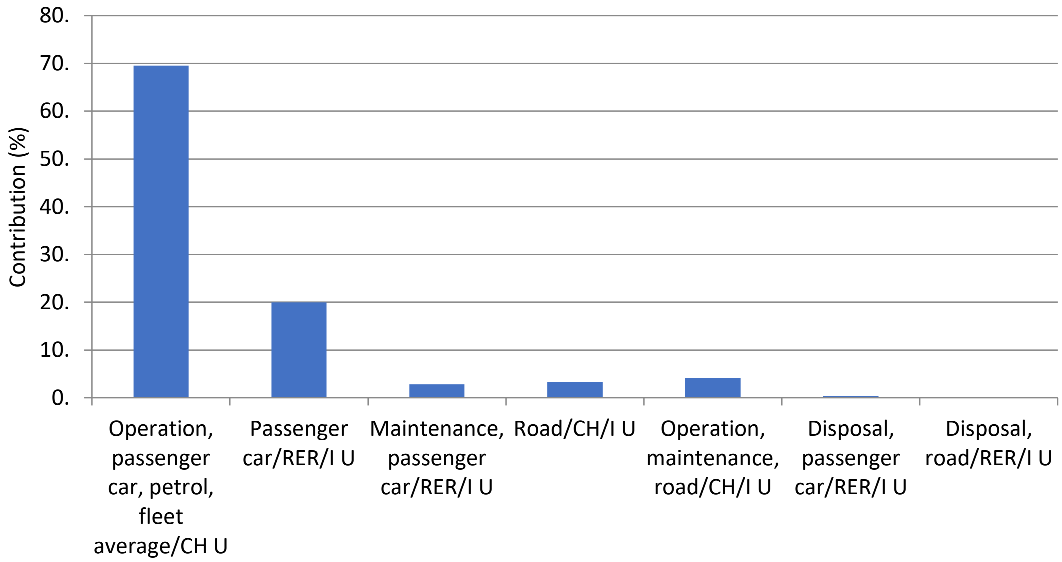

Figure 5.20 Contributions of various LCA processes to acidification of gasoline vehicle (fleet average)

Figure 5.21 and Figure 5.22 represent the environmental impact of an electric car for acidification category. Vehicle use has very low emissions while production and maintenance of the vehicle have about 76 % of total emissions. Production of battery, electricity consumption during vehicle manufacturing and production of copper has a high level of contribution.

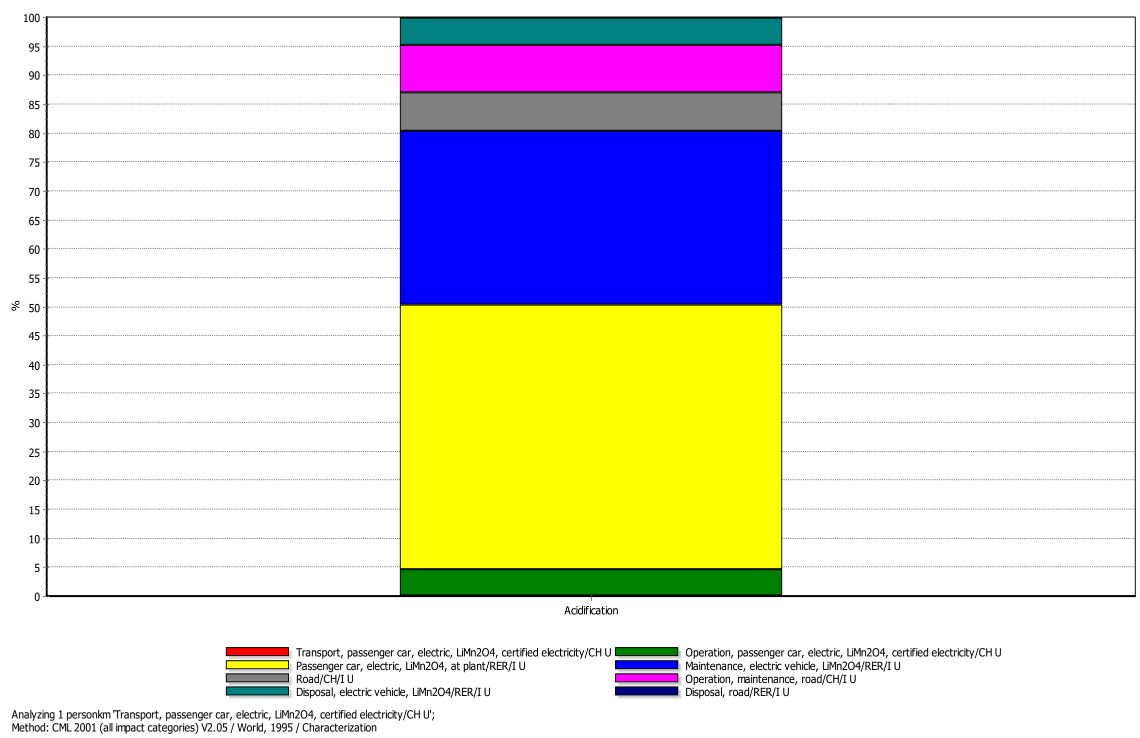

Figure 5.21 Contributions of various LCA processes to acidification of electric vehicle.

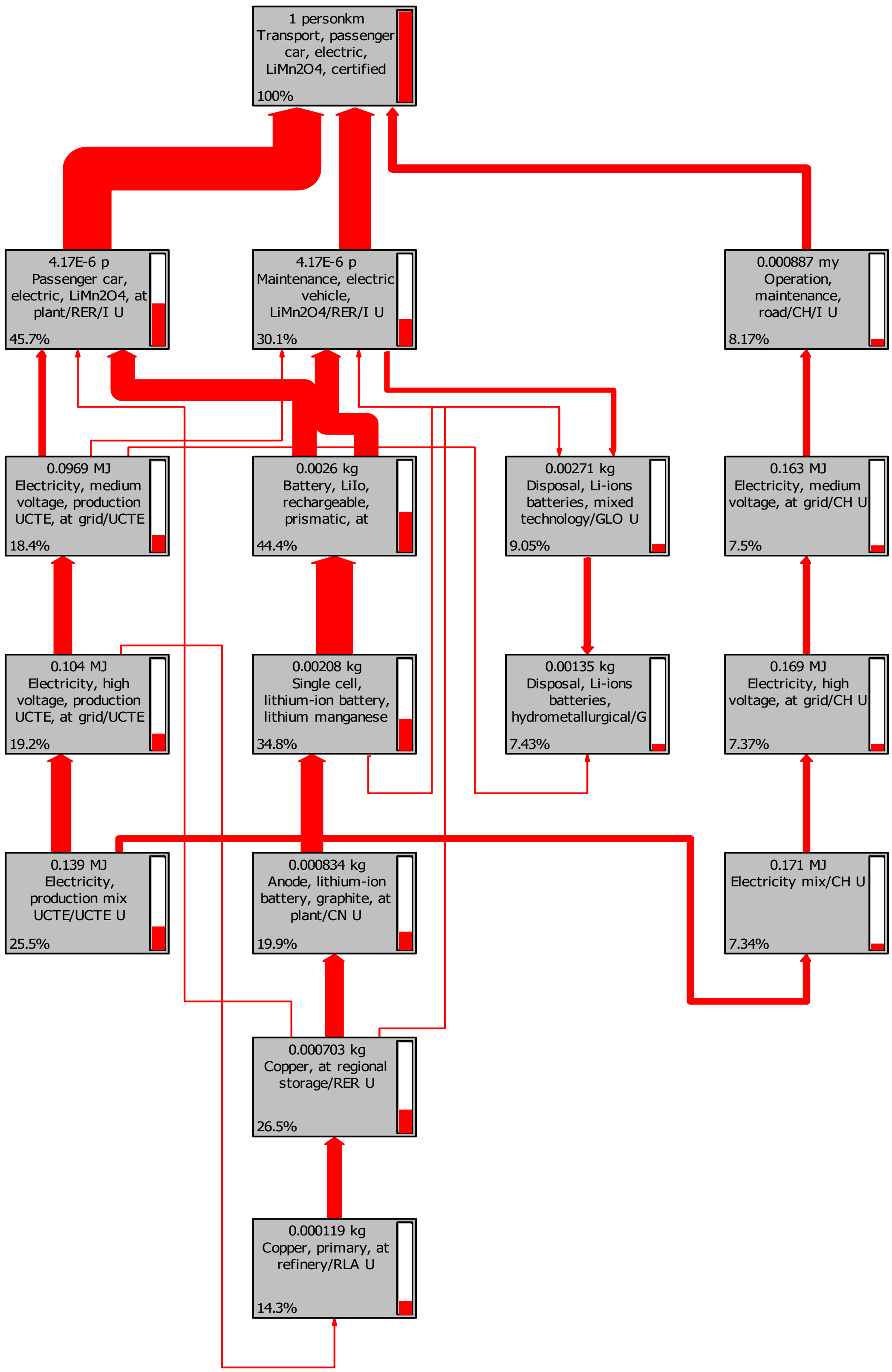

Figure 5.22 LCA process flow chart for acidification of electric car vehicle (cut-off 7%)

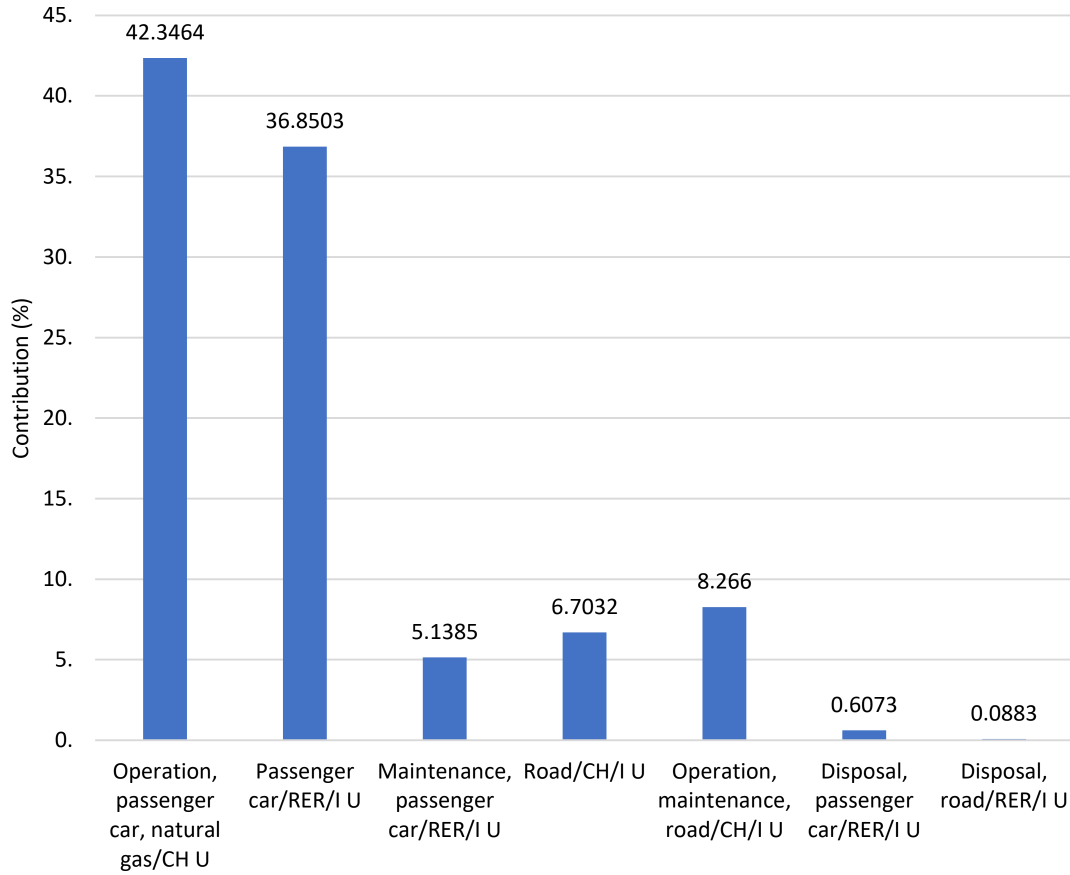

Figure 5.23 Contributions of various LCA processes to acidification of natural gas vehicle.

Figure 5.23 shows all stages considered for LCA of natural gas, as observed operation and manufacturing phases of this vehicle have higher impacts due to natural gas production at a service station and transportation of natural gas via pipelines from long distance. The emission from manufacturing stage is due electricity consumption at vehicle assembly plant and power production mix from UCTE.

5.4.3. Eutrophication Potential

The burning of fossil fuels releases nitrogen products into the air, which are passed down by rain and other procedures, triggering eutrophication inside the water bodies. As seen in Figure 5.24, in eutrophication category here, highest impacts obtained from EVs corresponding to 0.000238 kg PO_4 eq/km and lowest impacts comes from hydrogen vehicle and followed by the natural gas vehicle. In this CML 2001 impact category both conventional and alternative fuel categories have close results, but the most environmental benign option is hydrogen car.

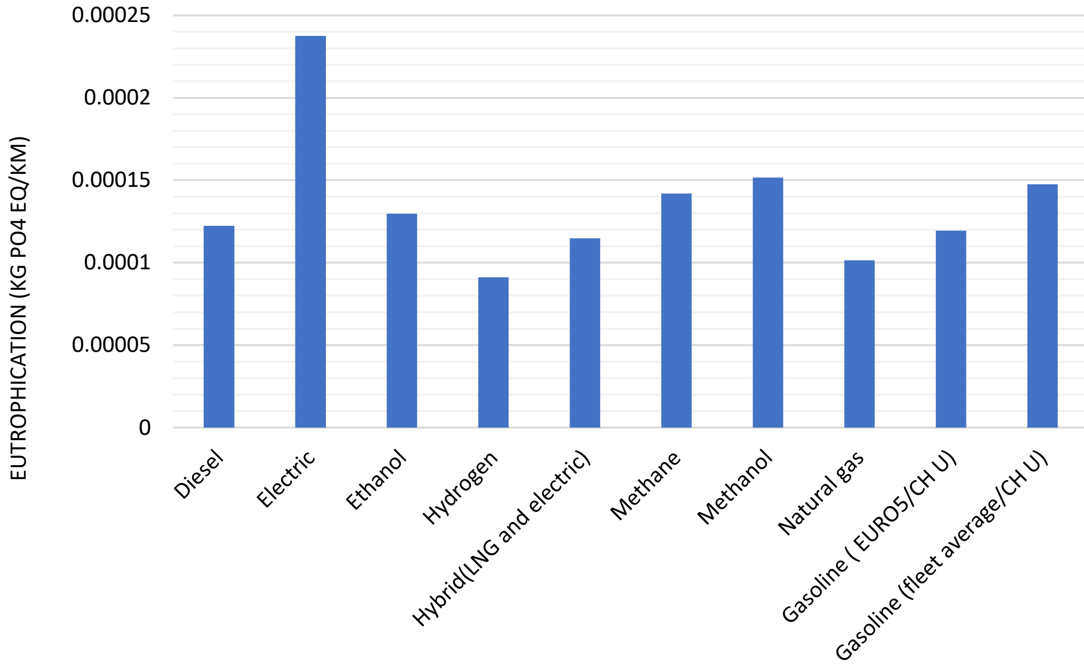

Figure 5.24 Impact assessment results comparison for various vehicle technologies on eutrophication per 1 km traveled

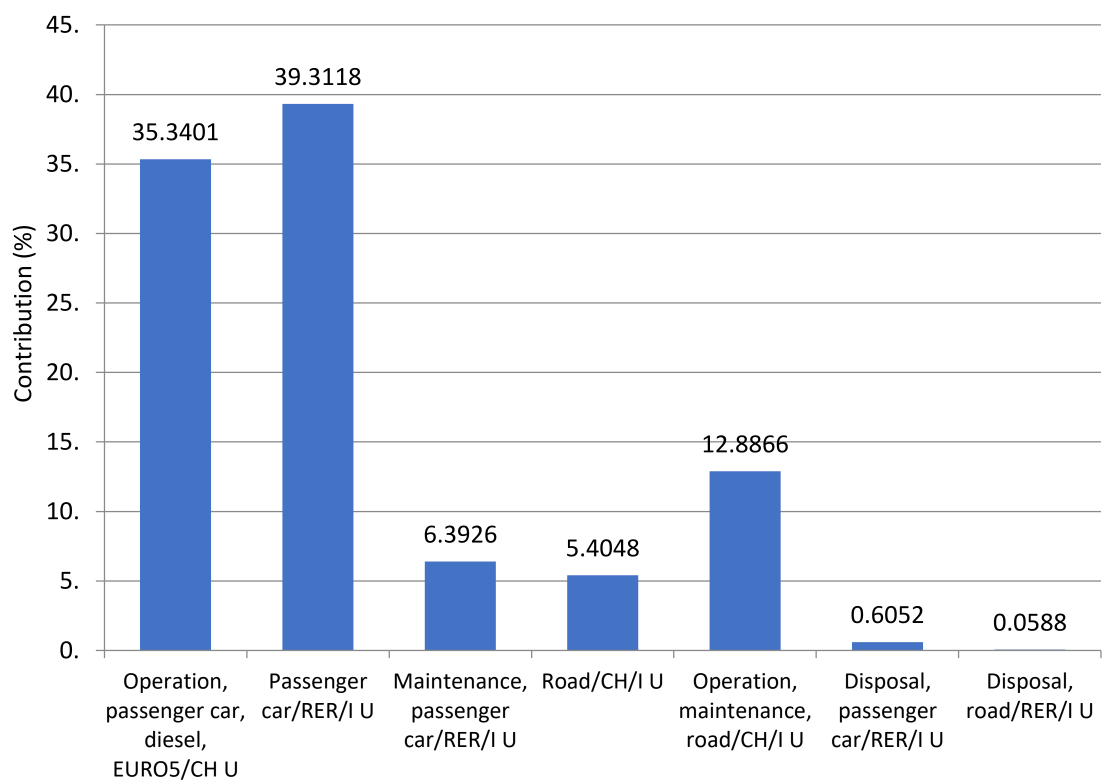

Figure 5.25 Contributions of various LCA processes to Eutrophication of diesel vehicle

Figure 5.26 LCA process flow chart for Eutrophication of diesel vehicle

As shown in Figure 5.25, the highest percentage of impacts produced during manufacturing of vehicle followed by operation of the vehicle with 35% and 39% respectively. Operation and maintenance of roads have about 13 % of total emitted emissions. Disposal of vehicle and roads in total have less than 1 % of eutrophication impact. Consumption and production of diesel, electricity production and usage are the hotspots in this category as illustrated in Figure 5.26. The thick red lines represent hotspots in the production process.

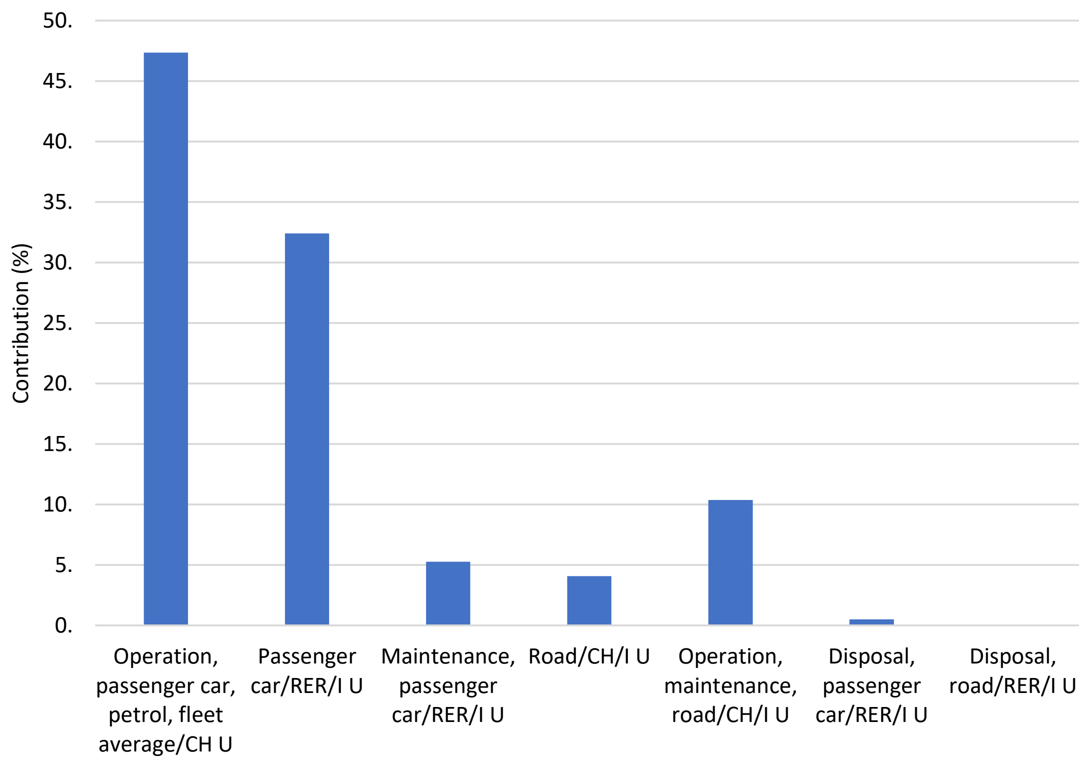

Figure 5.27 Contributions of various LCA processes to Eutrophication of gasoline vehicle(fleet average)

Similar to diesel car high-value eutrophication impacts of gasoline car obtained from operation and vehicle manufacturing processes. As shown in Figure 5.27 the calculated values for operation and manufacturing phase are 47 % and 32.4 % respectively. Maintenance of the car has about 5% eutrophication impact only. The hotspots can be observed in Figure 5.28. Gasoline usage, production, storage of gasoline is the main cause of eutrophication here. On the other hand, Electricity consumption and production are the main factors of eutrophication in the manufacturing process.

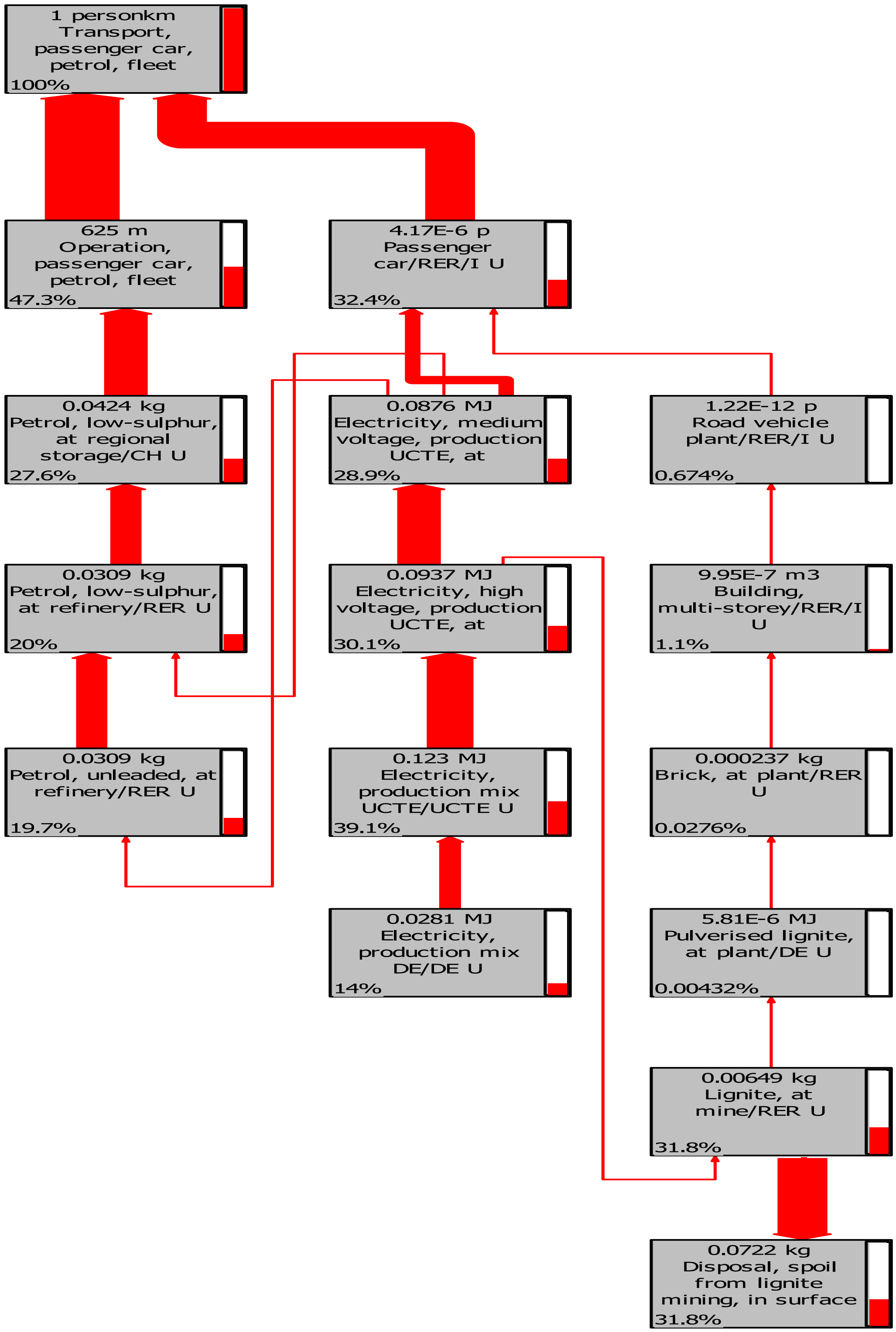

Figure 5.28 LCA process flow chart for Eutrophication of gasoline vehicle (fleet average)

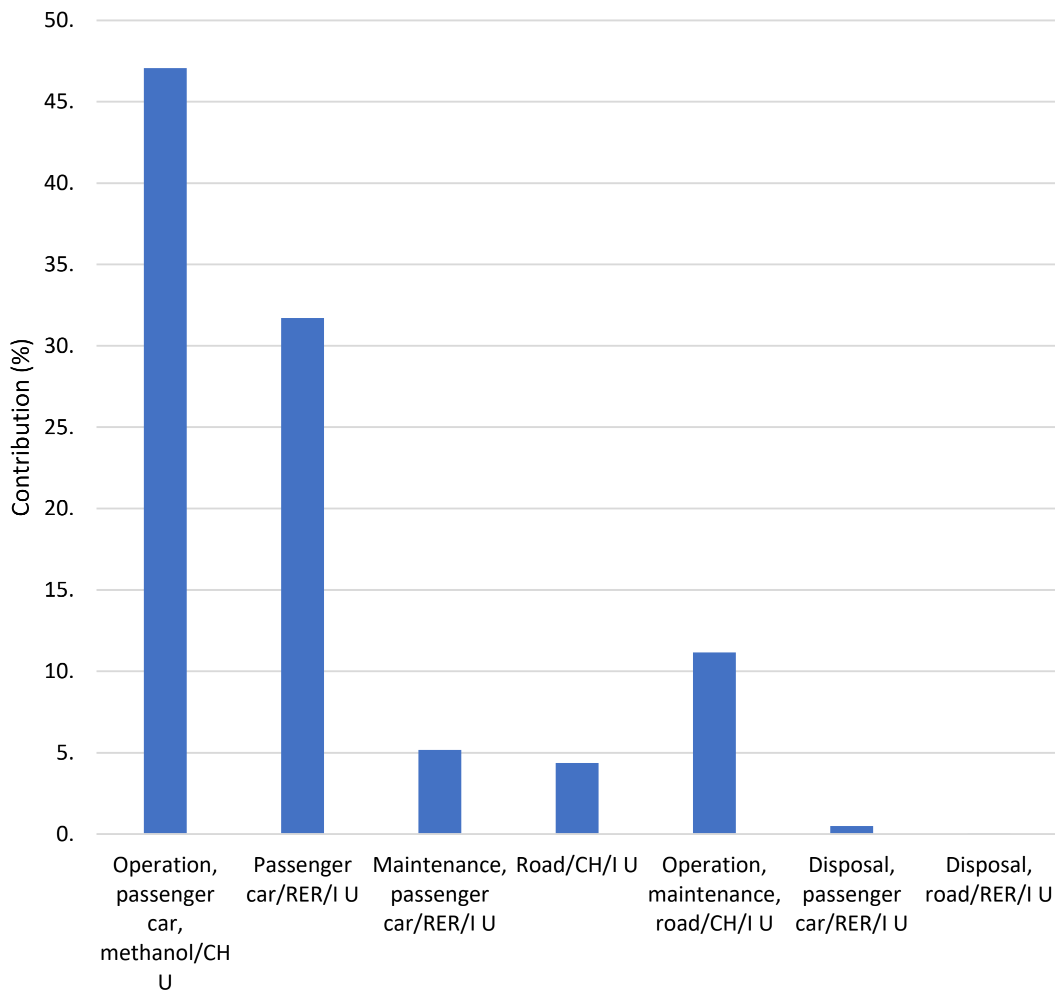

Figure 5.29 Contributions of various LCA processes to Eutrophication of methanol vehicle

As similar to other vehicles, methanol vehicle's highest values of eutrophication was calculated for operation and vehicle manufacturing process. The calculated eutrophication percentages for each phase are 47% and 31.7% respectively. Maintenance of vehicle, road and disposal phase all together have about 21% percent of total emissions as it can be observed in Figure 5.29. The process flow chart of all involved processes is illustrated in Figure 5.30. The hotspots in the product chain of methanol vehicle's eutrophication life cycle effects can be easily followed by thick red lines between processes. Methanol production from biomass and synthetic gas are a most notable contributing process. UCTE electricity production is another process needs to be watched closely and advancing with environmental measurement and improvement in the supply chain.

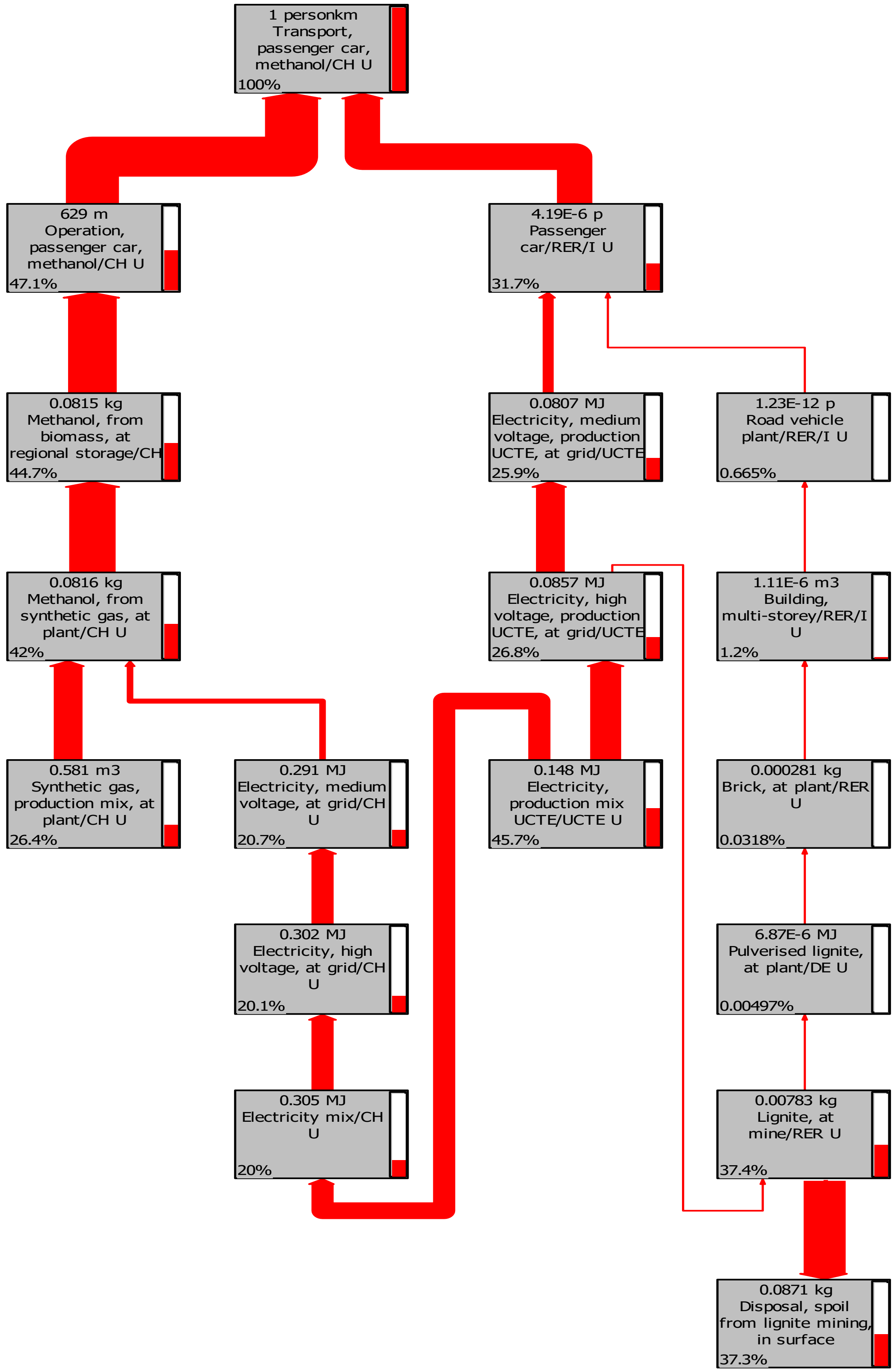

Figure 5.30 LCA process flow chart for Eutrophication of methanol vehicle.

5.4.4. Global Warming Potential (GWP)

Time horizon choice is important in global warming LCIA results. Generally, in LCA as in other carbon foot-printing approaches, the calculation is performed after the time horizon is selected. Time horizon lets decision makers assess the sensitivity of the calculated results. Table 5.17 shows GWP calculation for methane and CO_2.

Table 5.17 The global warming calculation for CH_4 and CO_2

GWP ($kgCO_2$-eq/km)	**20 years**	**100 years**	**500 years**
CO_2	1	1	1
Methane	72	25	7.6

In global warming category with 100 years' time horizon, highest impacts obtained from both gasoline vehicles followed by ethanol, natural gas, hybrid (LNG and electric), diesel, methane, hydrogen, methanol, electric as shown in Figure 5.31. Based on the observation from LCIA results conventional fueled vehicles are worst in global warming as they burn fossil fuels, which is the key human sources of greenhouse gas emissions. To mitigate global warming use of alternative fueled vehicles should be encouraged.

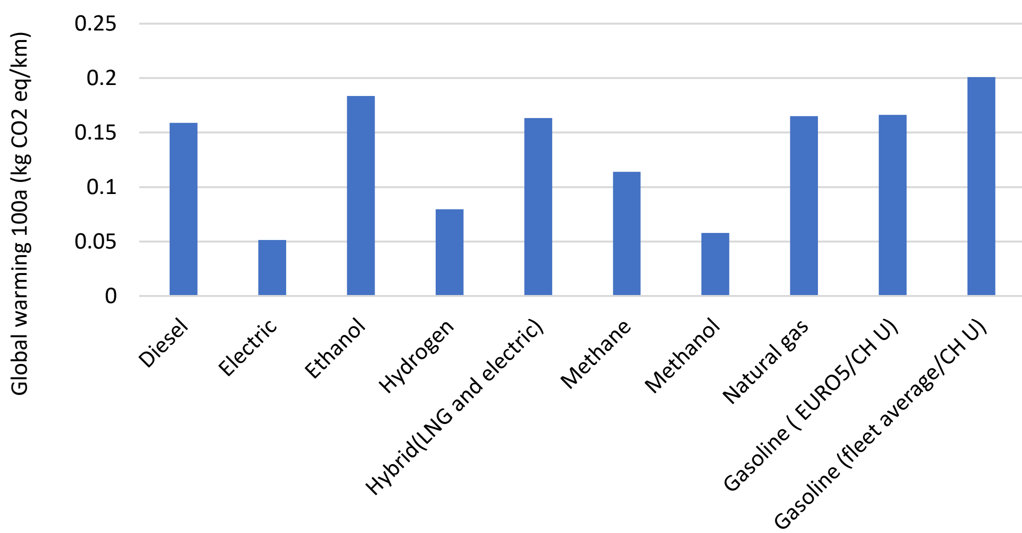

Figure 5.31 Impact assessment results comparison for various vehicle technologies on global warming per 1 km traveled.

The GWP of the selected passenger cars is comparatively illustrated in Figure 5.31. The minimum GHG emissions are calculated for electric vehicle corresponding to 0.051

kg CO_2 eq/km. If electricity generation can be switched with sustainable and renewable sources, overall emissions would reduce for EVs. Methanol vehicles GHG values are very close with an electric vehicle, which corresponding to 0.057 kg CO2 eq/km.

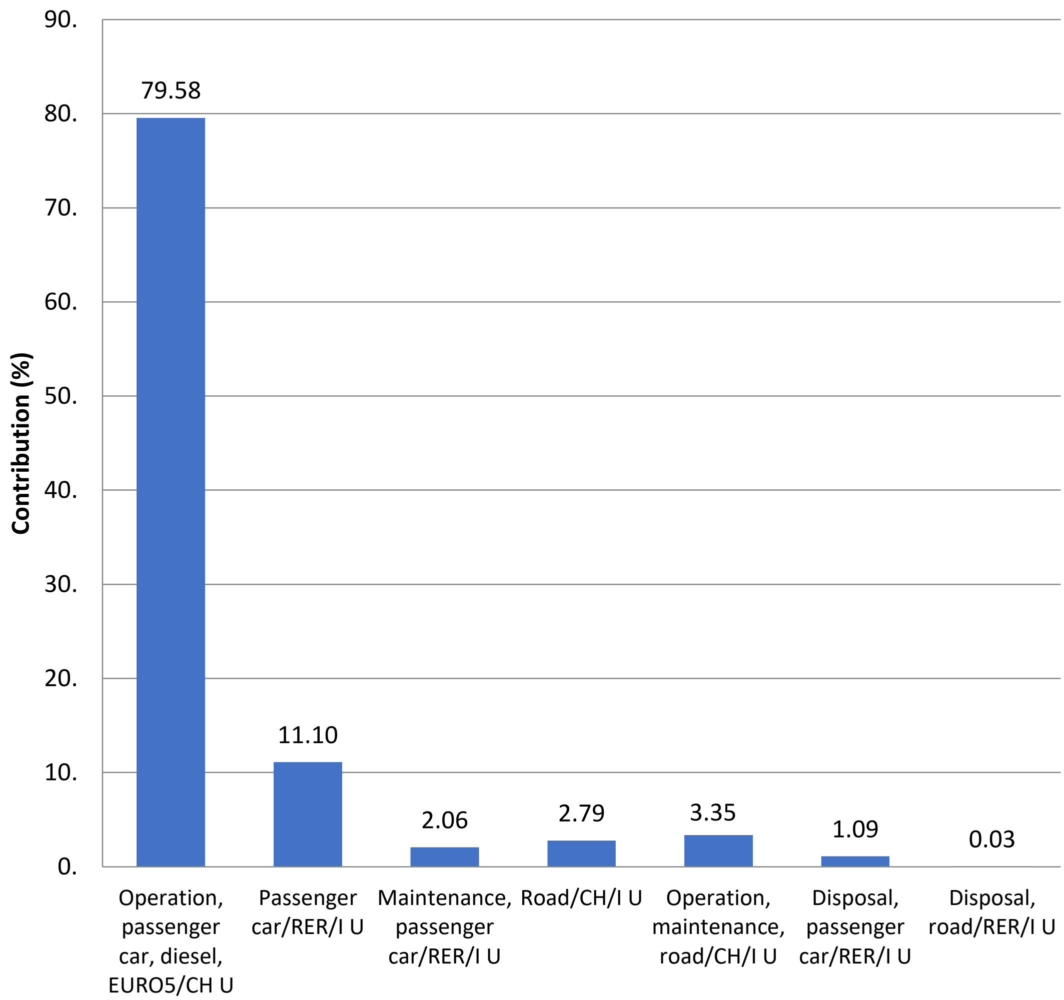

Figure 5.32 Contributions of various LCA processes to Global Warming (100a) of Diesel vehicle

Figure 5.32 and Figure 5.33 represents GHG emissions of selected diesel vehicle based on 100 years time horizon. A great amount of emissions is emitted during operation of vehicle, which corresponds to 79.6 % of total emitted GHGs. Vehicle manufacturing stage represents 11% of total GHG. Diesel fuel consumption is the most notable hotspot in the process contribution due to CO_2 emissions during fuel use.

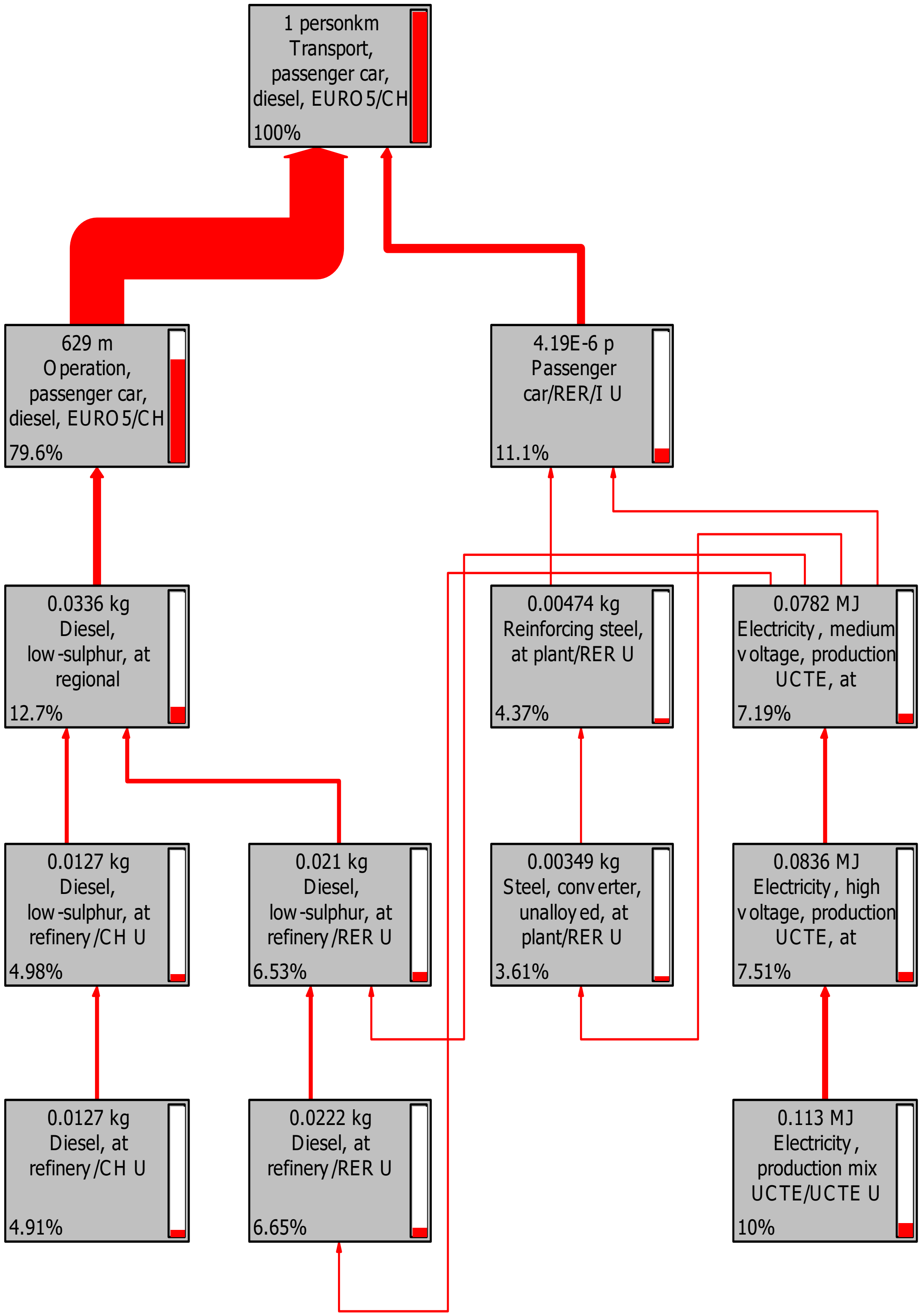

Figure 5.33 LCA process flow chart for Global Warming (100a) of diesel vehicle (cut off-%3.5)

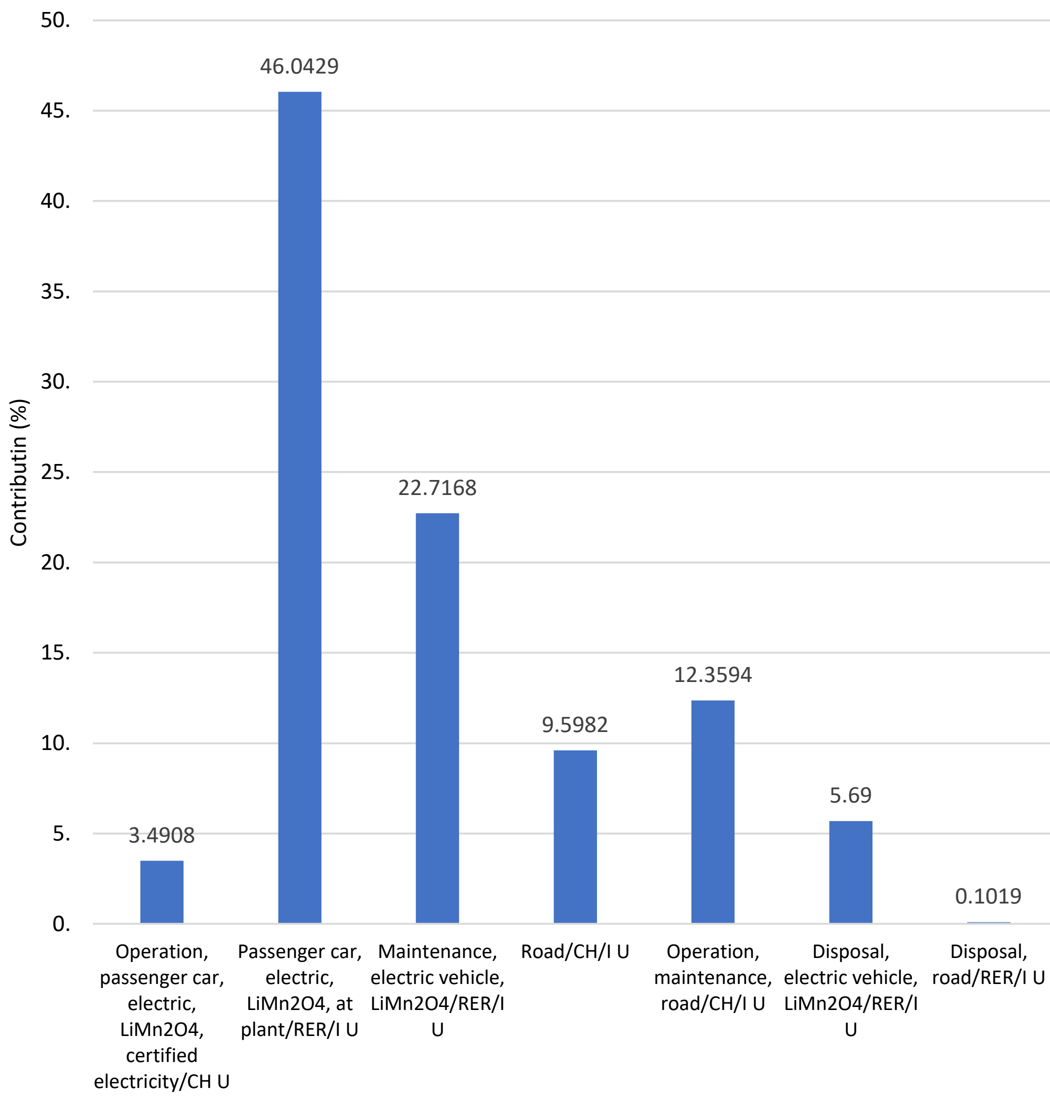

Figure 5.34 Contributions of various LCA processes to Global Warming (100a) of the electric car.

Figure 5.34 represents the LCIA global warming results of the electric vehicle based on accounted stages for the LCA. The electric car has very low GHGs impact during vehicle operation stage as compared with all other vehicles. Only 3.5 % of total emissions is emitted by vehicle use stage, which means the electric car is the greenest option in all other cars. Figure 5.35 shows contributions between all processes involved in the life cycle of EV for global warming potential. As observed vehicle manufacturing shares correspond to 46 % all emissions and 22% comes from maintenance of the vehicle. Electricity is used during the battery production and assembly of the vehicle is the main factor for CO_2 emissions.

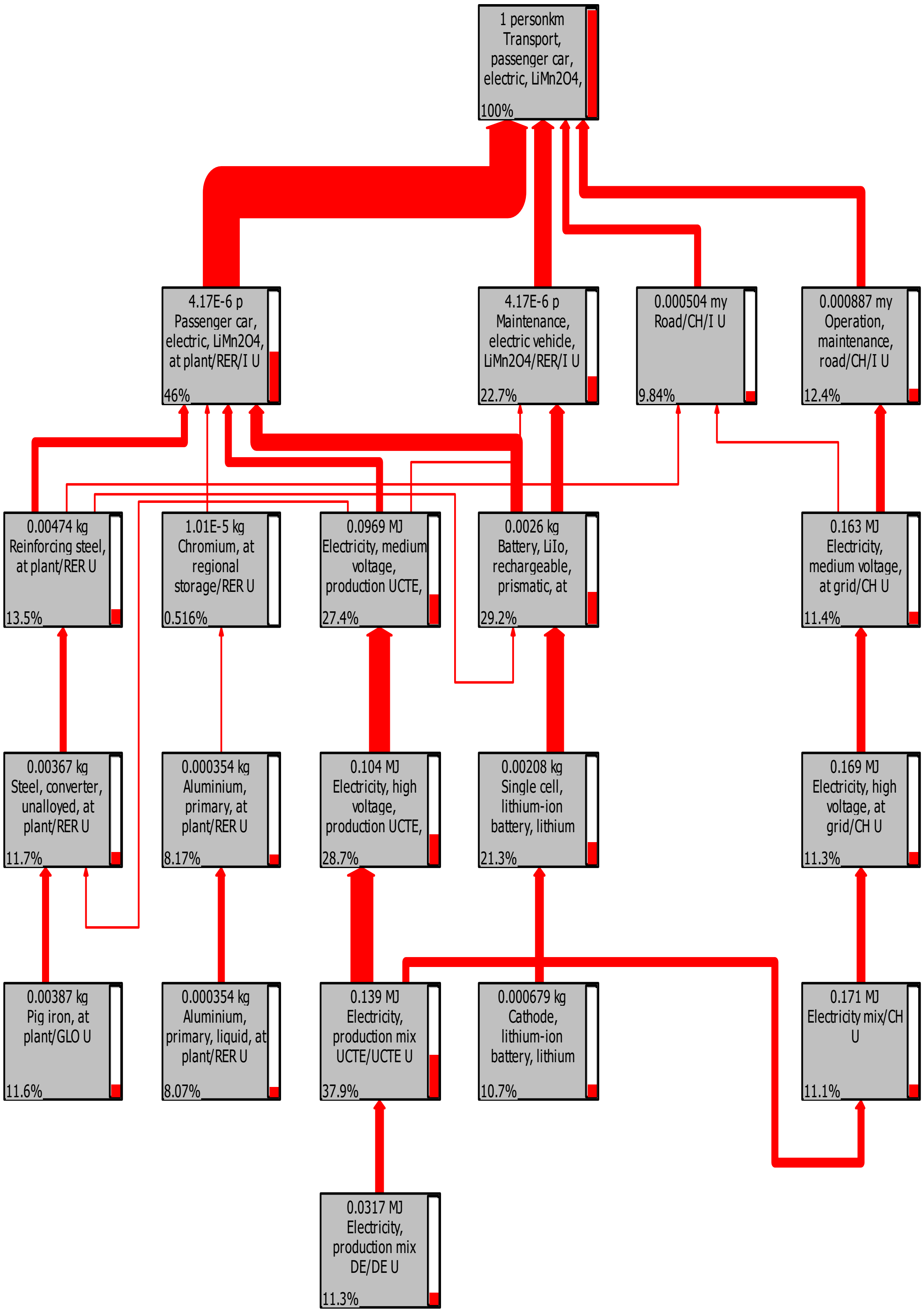

Figure 5.35 LCA process flow chart for Global Warming (100a) of electric vehicle (cut off-6.3%)

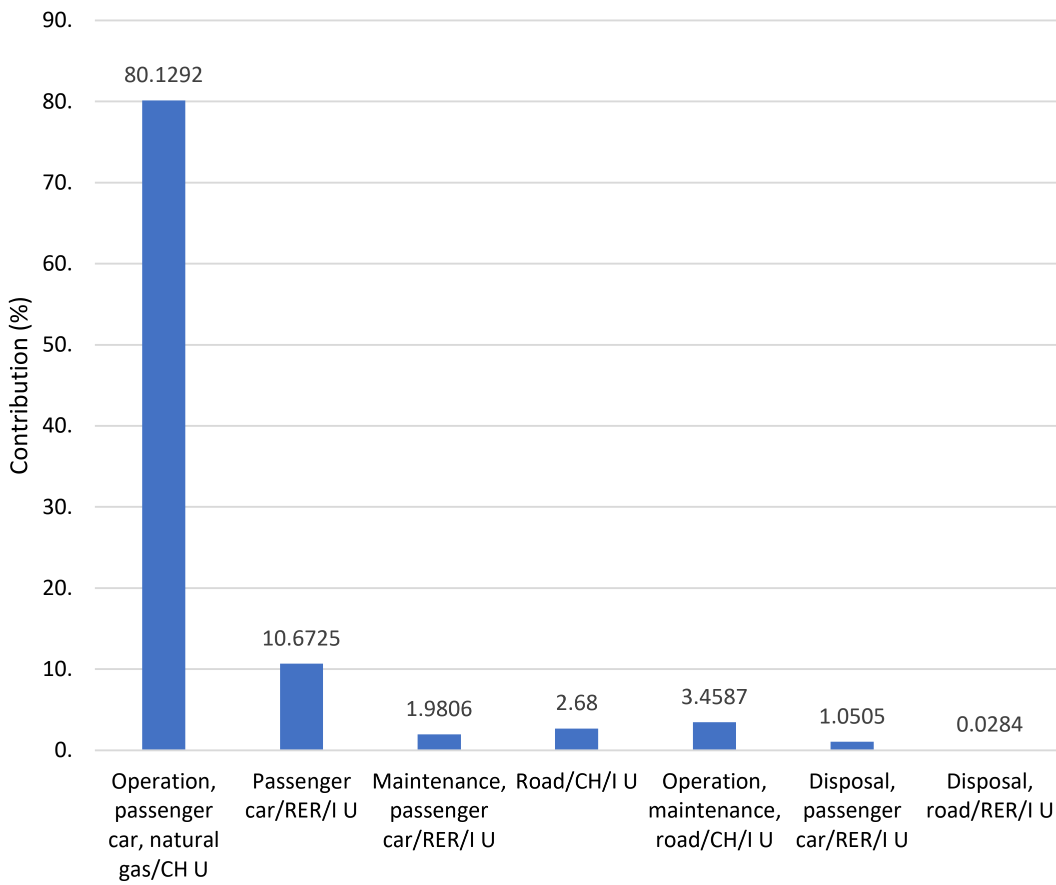

Figure 5.36 Contributions of various LCA processes to global warming (100a) of natural gas.

Figure 5.36 shows total global warming impact of the natural gas vehicle. Operation phase has a huge global warming effect on the environment with over 80 % of all GHG emission are emitted by this phase itself, while only 10.6 % of emission is attributed to vehicle manufacturing stage. All other stages together have about 9 % total emissions. Figure 5.37 shows a network of all processes together. Each box represents a process. The arrows present the flows between the processes. The red bar charts (or thermometers) indicate the environmental load generated in each process and its upstream processes. As we can see here, the most important process is the operation of the natural gas vehicle. Natural gas fuel consumption in the vehicle and natural gas production at service station has a considerable GHG effect. Storing natural gas under high pressure and transportation of natural gas via pipelines from a long distance have a notable global warming effect as well. Natural gas burned in a gas turbine for the compressor has a considerable flow to fuel production process as well.

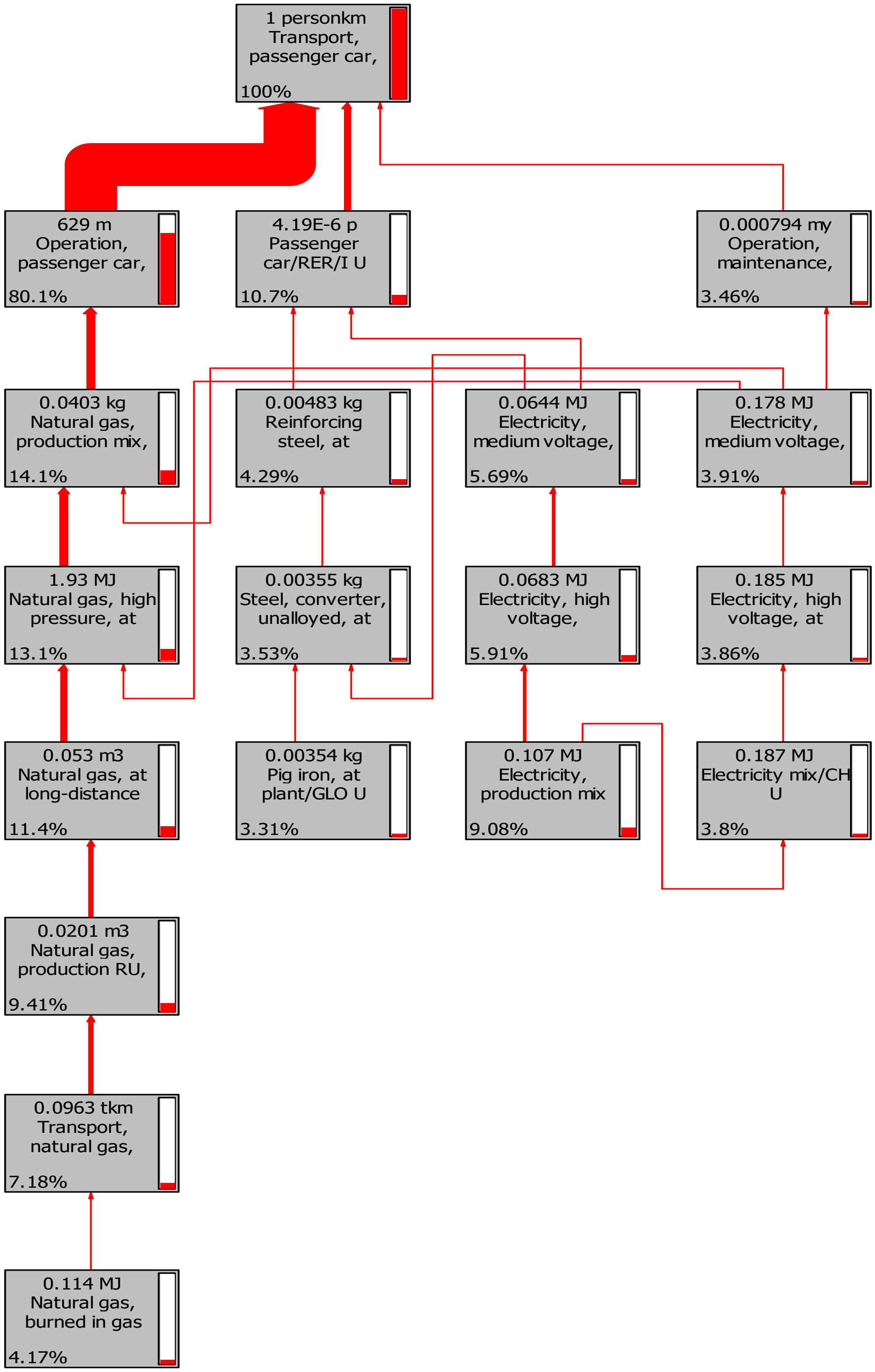

Figure 5.37 LCA process flow chart for global warming (100a) of natural gas (cut off-3%)

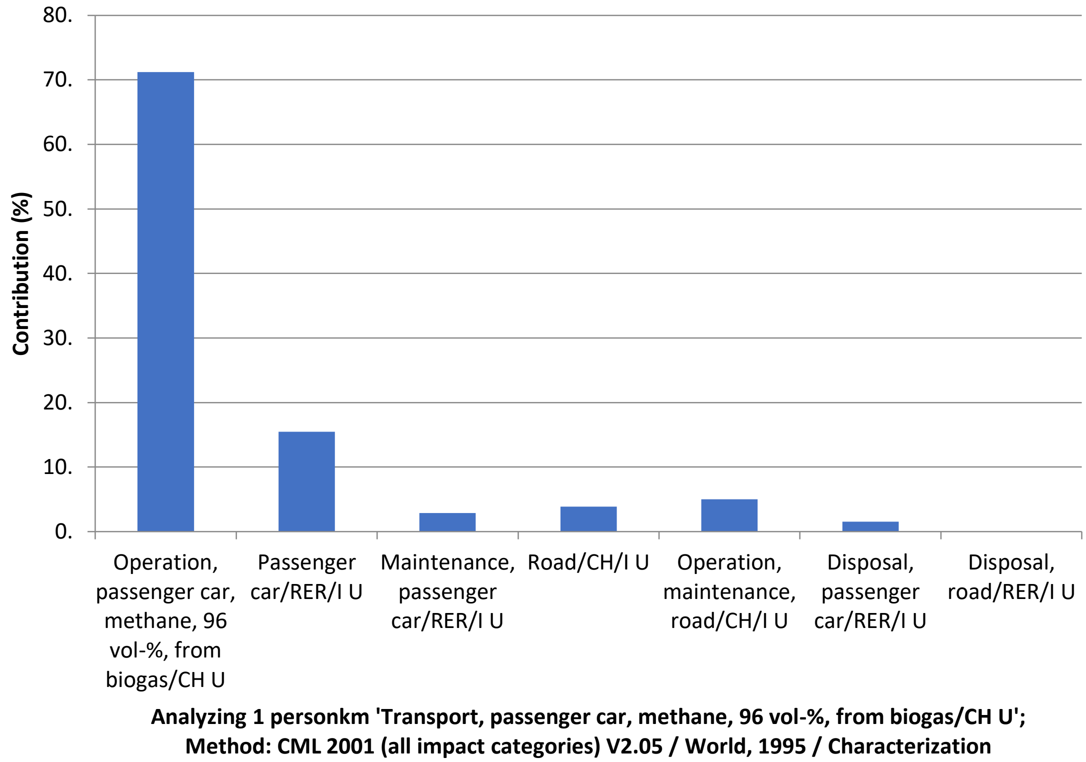

Figure 5.38 Contributions of various LCA processes to global warming (100a) of methane vehicle.

Figure 5.38 shows total global warming impact of methane vehicle. Similarly, with the natural gas vehicle, operation phase has a huge global warming effect on the environment with over 71.2 % of all GHG emission are emitted by this phase itself, while only 15.5 % of emission is attributed to vehicle manufacturing stage. All other stages together have about 13.5 % total emissions. Figure 5.39 shows a network of all processes together. Each box represents a process. The arrows present the flows between the processes. The red bar charts (or thermometers) indicate the environmental load generated in each process and its upstream processes. As we can see here, the most important process is the operation of methane gas vehicle. Methane fuel consumption in the vehicle and methane production from biogas has a considerable GHG effect. Storing biogas, biogas from biowaste, biogas from sewage sludge and its storage, natural gas at boiler condensing and natural gas burned in boiler condensing have a notable global warming effect. Electricity usage in the production of the vehicle has an important flow to total life cycle emissions.

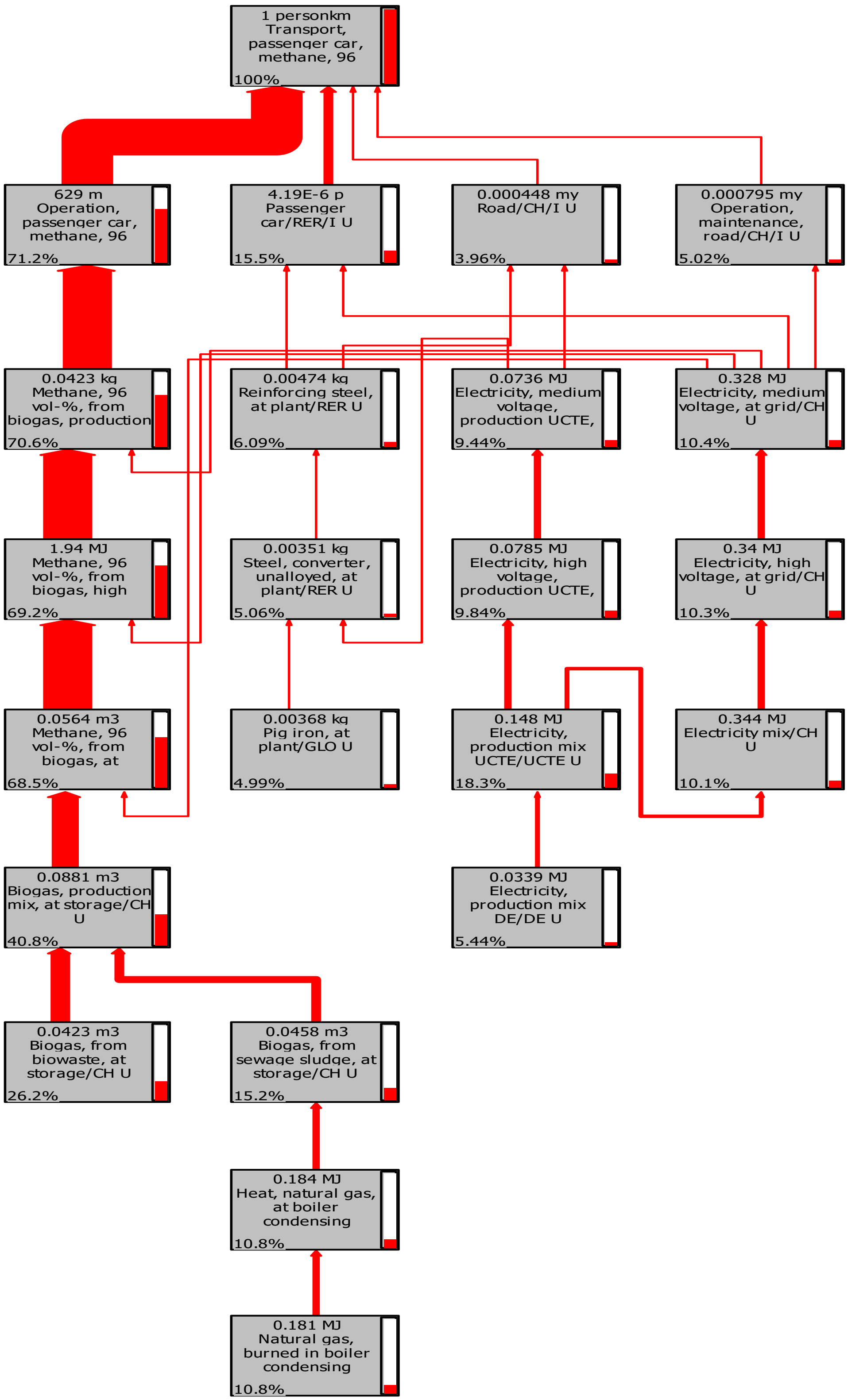

Figure 5.39 LCA process flow chart for global warming (100a) of methane vehicle (cut off-3%)

5.4.5. Ozone Layer Depletion Potential

Ozone layer depletion is one of the key contributors to climate change globally. As seen in Figure 5.40, the natural gas vehicle has the maximum ozone layer depletion effect since it is produced by fossil-based resources, which have a huge amount of carbon element. In ozone layer depletion category with 40 years' time horizon, best-performing cars are hybrid, and hydrogen vehicles, emissions they produced per km is respectively 4.74E-10 kg CFC-11 eq/km, 8.14E-10 kg CFC-11 eq/km. On the other hand, natural gas and gasoline vehicles have the highest effect to this category.

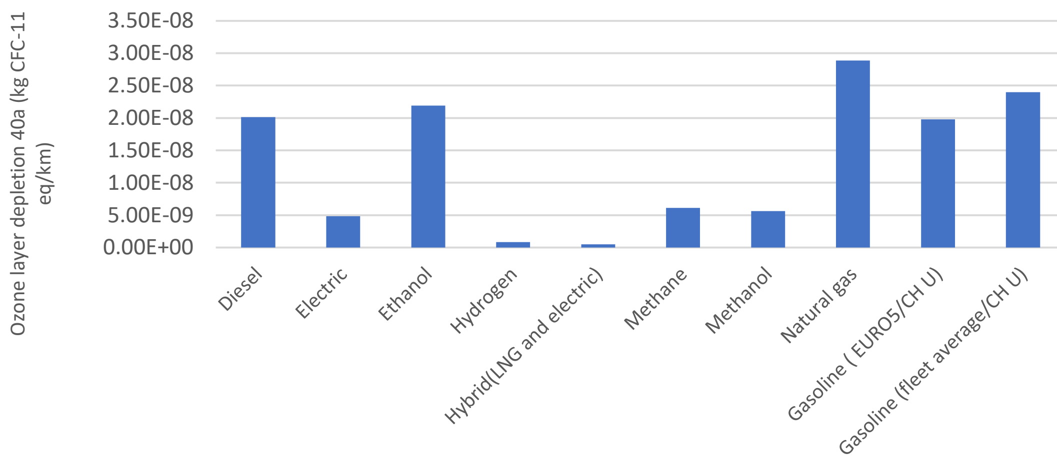

Figure 5.40 Impact assessment results comparison for various vehicle technologies on ozone layer depletion per 1 km traveled.

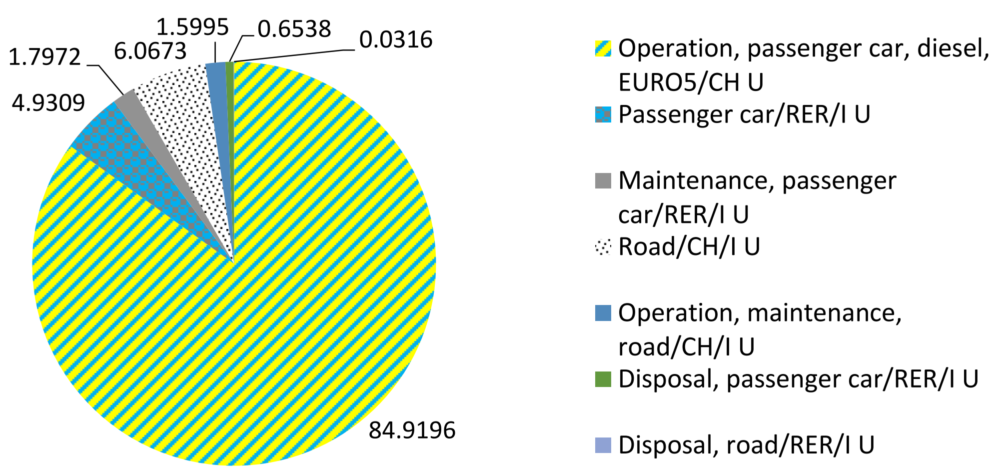

Figure 5.41 Contributions of various LCA processes to ozone layer depletion (40a) of a diesel vehicle.

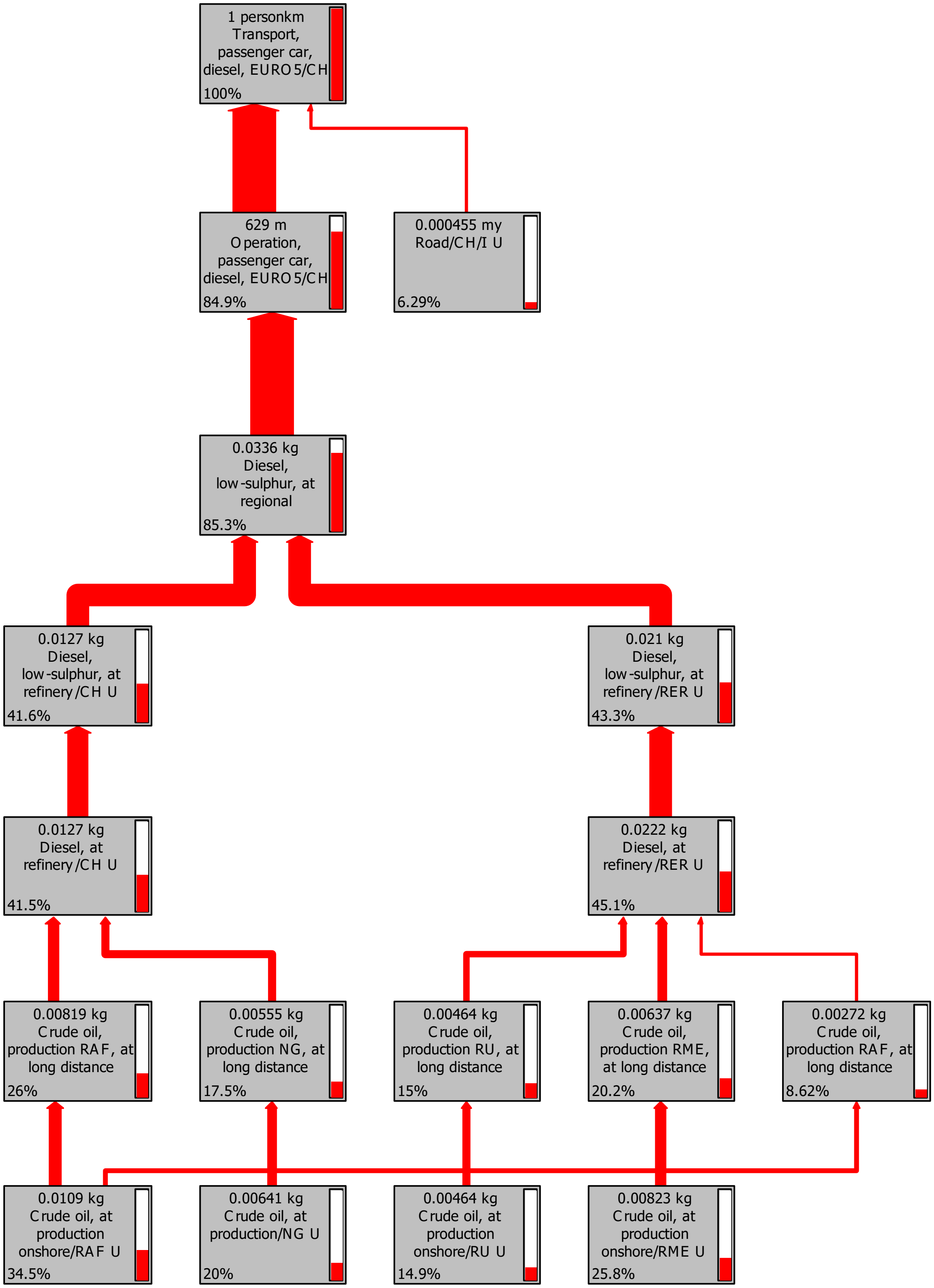

Figure 5.42 LCA process flow chart for ozone layer depletion of diesel vehicle (cut off- 5%)

Figure 5.41 shows total ozone layer depletion impact of the diesel vehicle. Operation phase has enormous ozone layer depletion effect on the environment with about 85 % of all emission are emitted by this phase itself, while only 15 % of total emissions are attributed to all other phases. Figure 5.42 shows a network of all processes together. Each box represents a process effects the ozone layer depletion category. As we can see here, the most important process is the operation of the diesel vehicle. Diesel fuel consumption in the vehicle and low-sulfur diesel production at the refinery has a most important flow to this category. Crude oil production and its transportation to consumer site have remarkable effects on ozone layer depletion category.

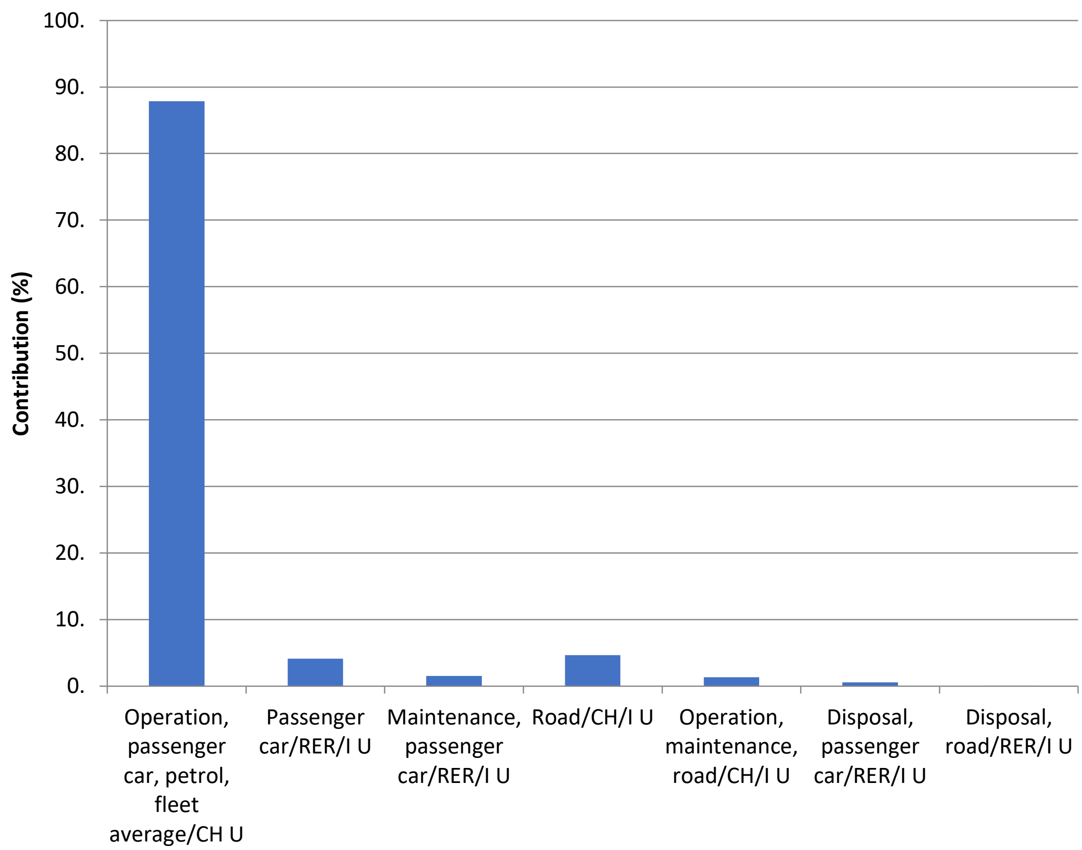

Figure 5.43 Contributions of various LCA processes to Ozone Layer Depletion (40a) of gasoline vehicle (fleet average)

Gasoline is most widely used fuels in small passenger vehicles. Figure 5.43 shows total ozone layer depletion impact of the gasoline vehicle. Similar to diesel vehicle, operation phase of gasoline has enormous ozone layer depletion effect on the environment with about 88 % of all emission are emitted by this phase itself, while only 12 % of total emissions are attributed to all other phases. Conventional fueled vehicles have an enormous environmental load on the environment in operation phase of vehicle life cycle. Figure 5.44 shows a network of all processes together. Each gray box represents a process effects the ozone layer depletion category. As it can be seen here, the most important process is the operation of the gasoline vehicle. Gasoline fuel consumption in the vehicle and low-sulfur gasoline production at the refinery has a most important flow to this category. Crude oil production and its transportation to consumer site have remarkable effects on ozone layer depletion category.

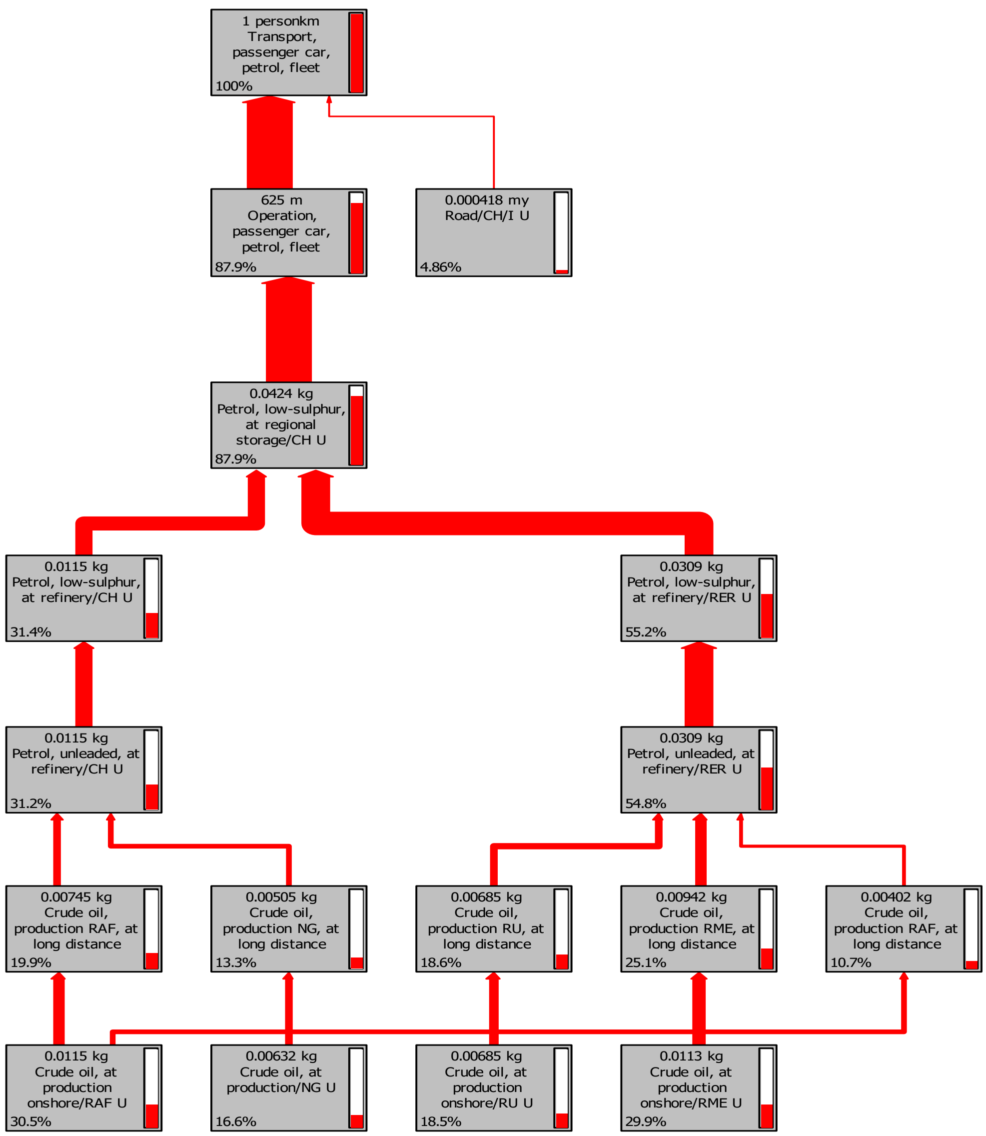

Figure 5.44 LCA process flow chart for Ozone Layer Depletion (40a) of gasoline vehicle (cut off-%4.5)

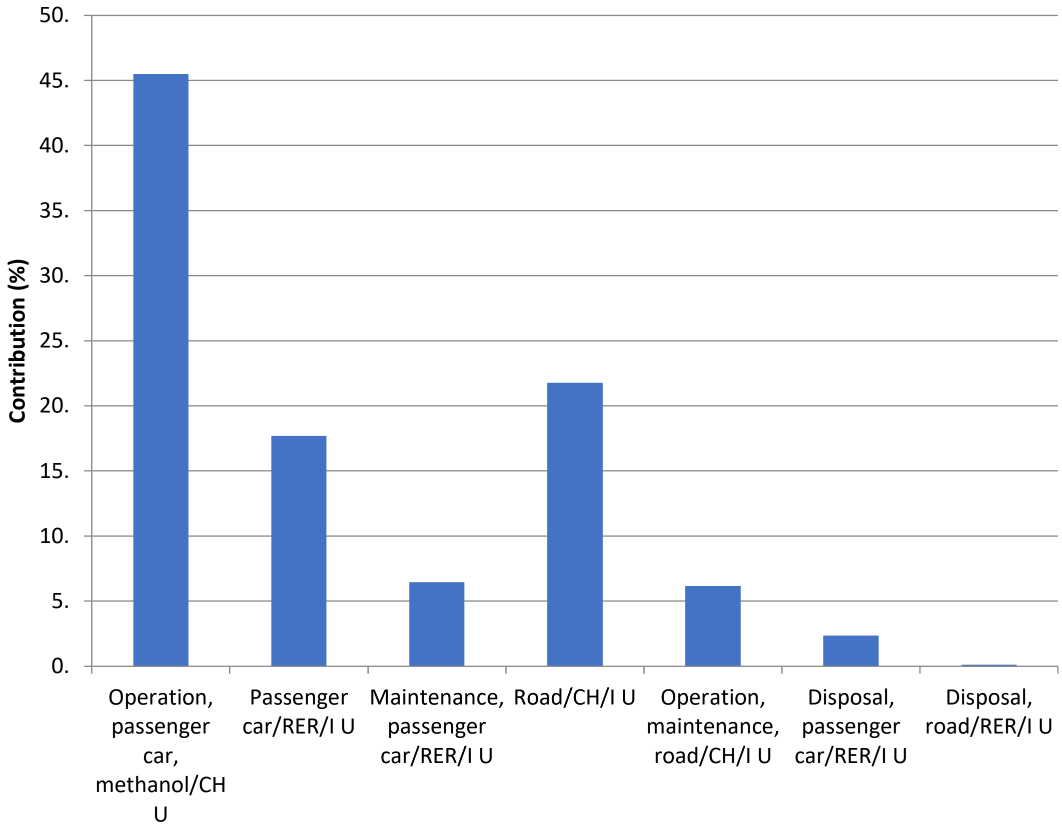

Figure 5.45 Contributions of various LCA processes to Ozone Layer Depletion (40a) of methanol vehicle

Methanol is a clear liquid chemical that can solve in water and considered eco-friendly. Methanol is consisting of four parts H, one-part O and one-part C. Methanol is generally produced using natural gas as the main feedstock.

Figure 5.45 shows total ozone layer depletion impact of a methanol vehicle. Operation phase of methanol has the largest ozone layer depletion effect on the environment with about 45.5 % of all emission is emitted by this phase, while 21.7 % of total emissions are attributed to the construction of roads and 17.6% to the manufacturing of passenger vehicle. Figure 5.46 shows a network of all processes together. Each gray box represents a process effects the ozone layer depletion category. As it can be seen here, the most important process is the operation of methanol vehicle. Methanol fuel consumption in the vehicle, methanol production from biomass and synthetic gas, and synthetic gas from wood at fluidized bed gasifier are important processes has a large load in operation phase. Road construction has a large impact due to use of bitumen, bitumen production at the refinery and crude oil production has remarkable effects too. Transportation of crude oil has an important flow to the category as well.

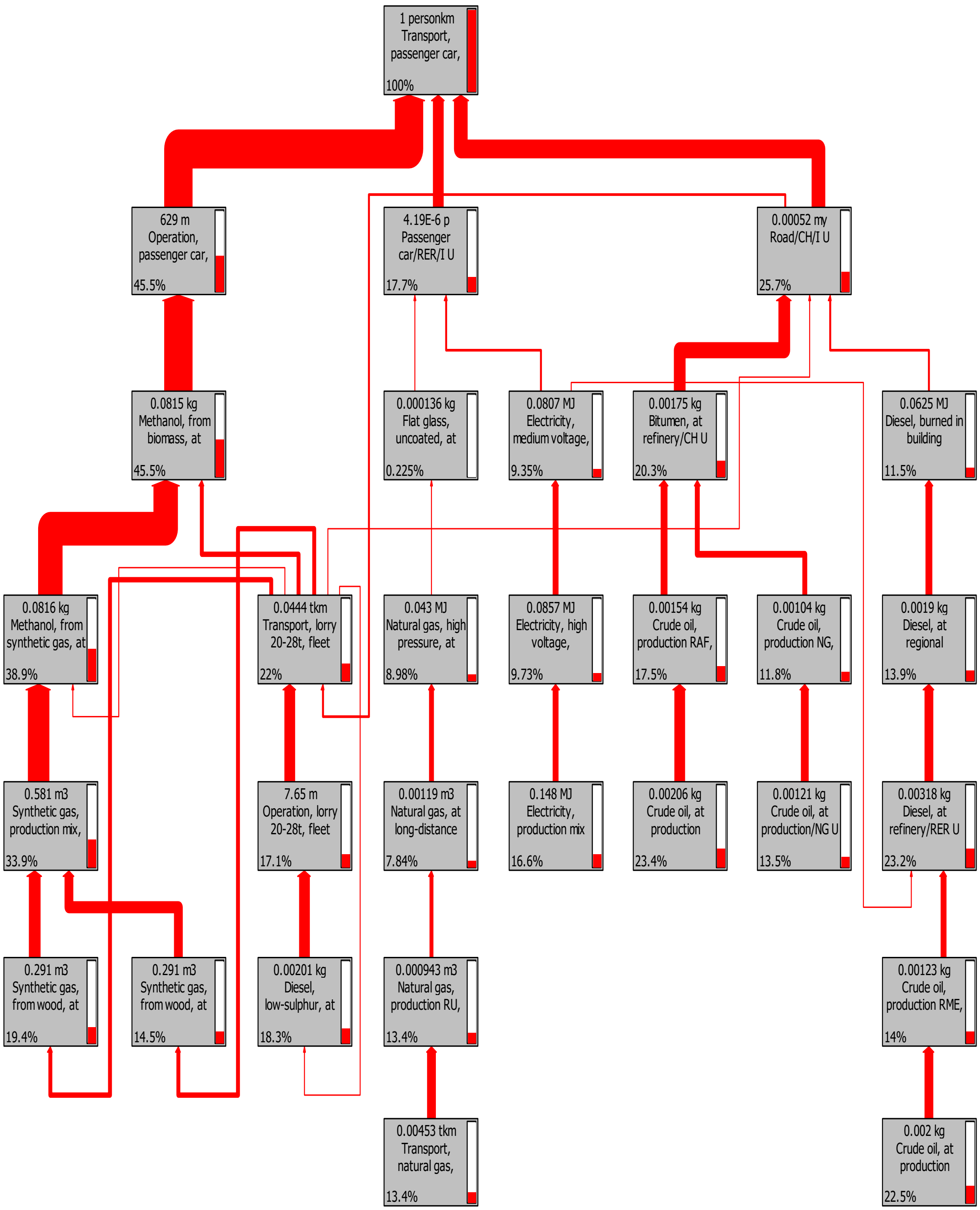

Figure 5.46 LCA process flow chart for Ozone Layer Depletion (40a) of gasoline vehicle (cut off-%13)

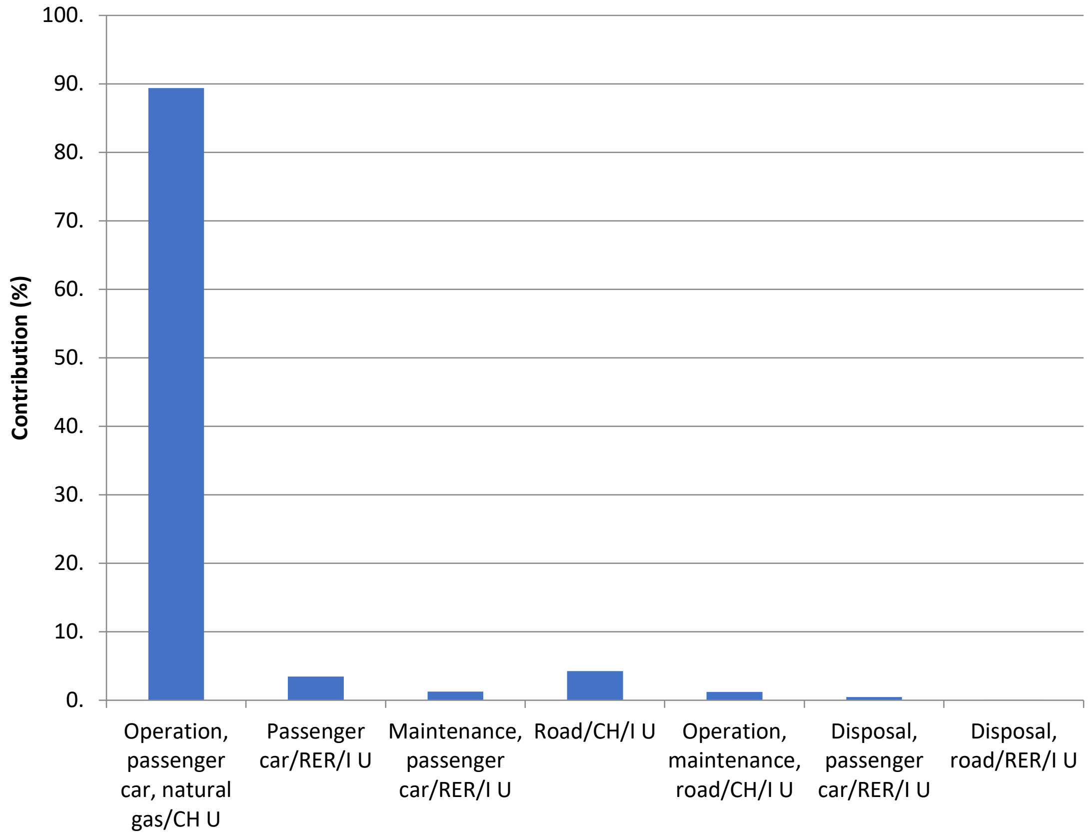

Figure 5.47 Contributions of various LCA processes to ozone layer depletion of natural gas vehicle

Natural gas is one of the most widely used fuel worldwide, and it is being used in vehicles as well. Figure 5.47 shows total ozone layer depletion impact of the natural gas vehicle. Similar to gasoline and diesel vehicles, operation phase of gasoline has vast ozone layer depletion effect on the environment with about 89.3 % of all emission are emitted by this phase itself, while only 10.7 % of total emissions are attributed to all other phases. Figure 5.48 shows a network of all processes in the natural gas vehicle together. Each gray box represents a process effects to the ozone layer depletion category. As it is observed in the Figure 5.48, the most important process is the operation of the natural gas vehicle. Natural gas fuel use in the vehicle and natural gas production mix at a service station, high pressured natural gas at the consumer site, and transportation of natural gas via pipelines from long distance has a most important flow to this category. Natural gas vehicle operation is one of the largest contributors to ozone layer depletion category in this LCA.

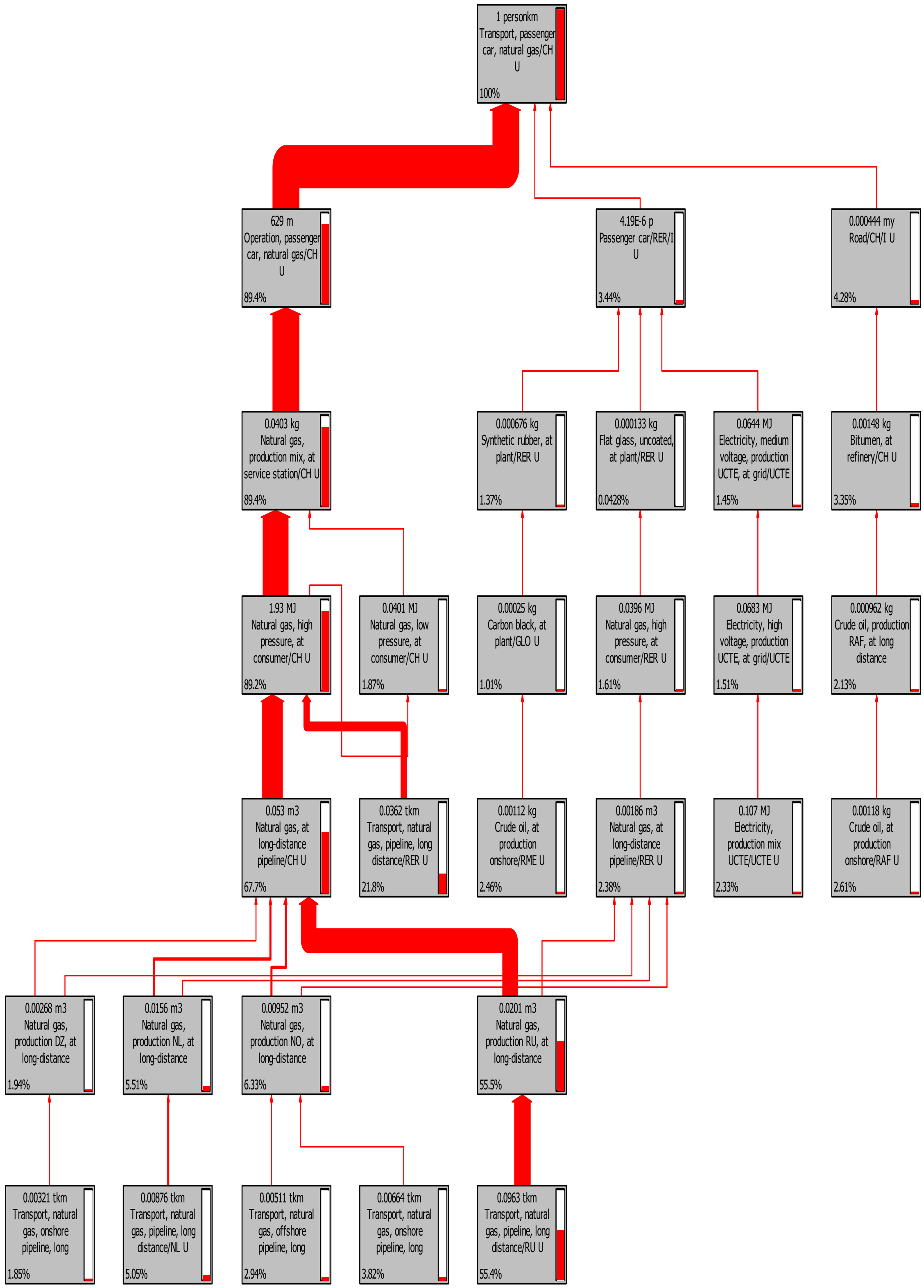

Figure 5.48 LCA process flow chart for Ozone Layer Depletion (40a) of the natural gas vehicle (cut off- %1.8)

5.4.6. Human Toxicity Potential

The human toxicity potential (HTP) is a calculated index that reveals the potential damage of a chemical unit released to the environment; it is based on the natural toxicity of both the compound and the potential dose.

As illustrated in Figure 5.49 in human toxicity category, electric car contributes significantly due to the emissions from the manufacture of batteries in the course of the vehicle production stage, which represent an important share of the environmental impacts in electric car manufacturing. Gasoline vehicles are second poor performing cars in this category. Most environmentally friendly car in his category is hydrogen vehicle

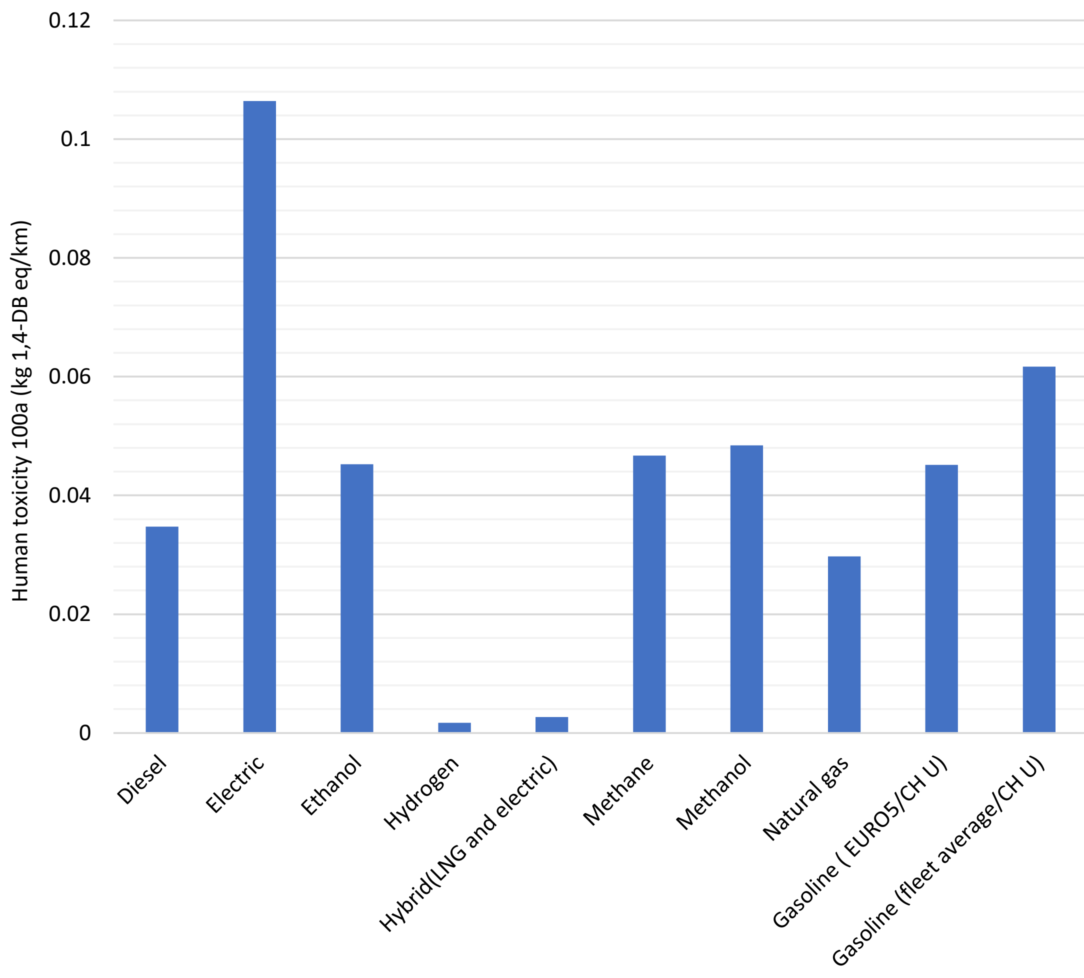

Figure 5.49. Impact assessment results comparison for various vehicle technologies on human toxicity per 1 km traveled for 100-years time horizon

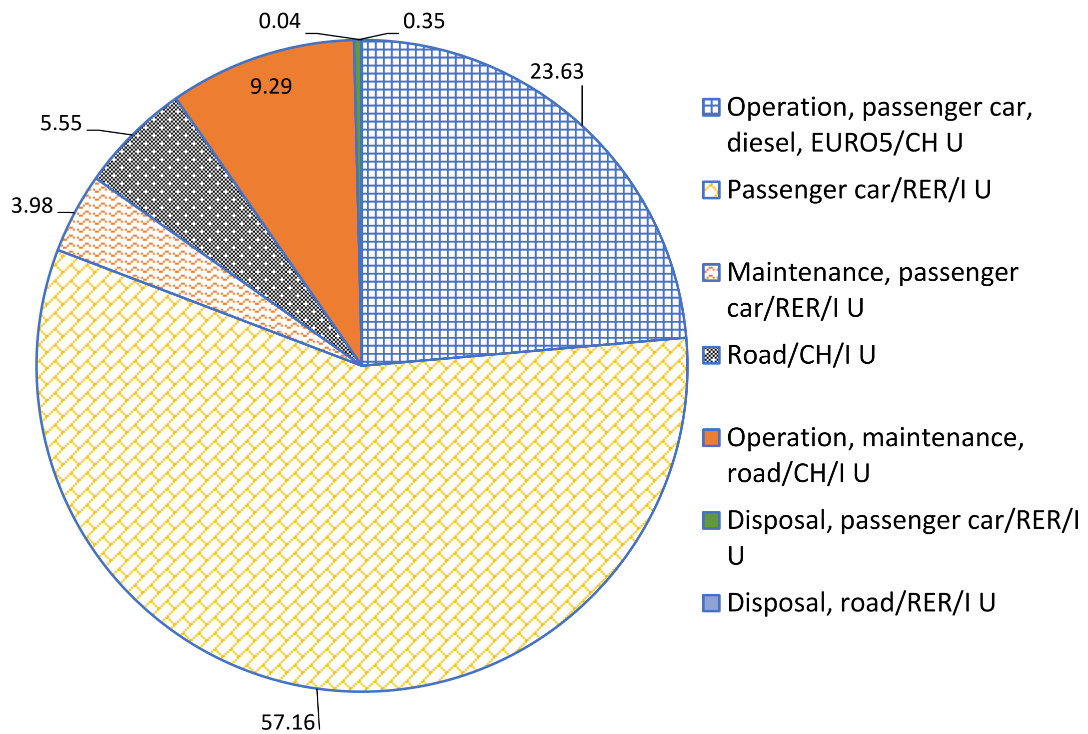

Figure 5.50 Contributions of various LCA processes to Human Toxicity (100a) of Diesel vehicle

Figure 5.50 shows the total human toxicity impact of the diesel vehicle. Manufacturing phase has high human toxicity effects, which is 57 % of all emission are emitted by this phase itself, while only 23.6 % of total emissions are attributed to vehicle operation stage. It is interesting that operation phase has lower impact than manufacturing phase. Figure 5.51 shows a network of all processes together. Each box represents a process effects the ozone layer depletion category. As we can see here, the most important process is the manufacturing diesel vehicle. Aluminum needed for the production of the vehicle has a big load. Also, copper and steel needed for manufacturing have notable effects. Ferrochromium high carbon, 68% Cr at the plant has a notable flow to steel production stage.

Figure 5.52 shows the total human toxicity impact shares of an electric vehicle. Manufacturing phase has high human toxicity effects, which is 50 % of all emission are emitted by this phase, while 32.8 % of total emissions are attributed to vehicle maintenance stage. Moreover, operational impact of the vehicle is only 11 %. It is interesting that operation phase has a much lower impact than manufacturing phase.

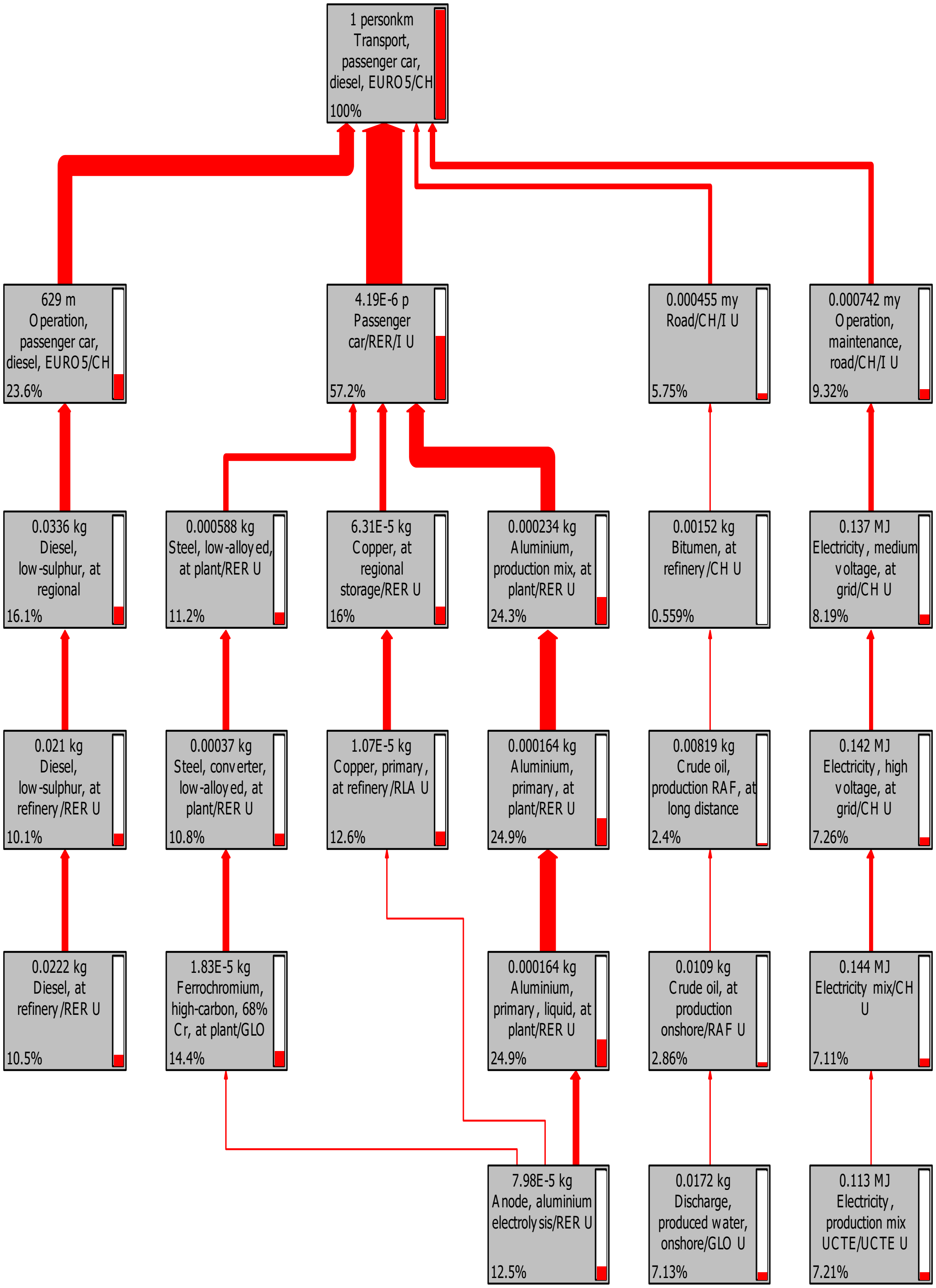

Figure 5.51 LCA process flow chart for Human Toxicity (100a) of Diesel vehicle (cut off- %7)

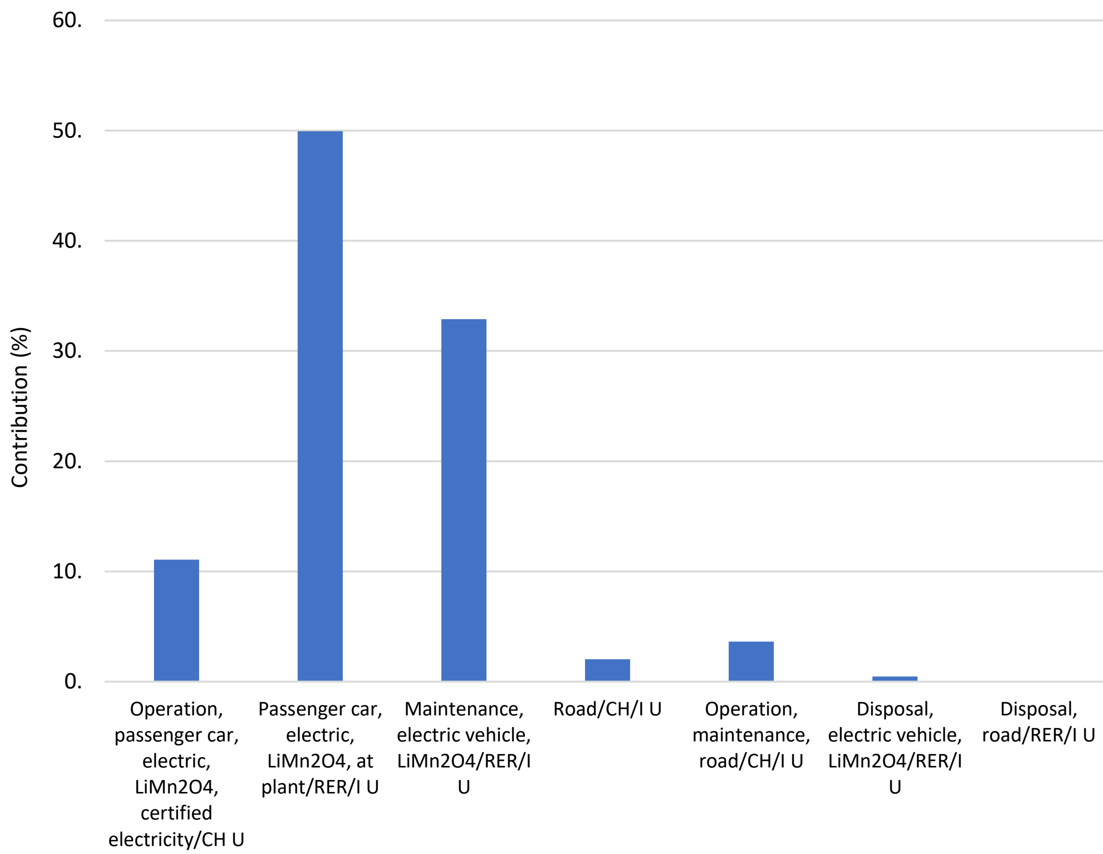

Figure 5.52 Contributions of various LCA processes to Human Toxicity (100a) of electric vehicle(EV)

Figure 5.53 shows a network of all processes together. Each box represents a process effects the ozone layer depletion category. As we can see here, the most significant process is the manufacturing of electric vehicle due to vehicle assembly. Also, notable impact flow comes from electric vehicle components manufacturing, such as electric motor production, LiIo battery production, chromium production, single cell lithium ion battery production, anode lithium-ion production and copper needed for the manufacturing process. The emission emitted at operation stage of the vehicle comes from electricity use for battery recharging. A change in the supply chain of manufacturing and electricity generation will make EVs greener cars. Figure 5.54 shows total human toxicity impact shares of a methanol vehicle. Operation phase of methanol has largest human toxicity effect with 44.7 % shares of all emission emitted by this phase, while 41 % of total emissions are attributed to vehicle manufacturing stage. Operation and maintenance of road have 7.1 % impact on human toxicity.

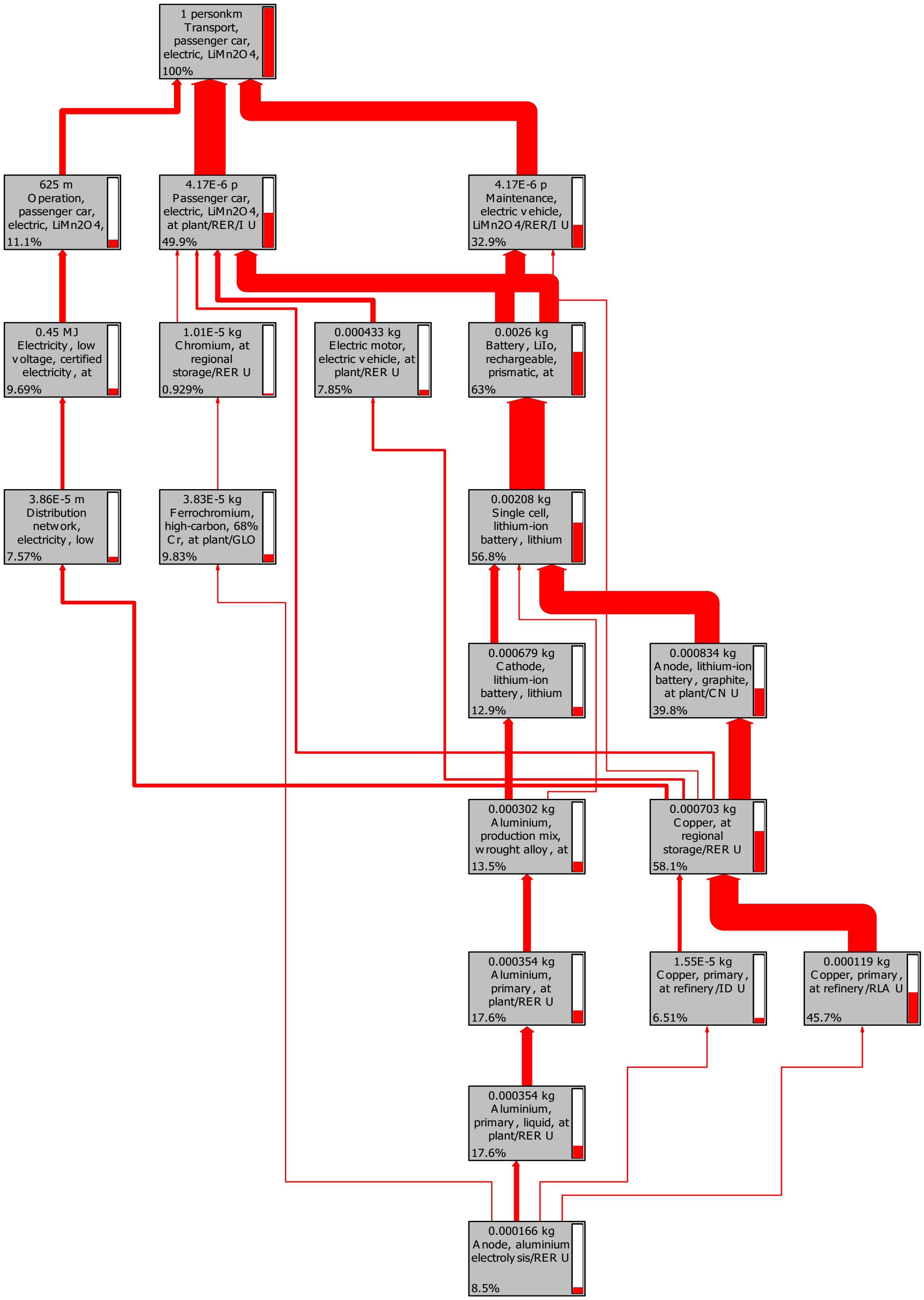

Figure 5.53 LCA process flow chart for human toxicity (100a) of electric vehicle (cut off- %6.5)

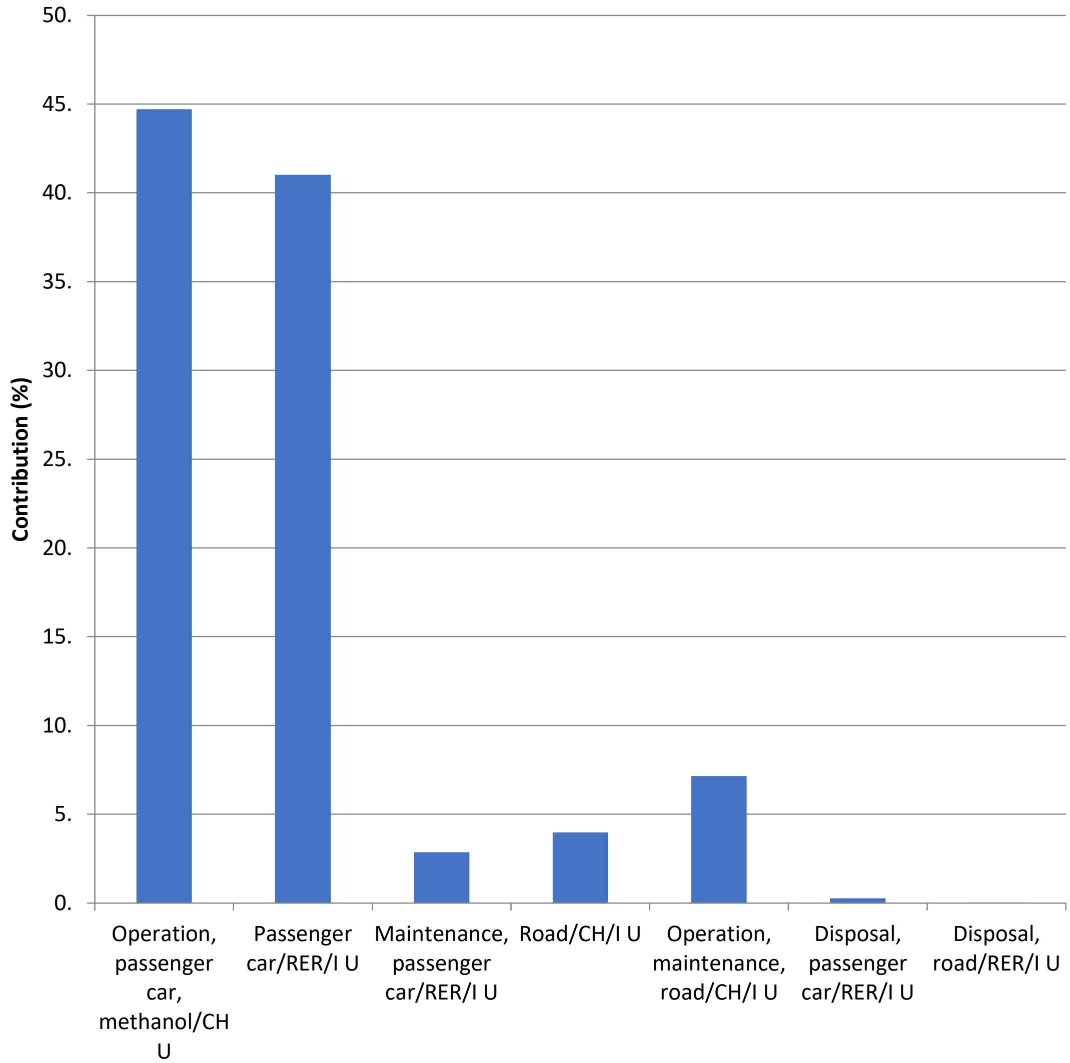

Figure 5.54 Contributions of various LCA processes to human toxicity (100a) of methanol vehicle

Figure 5.55 shows a network of all processes together. Each gray box represents a process effects the ozone layer depletion category. As it is shown here, the most important process is the operation of methanol vehicle. Methanol fuel consumption in the vehicle, methanol production from biomass and synthetic gas, and synthetic gas from wood at fluidized bed gasifier are important processes has a large load on operation phase. At vehicle manufacturing phase, aluminum, copper, and steel production has contribution especially aluminum production and use has a large flow to this phase. Operation and maintenance of roads have a large impact due to use of bitumen and bitumen production at the refinery.

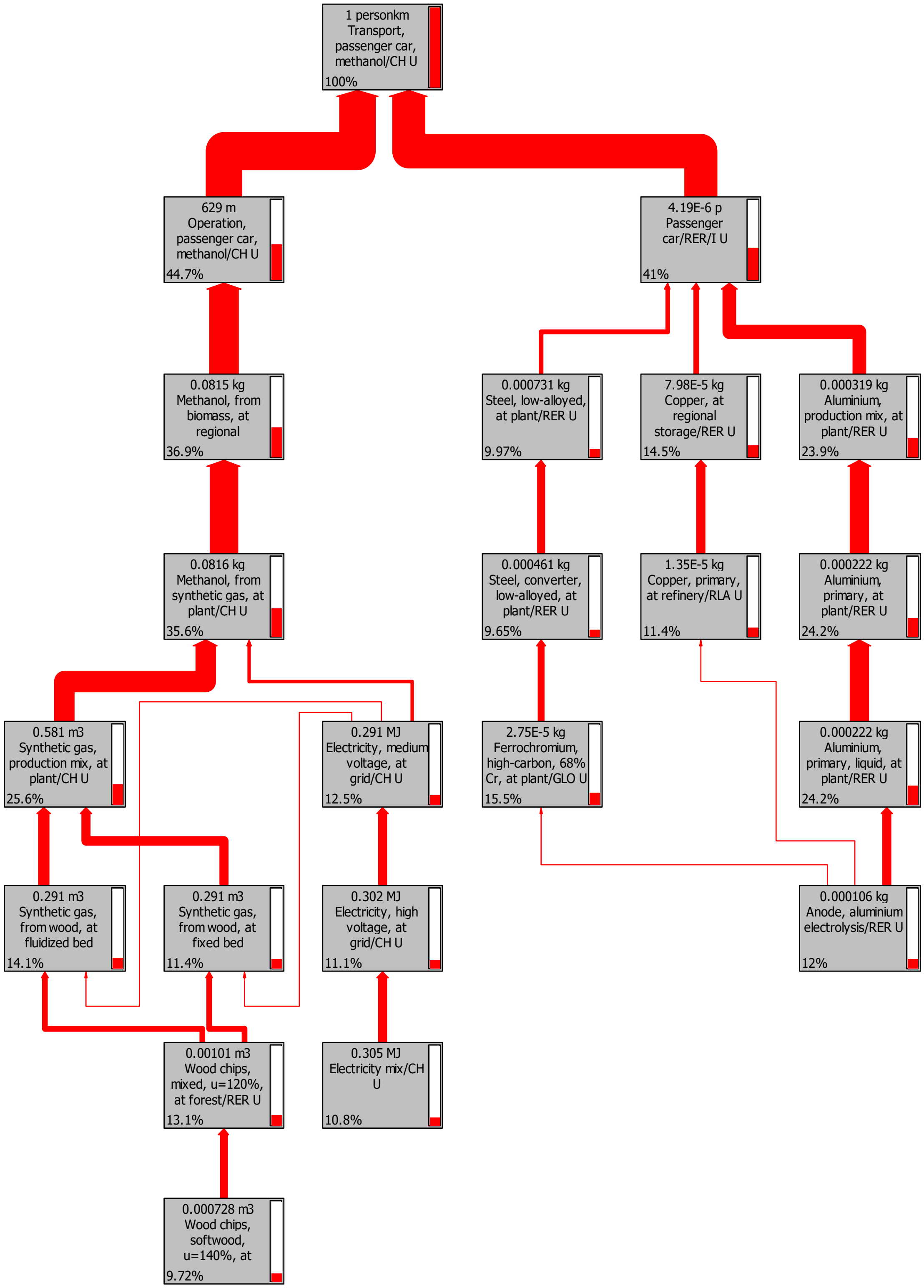

Figure 5.55 LCA process flow chart for human toxicity (100a) of methanol vehicle (cut off- %9)

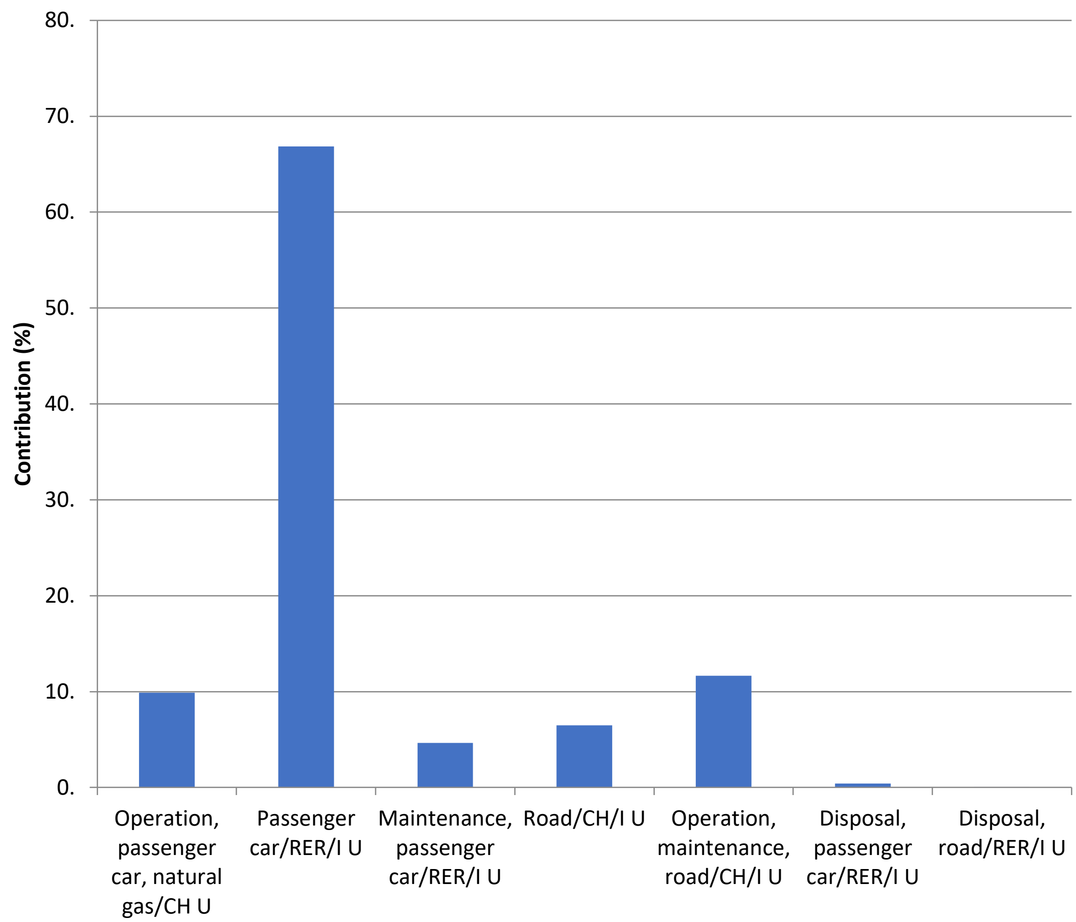

Figure 5.56 Contributions of various LCA processes to human toxicity (100a) of natural gas vehicle

Figure 5.56 shows total human toxicity impact of the natural gas vehicle. Vehicle manufacturing has about 66.8 % share of all emission were emitted, while 11.6 % of total emissions belong to operation and maintenance of roads. Vehicle operation's human toxicity has only 9.8 shares of total impacts. Figure 5.57 shows a network of all processes in a natural gas vehicle together. Each gray box represents a process effects to the ozone layer depletion category. As it is observed in the Figure 5.57, the most important process is the manufacturing of the natural gas vehicle. The manufacturing emission flow comes from aluminum production mix at the plant, steel, low-alloyed at the plant, copper use at regional storage and copper use at the refinery, especially aluminum primary at the plant has high human toxicity effects. The cause of human toxicity at operation and maintenance of roads phase is electricity consumption during the process.

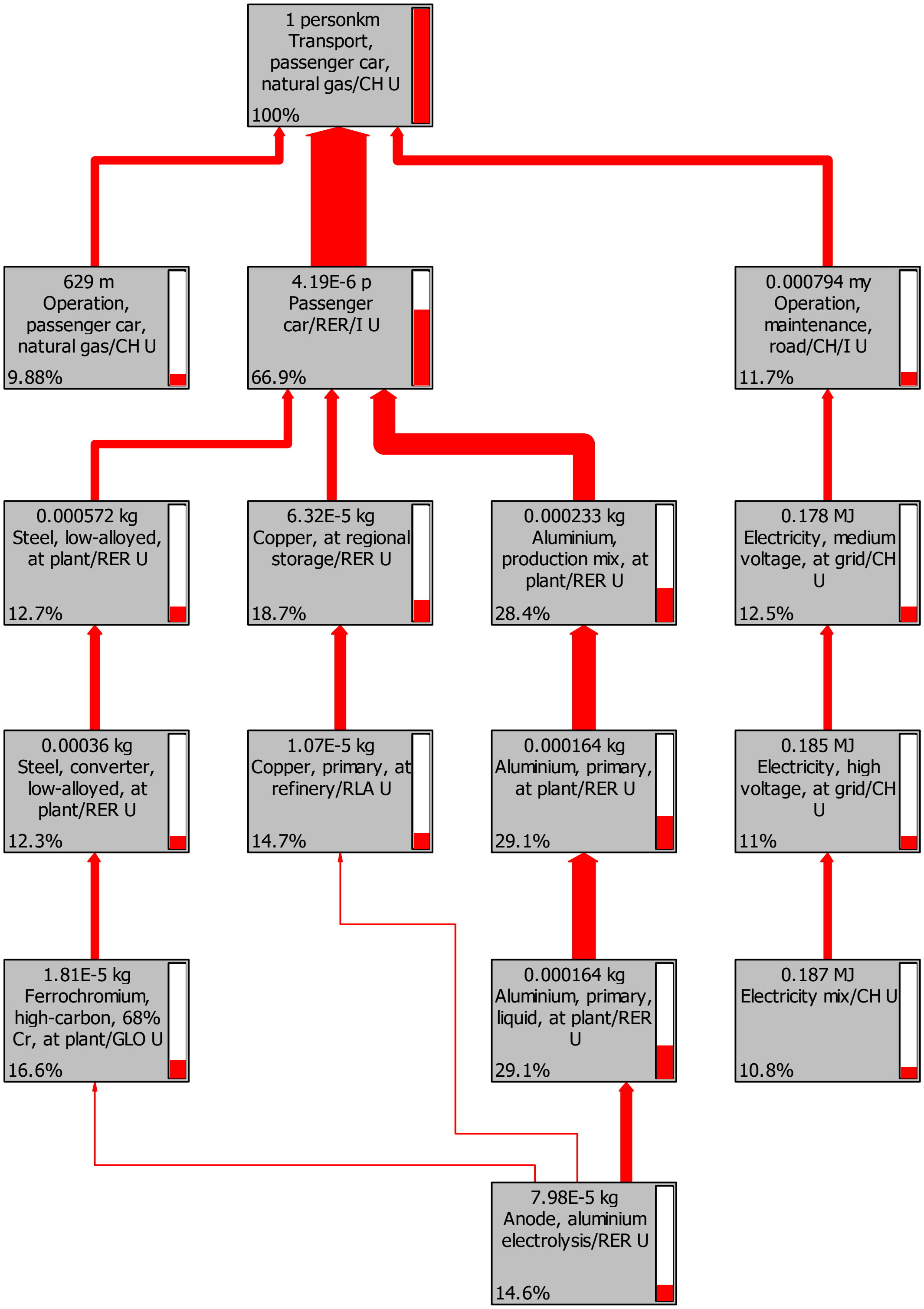

Figure 5.57 LCA process flow chart for the human toxicity (100a) of the natural gas vehicle (cut off- %9.3)

5.5. Validation and Comparison of the Results with Literature Data

Table 5.18 provides validation and comparison of LCA results with latest studies in the literature for abiotic depletion potential, acidification potential and eutrophication potential. The results of this LCA are very similar with two LCA studies performed by Bicer and Dincer [40,112] and also matches with results from Messagie et al. [12,38] and Suleman et al. [113]. There are some minor differences with Bartollozi et al.[114] and Ahmadi and Kjeang [51] due to assumptions for LCA and vehicles, allocation, source of data, geographic location, the different impact assessment methods were used for their calculations. The electricity sources were considered for the LCA studies made differences in the results as well. For some vehicles data was not available in literature because it is first time performed in present LCA.

Table 5.18 Comparison of impact categories' results with literature data

Impact category	Fuel type	The results	Literature data	
Abiotic depletion (kg Sb-eq/km)	Hydrogen	0.00063	0.00084	[112]
	Electric	0.00043	0.00085	[114]
	Methanol	0.00047	0.0025	[112]
	Gasoline	0.0011	0.0018	[112]
	Natural Gas	0.0014	0.0016	[112]
	Diesel	0.0011	0.0015	[112]
	Ethanol	0.0012	NA	
	Hybrid	0.0013	NA	
Acidification (kg SO_2-eq/km)	Hydrogen	0.00061	0.0002	[113]
	Electric	0.00036	0.00095	[114]
	Methanol	0.00037	0.00042	[112]
	Gasoline	0.00046	0.0007	[112]
	Natural Gas	0.00033	0.00032	[112]
	Diesel	0.00041	0.00042	[112]
	Ethanol	0.00051	NA	
	Hybrid	0.0012	NA	
Eutrophication (kg PO_4-eq/km)	Hydrogen	9.10E-05	7.29E-05	[112]
	Electric	0.00024	0.0005	[114]
	Methanol	0.00015	0.00013	[112]
	Gasoline	0.00012	0.001	[38]
	Natural Gas	0.0001	0.00012	[112]
	Diesel	0.00012	0.00128	[38]
	Ethanol	0.00013	NA	
	Hybrid	0.00011	0.00984	[38]

Table 5.19 provides validation and comparison of LCA results with latest studies in the literature for global warming potential, ozone layer potential and human toxicity potential. The results of this LCA study are very similar with two LCA studies performed by Bicer and Dincer [40] and matches with results from Messagie et al. [12,38]. Moreover, Bicer and Dincer [112] performed an LCA in 2018, and they considered a renewable based and a mixed electricity based electric vehicle in their study. They obtained different results for both vehicles. However, their results for renewable based vehicle matches with the results of electric vehicle in this LCA due to same renewable sources used for EVs. Therefore, clean electricity sources make difference in the results, assumptions and geographic location have impact on the results as well.

Table 5.19 Comparison of impact categories' results with literature data (continued)

Impact category	Fuel type	The results	Literature data
Global warming ($kg\ CO_2$ eq/km)	Hydrogen	0.079	0.051 [40]
	Electric	0.051	0.17 [40]
	Methanol	0.058	0.31 [40]
	Gasoline	0.166	0.29 [51]
	Natural gas	0.165	0.15 [12]
	Diesel	0.159	0.16 [12]
	Ethanol	0.184	NA
	Hybrid	0.163	0.155 [12]
Ozone layer depletion (kg CFC-11 eq/km)	Hydrogen	8.14E-10	1.50E-09 [40]
	Electric	4.81E-09	8.63E-09 [40]
	Methanol	5.62E-09	2.14E-08 [40]
	Gasoline	1.98E-08	3.21E-08 [112]
	Natural gas	2.89E-08	2.88E-08 [112]
	Diesel	2.02E-08	3.30E-08 [112]
	Ethanol	2.19E-08	NA
	Hybrid	4.74E-10	NA
Human toxicity (kg 1,4-DB-eq/km)	Hydrogen	0.0017	0.03 [40]
	Electric	0.11	0.39 [40]
	Methanol	0.048	0.07 [40]
	Gasoline	0.045	0.045 [112]
	Natural gas	0.029	0.025 [112]
	Diesel	0.035	0.033 [112]
	Ethanol	0.045	NA
	Hybrid	0.0027	NA

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the main findings of this thesis are summarized and briefly explained. On the basis of the results obtained, further recommendations are made for future studies in this area of research.

6.1. Conclusions

In this study, the results are obtained through modeling a comprehensive LCA study of conventional and alternative fuels for small passenger vehicles in SimaPro software. For the study, ten different vehicle technologies were selected from conventional and alternative vehicle segments, and the results are presented and assessed comparatively. The vehicles selected for this study are diesel, electric, ethanol, gasoline, hybrid, hydrogen, methane, methanol, and natural gas. This research delivers a cradle-to-grave LCA that presents the results comparatively in six impact categories namely; abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and human toxicity potential.

This study contributes to the existing literature in four aspects. Firstly, it implements the life cycle assessments on fuel production, then it performs the life cycle assessments on materials production for vehicles, and then it combines the two assessments to estimate the cradle-to-grave impact of different vehicle technologies. Secondly, the environmental impacts of ten different passenger vehicles analyzed regarding impact categories with CML 2001 method. Thirdly, the environmental impacts of the selected vehicles are analyzed with Eco-indicator 99 and IMPACT 2002+ methodologies to test reliability in LCA results. Lastly, the environmental impacts at each life cycle stage is calculated; moreover, the hot spots in supply chain are identified. The key findings extracted from this study are listed below:

- The natural gas vehicle is found to have the highest abiotic depletion impact category of 0.001423 kg Sb-eq/km, followed by gasoline vehicle with 0.0014 kg Sb-eq/km, ethanol vehicle with 0.0013 kg Sb-eq/km, hybrid vehicle with 0.0012 kg Sb-eq/km, gasoline vehicle (petrol, EURO5) with 0.0011 kg Sb-eq/km, diesel vehicle with 0.00109 kg Sb-eq/km, hydrogen vehicle with 0.00063 kg Sb-eq/km, methane vehicle with 0.00048 kg Sb-eq/km, methanol vehicle with 0.00047 kg Sb-eq/km, and electric vehicle with 0.00043 kg Sb-eq/km. The best performing vehicle is electric car in abiotic depletion potential with 0.00043 kg Sb-eq/km.

- The hybrid (LNG and electric) vehicle is found to have the highest acidification potential of 0012 kg SO_2-eq/km, and natural gas vehicle has the lowest acidification potential of 0.00033 SO_2-eq/km.
- The EVs are found to have highest eutrophication potential of 0.00024 kg PO_4-eq/km, and lowest impacts come from hydrogen vehicle with 9.1×10^{-5} kg PO_4-eq/km. The most environmentally-benign option is hydrogen vehicle in eutrophication potential category.
- The gasoline vehicle (fleet average) found to have the highest global warming potential of 0.20 kg CO_2-eq/km. The electric vehicle shows lowest global warming potential of 0.052 kg CO_2-eq/km. Based on the LCIA results, the conventional fueled vehicles are worst in terms of global warming potential as they burn fossil fuels, which is the key human sources of greenhouse gas emissions.
- The hybrid and hydrogen vehicles are found to have the lowest ozone layer depletions of 4.74×10^{-10} kg (CFC-11)-eq/km and 8.14×10^{-10} kg (CFC-11)-eq/km respectively.
- The electric vehicle contributes significantly to human toxicity potentials with 0.10 kg (1,4-DB)-eq/km. This is due to the emissions from the manufacture of batteries in the course of the vehicle production stage, which represent an important share of the environmental impacts of electric car manufacturing. However, the most environmental-friendly car in his category becomes hydrogen vehicle with 0.0017 kg (1,4-DB)-eq/km.
- The CML 2001 and Eco-indicator 99 and IMPACT 2002+ methods' results are very similar in ozone layer depletion category.
- The CML 2001 and IMPACT 2002+ results closely match for the ozone layer depletion category as well as eutrophication category, but minor differences observed in comparison with the eco-indicator 99 method.
- In global warming potential and abiotic depletion potential impact categories, the results obtained from all three LCIA methods remain almost the same.

6.2. Recommendations

Based on the findings and observation of this thesis study, following recommendations are made for potentially future studies as to be conducted. It is important to complete the following works in order to achieve more sustainable transportation pathways.

- Comprehensive thermodynamic analyses of the vehicle powering and fueling systems should be conducted through energy and exergy approaches. In this regard, energy and exergy efficiencies of the vehicles can be determined, which will determine the fuel consumption for each specific fuel type considered, such as diesel, electric, ethanol, gasoline, hybrid, hydrogen, methane, methanol and natural gas.

- One of the main performance indicators of the vehicles is cost per km travelled, which is directly associated with fuel consumption and exergetic performance of the engines. Therefore, exergoeconomic analyses of all vehicle types and their powering and fueling options should be performed to find out the cost of exergy destruction.

- Environmental impact analyses should be integrated with thermodynamic analyses, which will find the exergoenvironmental performance of the vehicles. In this way, the relations between the emissions characteristics and vehicle performance can be completely understood.

- There are other emerging alternative clean fuels, such as ammonia, which were not included in this study. Therefore, the scope of the selected fuels should be enhanced by considering them and their hybrid options for fuel cell vehicles.

- Various hydrogen storage techniques should be investigated to determine the most feasible type of on-board fuel storage.

- The production pathways of the fuels should be investigated to determine the cleanest route for the environment.

- The selected environmental impact categories should be enhanced to better represent the diverse environmental effects.

- In order to test accuracy of the results further, a comprehensive uncertainty analysis for each vehicle type should be carried out for various impact categories under numerous conditions.
- The battery and engine of the hybrid and electric vehicles should be modeled using Aspen Plus simulations in conjunction with the life cycle assessment studies.
- The sizes and weights of the vehicles should be considered for analyses and assessments which will include small-, mid-, large- size vehicles, such as SUVs, trucks, buses and even trains.

REFERENCES

1. Sousanis J. 2011. World Vehicle Population Tops 1 Billion Units/Industry content from WardsAuto. *WardsAuto*. [cited 1 June 2018]. Available from http://wardsauto.com/news-analysis/world-vehicle-population-tops-1-billion-units.
2. Bauer C, Hofer J, Althaus HJ, Del Duce A, Simons A. 2015. The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. *Appl. Energy*. 157:871–883.
3. Hacatoglu K, Rosen MA, Dincer I. 2012. Comparative life cycle assessment of hydrogen and other selected fuels. *Int. J. Hydrogen Energy*. 37:9933–9940.
4. Abdul-Manan AFN. 2015. Uncertainty and differences in GHG emissions between electric and conventional gasoline vehicles with implications for transport policy making. *Energy Policy*. 87:1–7.
5. American Transportation Research Institute. Trucking and the Environment. [cited 1 June 2018]. Available from http://atri-online.org/.
6. Dincer I, Zamfirescu C. 2011. *Sustainable Energy Systems and Applications*. doi:10.1007/978-0-387-95861-3.
7. Dincer I. 2012. Green methods for hydrogen production. *Int. J. Hydrogen Energy*. 37, pp 1954–1971.
8. Transport-International Energy Agency. [cited 1 June 2018]. Available from https://www.iea.org/topics/transport/.
9. Energy Use for Transportation - Energy Explained, Your Guide To Understanding Energy - Energy Information Administration. [cited 24 May 2018]. Available from https://www.eia.gov/energyexplained/.
10. Corporate Average Fuel Economy | NHTSA. [cited 24 May 2018]. Available from https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy.
11. Granovskii M, Dincer I, Rosen MA. 2007. Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: Economic factors. *Int. J. Hydrogen Energy*. 32:927–931.
12. Messagie M, Boureima FS, Coosemans T, Macharis C, Mierlo J Van. 2014. A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. *Energies*. 7:1467–1482.
13. Argonne National Laboratory-Greet-U.S. Department of energy. [cited 24 May 2018]. Available from https://greet.es.anl.gov/greet/gettingstarted/wtw.html.
14. Menoufi KAI. 2011. Life Cycle Analysis and Life Cycle Impact Assessment methodologies: State of the art. *Masters Thesis*.:1–84. Available from http://repositori.udl.cat/bitstream/handle/10459.1/45831/Ali.pdf?sequence=2.
15. Cámara EM, Macías EJ, Fernández JB. 2013. Life Cycle Assessment of Renewable Energy Sources. doi:10.1007/978-1-4471-5364-1.

16. Sarkar J, Bhattacharyya S. 2012. Operating characteristics of transcritical CO2 heat pump for simultaneous water cooling and heating. *Arch. Thermodyn.* 33:23–40.

17. Onat NC, Noori M, Kucukvar M, Zhao Y, Tatari O, Chester M. 2017. Exploring the suitability of electric vehicles in the United States. *Energy*. 121:631–642.

18. Koroneos C, Dompros A, Roumbas G, Moussiopoulos N. 2004. Life cycle assessment of hydrogen fuel production processes. *Int. J. Hydrogen Energy*. 29:1443–1450.

19. Sardar A, Muttana SB. 2012. Life cycle GHG emissions from conventional IC engine vehicles and EVs : A comparative assessment: Autotechreview. volume 1, issue 12:18–23.

20. Huang KD, Tzeng SC. 2005. Development of a hybrid pneumatic-power vehicle. *Appl. Energy*. 80:47–59.

21. Owsianiak M, Laurent A, Bjorn A, Hauschild MZ. 2014. Impact 2002+, ReCiPe 2008 and ILCD's recommended practice for characterization modelling in life cycle impact assessment : a case study-based comparison:*Int J Life Cycle Assess* 19:1007–1021. doi:10.1007/s11367-014-0708-3.

22. Cavalett O, Chagas MF. 2013. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. *Int J Life Cycle Assess* 18:647–658. doi:10.1007/s11367-012-0465-0.

23. Cherubini E, Franco D, Zanghelini GM, Soares SR. 2018. Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-017-1432-6

24. Dreyer LC, Niemann AL, Hauschild MZ. 2003. Comparison of Three Different LCIA Methods : *Int J LCA* 8 (4) 19I - 200

25. Peng T, Zhou S, Yuan Z. 2017. Life Cycle Greenhouse Gas Analysis of Multiple Vehicle Fuel Pathways in China. *Sustainability*, 2183:1-24 doi:10.3390/su9122183.

26. Sharma A, Strezov V. 2017. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. *Energy*. 133:1132–1141.

27. Messagie M, Boureima FS, Coosemans T, Macharis C, Mierlo JV. 2014. A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels: *Energies* 7:1467–1482. doi:10.3390/en7031467.

28. Sander K, Murthy GS. 2010. Life cycle analysis of algae biodiesel. *Int. J. Life Cycle Assess.* 15:704–714.

29. Hawkins TR, Singh B, Majeau-Bettez G, Stromman AH. 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* 17:53–64.

30. Schmidt WP, Dahlqvist E, Finkbeiner M, Krinke S, Lazzari S, Oschmann D, Pichon S, Thiel C. 2004. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. *Int. J. Life Cycle Assess.* 9:405–416.

31. Cooney G, Hawkins TR, Marriott J. 2013. Life cycle assessment of diesel and electric public transportation buses. *J. Ind. Ecol.* 17:689–699.

32. Chua CBH, Lee HM, Low JSC. 2010. Life cycle emissions and energy study of biodiesel derived from waste cooking oil and diesel in Singapore. *Int. J. Life Cycle Assess.* 15:417–423.

33. Cadotte M, Deschênes L, Samson R. 2007. Selection of a remediation scenario for a diesel-contaminated site using LCA. *Int. J. Life Cycle Assess.* 12:239–251.

34. Chua CBH, Lee HM, Low JSC. 2010. Life cycle emissions and energy study of biodiesel derived from waste cooking oil and diesel in Singapore. *Int. J. Life Cycle Assess.* 15:417–423.

35. Samaras C, Meisterling K. 2008. Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. *Environ. Sci. Technol.* 42:3170–3176.

36. Lombardi L, Tribioli L, Cozzolino R, Bella G. 2017. Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA. *Int. J. Life Cycle Assess.* 22:1989–2006.

37. Zhou Z, Jiang H, Qin L. 2007. Life cycle sustainability assessment of fuels. *Fuel*. 86:256–263.

38. Messagie M, Boureima F, Matheys J, Sergeant N, Turcksin L, Macharis C. 2007. Life Cycle Assessment of conventional and alternative small passenger vehicles in Belgium. 32.

39. Onat NC, Kucukvar M, Tatari O. 2015. Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. *Appl. Energy*. 150:36–49.

40. Bicer Y, Dincer I. 2017. Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. *Int. J. Hydrogen Energy*. 42:3767–3777.

41. Rose L, Hussain M, Ahmed S, Malek K, Costanzo R, Kjeang E. 2013. A comparative life cycle assessment of diesel and compressed natural gas powered refuse collection vehicles in a Canadian city. *Energy Policy*. 52:453–461.

42. Noshadravan A, Cheah L, Roth R, Freire F, Dias L, Gregory J. 2015. Stochastic comparative assessment of life-cycle greenhouse gas emissions from conventional and electric vehicles. *Int. J. Life Cycle Assess.* 20:854–864.

43. Hawkins TR, Singh B, Majeau-Bettez G, Stromman AH. 2013. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* 17:53–64.

44. Miotti M, Hofer J, Bauer C. 2017. Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int. J. Life Cycle Assess.* 22:94–110.

45. González-García S, Gasol CM, Moreira MT, Gabarrell X, Pons JRI, Feijoo G. 2011. Environmental assessment of black locust (Robinia pseudoacacia L.)-based ethanol as potential transport fuel. *Int. J. Life Cycle Assess.* 16:465–477.

46. Silva C, Farias T. 2010. Evaluation of Energy Consumption, Emissions, and Costs of Plug-in Hybrid Vehicles. *Electr. Hybrid Veh.*, pp 193–210. doi:10.1016/B978-0-444-53565-8.00007-5.

47. Hussain MM, Dincer I. 2010. Chapter eleven - Life Cycle Assessment of Hydrogen Fuel Cell and Gasoline Vehicles. *Electr. Hybrid Veh.*, pp 275–286. doi:https://doi.org/10.1016/B978-0-444-53565-8.00011-7.

48. Nordelöf A, Messagie M, Tillman AM, Ljunggren Söderman M, Van Mierlo J. 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles: what can we learn from life cycle assessment. *Int. J. Life Cycle Assess.* 19:1866–1890.

49. Hawkins TR, Gausen OM, Strømman AH. 2012. Environmental impacts of hybrid and electric vehicles-a review. *Int. J. Life Cycle Assess.* 17:997–1014.

50. Hussain MM, Dincer I. 2010. Life Cycle Assessment of Hydrogen Fuel Cell and Gasoline Vehicles. *Electr. Hybrid Veh.*, pp 275–286. doi:10.1016/B978-0-444-53565-8.00011-7.

51. Ahmadi P, Kjeang E. 2015. Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces. *Int. J. Hydrogen Energy*. 40:12905–12917.

52. Suleman F. 2014. Comparative Study of Various Hydrogen Production Methods for Vehicles. Master's thesis, University of Ontario Institute of Technology, Oshawa, 1690200.

53. Ozbilen AZ. 2010. Life Cycle Assessment of Nuclear-Based Hydrogen Production via Thermochemical Water Splitting Using a Copper-Chlorine (Cu-Cl) Cycle. Master's thesis, University of Ontario Institute of Technology, Oshawa, 09596526.

54. Creutzig F, Papson A, Schipper L, Kammen DM. 2009. Economic and environmental evaluation of compressed-air cars. *Environ. Res. Lett.* 4.

55. Granovskii M, Dincer I, Rosen MA. 2007. Exergetic life cycle assessment of hydrogen production from renewables. *J. Power Sources*. 167:461–471.

56. Suleman F, Dincer I, Agelin-Chaab M. 2016. Comparative impact assessment study of various hydrogen production methods in terms of emissions. *Int. J. Hydrogen Energy*. 41:8364–8375.

57. Granovskii M, Dincer I, Rosen MA. 2006. Life cycle assessment of hydrogen fuel cell and gasoline vehicles. *Int. J. Hydrogen Energy*. 31:337–352.

58. Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP. 2010. Comparative analysis of battery electric , hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy*. 38:24–29.

59. Lombardi L, Tribioli L. 2017. Comparative environmental assessment of conventional , electric , hybrid , and fuel cell powertrains based on LCA.1989–2006. doi:10.1007/s11367-017-1294-y.

60. Yan X, Crookes RJ. 2009. Life cycle analysis of energy use and greenhouse gas emissions for road transportation fuels in China. 13:2505–2514.

61. Paulino F, Pina A, Baptista P. 2018. Evaluation of Alternatives for the Passenger Road Transport Sector in Europe : A Life-Cycle Assessment Approach. *Environments.* 5:21 doi:10.3390/environments5020021.

62. Baptista P, Ribau J, Bravo J, Silva C, Adcock P, Kells A. 2011. Fuel cell hybrid taxi life cycle analysis. *Energy Policy.* 39:4683–4691.

63. Hooftman N, Oliveira L, Messagie M, Coosemans T, Mierlo J Van. 2016. Environmental Analysis of Petrol , Diesel and Electric Passenger Cars in a Belgian Urban Setting. *Energies*. 9:84; doi:10.3390/en9020084

64. Hawkins TR, Gausen OM, Stromman AH. 2012. Environmental impacts of hybrid and electric vehicles: a review. *Int J Life Cycle Assess.* 17:997–1014. doi:10.1007/s11367-012-0440-9.

65. Karaaslan E, Zhao Y, Tatari O. 2018. Comparative life cycle assessment of sport utility vehicles with different fuel options. *Int J Life Cycle Assess.* 23:333–347. doi:10.1007/s11367-017-1315-x.

66. Mansour CJ, Haddad MG. 2017. Well-to-wheel assessment for informing transition strategies to low-carbon fuel-vehicles in developing countries dependent on fuel imports : A case-study of road transport in Lebanon. *Energy Policy*. 107:167–181.

67. Wallington TJ, Anderson JE, Kleine RD De, Kim HC, Maas H, Brandt AR, Keoleian GA. 2016. When Comparing Alternative Fuel-Vehicle Systems , Life Cycle Assessment Studies Should Consider Trends in Oil Production. *Journal of Industrial Ecology* 21:244-248.

68. Batista T, Freire F, Silva CM. 2015. Vehicle environmental rating methodologies : Overview and application to light-duty vehicles. *Renew. Sustain. Energy Rev.* 45:192–206.

69. Nordelöf A, Messagie M, Tillman AM, Ljunggren Söderman M, Van Mierlo J. 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicle: what can we learn from life cycle assessment? *Int. J. Life Cycle Assess.* 19:1866–1890.

70. Singh B, Guest G, Bright RM, Stromman AH. 2014. Life cycle assessment of electric and fuel cell vehicle transport based on forest biomass. *J. Ind. Ecol.* 18:176–186.

71. Ma H, Balthasar F, Tait N, Riera-Palou X, Harrison A. 2012. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. *Energy Policy*. 44:160–173.

72. Onat N, Kucukvar M, Tatari O. 2014. Towards Life Cycle Sustainability Assessment of Alternative Passenger Vehicles. *Sustainability*. 6:9305-9342 doi:10.3390/su6129305

73. Hawkins TR, Singh B, Majeau-bettez G, Stromman AH. 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*. 17:53–64.

74. Curran MA. 2012. Life cycle assessment handbook : a guide for environmentally sustainable products. Wiley.

75. Curran MA. 2006. Life Cycle Assessment: Principles and Practice. National Risk Management Research Laboratory, Office of Research and Development, *US Environmental Protection Agency.* 1-80

76. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. 2004. Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications. *LCA.* 30:701–20.

77. Schenck R. 2005. Why LCA? *Building Design and Construction supply.* 4–5. Available from http://search.ebscohost.com/login.aspx

78. Tillman AM. 2000. Significance of decision-making for LCA methodology. *Environ. Impact Assess. Rev.* 20:113–123.

79. Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S. 2009. Recent developments in Life Cycle Assessment. *LCA*. 91:1–21.

80. McAloone TC, Pigosso DCA. 2017. Ecodesign implementation and LCA. *Life Cycle Assess. Theory Pract.*, pp 545–576. doi:10.1007/978-3-319-56475-3_23.

81. European Environment Agency. 2006. Life cycle assessment (LCA): a guide to approaches, experiences and information sources. *Environ. Issues Ser.*1–6. doi:10.1016/B978-0-12-801775-3.00024-X.

82. Jimenez-Guerrero JF, Gazquez-Abad JC, Ceballos-Santamaría G. 2015. Innovation in eco-packaging in private labels. *Innov. Manag. Policy Pract.* 17:81–90.

83. Milner V, Braaf C, Kasner S. 2017. Eco-labels as a tool for sustainable choices. Civil Engineering : *Magazine of the South African Institution of Civil Engineering*, 25(7): 25-26.

84. Sto E, Strandbakken P. 2005. Eco-labels and consumers. *Futur. eco-labelling. Mak. Environ. Prod. Inf. Syst. Eff.*, pp 92–119.

85. Frydendal J, Hansen LE, Bonou A. 2017. Environmental labels and declarations. *Life Cycle Assess. Theory Pract.*, pp 577–604. doi:10.1007/978-3-319-56475-3_24.

86. Del Borghi A. 2013. LCA and communication: Environmental product declaration. *The International Journal of Life Cycle Assessment.*18(2):293-295

87. Firth P. 2012. Environmental Product Declarations. *Environ. Des. Constr.*:33–39.

88. ISO 14044: 2006. Environmental management: Life cycle assessment requirements and guidelines.

89. Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, Wegener Sleeswijk A, Udo De Haes H, De Bruijn J, Van Duin R, Huijbregts MJ. 2001. Life cycle assessment: An operational guide to the ISO standards. *LCA*: 692. doi:10.1300/J082v38n04_05.

90. ISO. 2006. Environmental management-life cycle assessment-principles and framework. *ISO 14040*.:46. doi:10.1136/bmj.332.7550.1107.

91. ISO. 2006. Environmental management-life cycle assessment-principles and framework. *ISO 14040*: 46. doi:10.1136/bmj.332.7550.1107.

92. Baumann H, Tillman AM. 2004. *The Hitch Hiker's Guide to LCA*. *Studentlitteratur Lund*. doi:10.1065/lca2006.02.008.

93. Curran MA. 2012. *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products*. *Book*. doi:10.1002/9781118528372.

94. ISO 14040:2006. Environmental management: Life cycle assessment principles and framework.

95. Frischknecht R, Niels J. 2007. Overview and Methodology - Data v2.0. *Ecoinvent Rep. No1*. 1:1–77.

96. Kelly JA. 2006. An Overview of the RAINS Model Environmental Research Centre Report. *Environmental Protection Agency*, Dublin.

97. Pre' Consultants. 2014. SimaPro Database. doi:10.1017/CBO9781107415324.004.

98. Pre' Consultants. 2014. SimaPro Database Manual. *PRe'*:1–48. doi:10.1017/CBO9781107415324.004.

99. Ecoinvent. 2013. Ecoinvent Database 3.0. *Ecoinvent Cent.* doi:10.4018/978-1-59140-342-5.ch003.

100. Pré Consultants. 2000. Eco-indicator 99 Manual for Designers. *Minist. Housing, Spat. Plan. Environ.* [cited 24 May 2018]. Available from http://www.pre-sustainability.com/download/manuals/EI99_Manual.pdf.

101. Goedkoop M, Effting S, Collignon M. Manual for Eco-indicators 99. PRé Consultants BV. Plotterweg 12, 3821

102. GREET Model | Life Cycle Associates, LLC. [cited 4 June 2018]. Available from http://www.lifecycleassociates.com/lca-tools/greet-model/.

103. 2017 Use of Gasoline - Energy Explained, Your Guide To Understanding Energy - Energy Information Administration. [cited 24 May 2018]. Available from https://www.eia.gov/energyexplained/index.php?page=gasoline_use.

104. Group F. 2008. Conventional Fuels for Land Transportation 2.1.:43–88.

105. Wakeley HL, Hendrickson CT, Griffin WM, Matthews HS. 2009. Economic and Environmental Transportation Effects of Large-Scale Ethanol Production and Distribution in the United States. *Environ. Sci. Technol.* 43:2228–2233.

106. Carnegie Mellon University. Approaches to LCA - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University. [cited 13 June 2018]. Available from http://www.eiolca.net/Method/LCAapproaches.html.

107. Flury RF. 2011. Life cycle assessment of electric mobility answers and challenges. *Int J Life Cycle Assess*.:691–695.

108. Boyden A, Soo VK, Doolan M. 2016. The Environmental Impacts of Recycling Portable Lithium-Ion Batteries. *Procedia CIRP*. 48:188–193.

109. Natural Resources Canada. Learn the facts: Emissions from your vehicle. Available from http://www.nrcan.gc.ca/energy/efficiency/transportation

110. Emissions. OICA. 2018. [cited 4 June 2018]. Available from http://www.oica.net/category/auto-and-fuels/emissions/.

111. Egede P, Dettmer T, Herrmann C, Kara S. 2015. Life Cycle Assessment of Electric Vehicles – A Framework to Consider Influencing Factors. *Procedia CIRP*. 29:233–238.

112. Bicer Y, Dincer I. 2018. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. *Resour. Conserv. Recycl.* 132:141–157.

113. Suleman F, Dincer I, Agelin-Chaab M. 2015. Environmental impact assessment and comparison of some hydrogen production options. *Int. J. Hydrogen Energy*. 40:6976–6987.

114. Bartolozzi I, Rizzi F, Frey M. 2013. Comparison between hydrogen and electric vehicles by life cycle assessment: A case study in Tuscany, Italy. *Appl. Energy*. 101:103–111.