Ref. Ares(2016)1512245 - 30/03/2016

Horizon 2020

Societal Challenge: Improving the air quality and reducing the carbon footprint of European cities

Project: 690105 – ICARUS

Full project title:

Integrated Climate forcing and Air pollution Reduction in Urban Systems

D2.3 Report on estimation of changes in emission based on life cycle analysis assessment for relevant activities

WP 2 Integrated emission modelling at the regional and urban scales

Lead beneficiary: USTUTT

Date: October 2018

Nature: Report

Dissemination level: Public

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Document Information

Grant Agreement Number	690105	**Acronym**	ICARUS
Full title	Integrated Climate forcing and Air pollution Reduction in Urban Systems		
Project URL	www.icarus2020.eu		
Project Officer	Mirjam Witschke - Mirjam.WITSCHKE@ec.europa.eu		

Delivery date	**Contractual**	October 2017	**Actual**	October 2018
Status	Draft ☐		Final √	
Nature	Demonstrator ☐	Report √	Prototype ☐	Other ☐
Dissemination level	Confidential ☐	Public √		

Responsible Author (Partners)	USTUTT			
Responsible Author	Julia Neuhäuser, Nicolas Barouki, Dorothea Schmid		**Email**	jneuh@ier.uni-stuttgart.de
	Partner	USTUTT, AUTH	**Phone**	
Other partners (Institution)	AUTH, EUC, kartECO, MU, NCSRD			

Document History

Name (Institution)	Date	Version
USTUTT, AUTH	April 2018	First draft
USTUTT, AUTH	June 2018	Second draft
USTUTT	October 2018	Final

Glossary and list of abbreviations

AEFDB	Activity emission factor database (developed in ICARUS Task 2.1 and Task 2.2)
BASE pathway	The BASE pathway takes into account all existing EU-wide greenhouse gas reduction goals as set in the 2020 Climate and Energy Package and the 2030 Climate and Energy Framework.
BAU	Business As Usual scenario
CFL	Compact Fluorescent Lamp, designed to replace an incandescent light bulb.
CNG	Compressed Natural Gas
EF	Emission Factor
ETS	EU Emission Trading System
GHG	Greenhouse Gases
HDV	Heavy Duty Vehicles
HighRES pathway	The HighRES pathway considers additional targets for the share of renewable energy sources in gross final energy consumption (RES) compared to the BASE pathway.
LCDB	Life Cycle Data Base (developed in ICARUS Task 2.3)
LDV	Light Duty Vehicles
LED lamp	Light fixtures that produce light using Light-Emitting Diode.
LPG	Liquefied Petroleum Gas
MC	Motor Cycles
NEEDS	New Energy Externalities Developments for Sustainability (http://www.needs-project.org/)
PC	Passenger Cars
Realistic optimistic scenario	A scenario where strong socio-economic drivers support dynamic market uptake and continuous technology development as defined in the NEEDS project.
REEEM	Role of technologies in an energy efficient economy – model based analysis policy measures and transformation pathways to a sustainable energy system (http://www.reeem.org/)

RES	Renewable energy sources in gross final energy consumption/ Renewable Energy Share
TIMES PanEU	Technically oriented model which illustrates in detail the whole energy system of the member states of the EU28+NO+CH for the period from 2000 to 2050. The modelling platform is The Integrated MARKAL-EFOM System (TIMES), developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA).
Very optimistic scenario	A scenario where a technological breakthrough makes the respective technology on the long term a leading global electricity supply technology as defined in the NEEDS project.
WP	ICARUS work package

1 Introduction

The need for integrated policies for air pollution reduction and climate change mitigation has become obvious in the past years. The current emission inventories developed in the frame of ICARUS Task 2.1 and Task 2.2 take all major anthropogenic emission sources of greenhouse gases and air pollutants into account. They are therefore an useful tool to estimate the effect of measures reducing greenhouse gases or air pollutants or both. Emissions occurring either within Europe or in a more detailed bottom-up level within the nine case study cities can be modelled and estimated for the years 2015, 2020 and 2030.

However, measures and policies not only have an effect on activities and resulting emissions within their target area, but often also affect processes outside the respective cities or even outside of Europe. Furthermore, each measure is accompanied by previous and subsequent steps along the life cycle of goods and services such as construction and demolition processes, which may have a huge effect on emissions beyond the spatial and temporal boundaries of the current study area. The integration of relevant up- and downstream processes becomes even more important when considering non-technical measures which affect behavioral and consumer choice patterns or institutional change.

Task 2.3 therefore aims at extending the scope of the developed emission inventories (Task 2.1, Task 2.2) in terms of spatial and temporal boundaries in order to fully estimate the change in the carbon footprint, air pollutant emissions and health impacts when implementing a measure.

2 Approach

Life cycle assessment typically focuses on emissions at each stage of the full life-cycle of a good or service. This includes emissions associated with the raw material extraction, manufacturing and processing, transportation, use and end-of-life management. Urban measures to reduce air pollution and the carbon footprint have a direct effect on product choices and behavioral patterns, that themselves change the consumed goods and used services within the city area. Thus, they do not only affect emissions within the respective target area, but also influence processes outside the city.

2.1 Scope of emissions

The extension of the system boundaries follows the general approach of community-level greenhouse gas emission inventories including life cycle impacts. The life cycle perspective accounts for all emissions, regardless of which sectors produce the emissions or when these effects occur over time. This is fundamentally different from emission inventories quantifying emissions of anthropogenic emission source sectors on an annual basis. The existing emission inventories of ICARUS WP2 consider all direct emissions causing processes that occur within the city area in the years 2015, 2020 and 2030. They therefore follow a territory principle. The tools generated in ICARUS WP2.3 allow for complementing the emission inventories with emission factors for up and downstream processes and indirect emissions such as electricity and heat use. This perspective follows consumption or process oriented principles taking into account all the emissions that are due to the activities within the respective area, even if they occur outside of the city.

Table 1 Characteristics of emission inventories with and without life cycle perspective

Emission inventories without life cycle perspective	Emission inventories with life cycle perspective
• Activities within the city area.	• Activities within and without the city area, but caused by activities within the city.
• Single processes (temporal boundary is one year; i.e. 2015, 2020, 2030).	• Up- and downstream processes (emissions can be released before or after the considered year, caused by processes and activities occurring within the considered year).
• Direct emissions.	• Direct and indirect emissions (electricity and heat).
→ Territory principle.	→ Consumption or process oriented principle.

The scopes, as defined by the World Resources Institute (2014), are used to structure the different metrics for emissions attributable to cities. Scope 1 comprises all the emissions occurring within the city area and includes components from fossil fuel combustion in energy, industry, households and transport sector and non-combustion related activities such as waste disposal, product use and industrial processes. As described above, scope 1 emissions are fully covered by the existing emission inventories already developed in Task 2.1 and Task 2.2. Scope 2 emissions origin from the cities consumption of electricity, heat and cooling supplied by distribution grids which may or may not cross city boundaries. Scope 3 finally includes out of boundary production chain emissions due to embodied emissions from food and goods consumed in the city as well as emissions related to their disposal. Table 2 shows the different scopes of city emissions and their spatial and temporal boundaries. The total emissions increase from the bottom of the table to the top. Scope 1 follows the territory principle including direct emissions within the city area, while scope 2 and 3 follow a consumption accounting principle. Since scope 1 emissions were already included in the emission inventories developed in Task 2.1 and Task 2.2 the following chapters describe the process of adding scope 2 and scope 3 emissions for relevant activities to the existing emission inventories.

Table 2 Scopes of attributing emissions to cities (cf. Kennedy et al. 2010, World Resources 2014)

Scope (WRI definition)	Spatial boundary	Life cycle perspective	Sectors
Scope 3	Out of boundary emissions not included in scope 2	Production chain emissions	Embodied emissions from food, products and materials consumed in cities
Scope 2	In boundary electricity[1] use (for all sectors of scope 1)	Single process emissions	Out of boundary electricity emissions at power plants and electricity distribution
Scope 1	In boundary emissions		Electricity and heat production
			Industry: production and combustion
			Road transport
			Railways
			Shipping and aviation
			Fugitive emissions
			Product and solvent use
			Waste disposal

[1] Electricity is used as shorthand to include purchased steam, heat, cooling, and electricity.

2.2 Workflow of Task 2.3

The general approach to allow the calculation of emission changes based on life cycle analysis follows a three step process:

1. Identification of measures determined in WP5 in order to identify those activities and processes that cause significant changes in life cycle emissions.
2. Collection of life cycle emission data from different sources.
3. Development of a satellite system for life cycle emissions. The satellite system can be linked to the developed emission inventories in WP2 and therefore allows the automated calculation of changes of life cycle emissions and direct urban-level emissions.

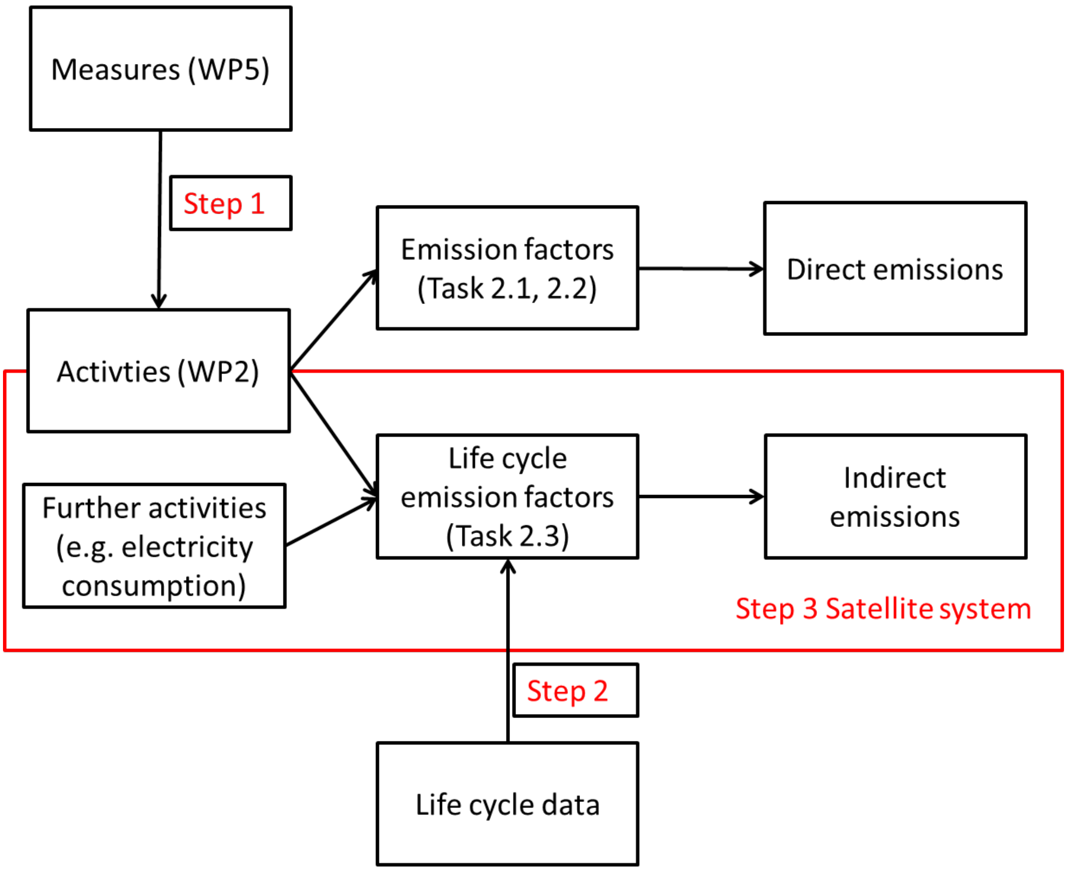

Figure 1 Workflow of Task 2.3

The first step is the identification of relevant policies and measures that cause significant changes in life cycle emissions. Therefore, the measure database of ICARUS WP5 has been leveraged. Selected measures and identified processes and activities are described in section 3.

The second step comprises the collection of life cycle data for relevant activities. To this aim we made use of several information sources including SimaPro 7.0, the Ecoinvent 2.0 database[2], the NEEDS[3] project and the ProBas database[4].

Data collection for each considered sector is described in section 4. Generally, life cycle emission factors for the pollutants included in the activity emission factor databases in WP2 have been collected. This comprises greenhouse gases (CH_4, CO_2, N_2O), classical air pollutants (PM_{10}, $PM_{2.5}$, NO_X, SO_2, CO, NH_3, NMVOC), heavy metals (Cd, As, Hg, Pb), benzo(a)pyrene and dioxins/furans.

The third step is the development of a satellite system for life cycle emissions. This comprises an allocation of life cycle emission factors to activities in existing activity emission factor databases and the introduction of activities not directly producing emissions, i.e. electricity and heat consumption. The disaggregation level of life cycle data (e.g. different vehicle types and technologies) has been defined depending on the available life cycle data and the activity emission factor database structure. The life cycle emission factors can thus directly be linked to the developed emission inventories in WP2 and allow the automated calculation of changes of life cycle emissions and direct urban-level emissions.

The terms "activities" and "processes" are used interchangeably in this report. "Activity" is taken from the vocabulary used in classical emission inventories, and describes emission causing processes and actions, while "processes" follows the life cycle perspective.

Table 3 Terminology of activity emission factor databases and life cycle databases

Activity emission factor database AEFDB[5] (Task 2.1, 2.2)	Life cycle database LCDB[6] (Task 2.3)
Activity	*Process*
Activity unit	*Functional unit*

[2] https://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/ecoinvent-version-2.html [cited 2018-10-12]
[3] http://www.needs-project.org/needswebdb/search.php [cited 2018-09-11]
[4] http://www.probas.umweltbundesamt.de/php/index.php [cited 2018-10-12]
[5] AEFDB: Activity emission factor database (developed in ICARUS Task 2.1, 2.2)
[6] LCDB: Life cycle database (developed in ICARUS Task 2.3)

3 Measures and relevant activities

In ICARUS WP5, over 720 potential policies and measures have been identified in relation to the incentives of the EU, national and municipal authorities, transport and energy providers. The measure collection was followed by a subsequent selection of approximately 10 measures per city based on common pre-defined criteria such as estimated effectiveness and relevance. The chosen measures for further detailed consideration cover a wide range of emission source sectors, namely:

1. (Residential) buildings and households
2. Tertiary and municipal
3. Transport
4. Energy supply
5. Industry
6. Waste management
7. Other

Despite the variety of addressed sectors, the majority of measures is related to energy consumption in buildings and households and the tertiary sector and transport policies, as these are the two areas that have the most direct impact on both air quality and climate change. Table 4 shows the selected measures, related sectors and the impact on the scopes of emissions for each measure.

Table 4 City measures in ICARUS

Sector	Policy thematic category	Standardized measure (policy intervention)	Possible impact on life cycle emissions (city/consumer perspective)
(Residential) buildings and households	Enhanced energy conscious behavior	Energy conscious use of appliances Energy conscious use of domestic heating	Reduction of scope 1 and scope 2 emissions (depending on heating system)
	Increase of building renovation and efficient design	Energetic renovation of residential buildings Energy efficient design of new buildings	Reduction of scope 1 and scope 2 emissions depending on heating system and energy savings Impact on scope 3 emissions due to material consumption
	Environment friendly heating technologies	Switch to gas boilers Switch to solar heating Switch to heat pumps Switch to district heating Switch to biomass burning Switch to modern systems	Decrease of scope 1 emissions due to more efficient heating systems Shift of scope 1 emissions to scope 2 emissions for electricity based heating or district heating Increase of scope 3 emissions due to infrastructure exchange
	Efficiency improvement of appliances	Use of CFL and LED lamps Use of air conditioners with new inverter technology Use of energy efficient appliances	Reduction of scope 2 emissions (electricity) Impact on scope 3 emissions due to material consumption

Sector	Policy thematic category	Standardized measure (policy intervention)	Possible impact on life cycle emissions (city/consumer perspective)
Tertiary and municipal	Increase of building renovation and efficient design	Energetic renovation of municipal buildings/properties Energetic renovation of tertiary buildings Installation of green roofs	Reduction of scope 1 and scope 2 emissions depending on heating system and energy savings Impact on scope 3 emissions due to material consumption
	Environment friendly heating technologies	Switch to modern systems Switch to gas boilers	Decrease of scope 1 emissions due to more efficient heating systems Increase of scope 3 emissions due to infrastructure exchange
	Enhanced energy conscious behavior	Energy conscious use of appliances	Reduction of scope 2 emissions
	Efficiency improvement of appliances	Use of CFL and LED lamps in municipal lighting systems	Reduction of scope 2 emissions (electricity) Impact on scope 3 emissions due to material consumption
	Other energy related investments	Penetration of photovoltaics in municipal buildings	Impact on scope 3 emissions
Transport	Car-independent lifestyles	Introduction of new underground railway/metro lines Expansion of bus lanes network Improving cycle networks Pedestrian friendly networks Price reductions in public transport Increased use of car sharing Increased use of park and ride Integrated public transportation Renovation of public transport fleet (electrified/hybrid/CNG buses, taxis)	Impact on scope 2 emissions due to electrification (metro/railways, hybrids/electrified public transport fleet) Impact on scope 3 emissions due to infrastructure
	Alternative fuels and driving technologies (e-mobility, hybrids, CNG, LPG)	Penetration of electric vehicles Penetration of hybrid vehicles Penetration of CNG Penetration of LPG Renovation of public transport fleet (electrified/hybrid/CNG buses, taxis)	Impact on scope 2 due to electrification Impact on scope 3 due to fuel generation
	Increase of vehicles with high emission standard	Withdrawal of old cars	Impact on scope 3 emissions due to production/disposal of vehicles
	Retrofitting of old cars	Hardware update of diesel EURO 5 Software update of diesel EURO 5	Decrease of Scope 1 emissions Impact of scope 3 emissions due to material consumption
	Efficient logistics	Efficient urban logistics	Depending on specific measure

Sector	Policy thematic category	Standardized measure (policy intervention)	Possible impact on life cycle emissions (city/consumer perspective)
	Sustainable mobility plans	Implementation of company mobility plans Sustainable mobility plan for city	Depending on specific measure
	Demand management strategies	Low emission zone City toll/congestion charge Parking regulations Traffic reduction Redesign of traffic routes	Depending on specific measure; possible impact on scope 2 emissions (use of electrified public transport) and scope 3 emissions
	Freight transport regulations and logistics	Prohibition of heavy freight vehicles Restrictions for commercial vehicles	Impact on scope 3 emissions
	Enhanced environmental conscious behavior	Eco-driving	Impact on scope 1 emissions (fuel consumption)
	Efficiency improvement of appliances	Use of LED lamps in municipal street lighting systems	Reduction of scope 2 emissions Impact on scope 3 emissions due to material consumption
Energy supply	Promotion of district heating	Expansion of district heating networks	Impact on scope 2 emissions (grid supplied heat)
	Switch to less carbon-intensive fuels	Switch from coal to gas power plants	Impact on scope 2 emissions (electricity)
Industry	Use of fuel alternatives	Use of refuse derived fuel	Impact on scope 3 emissions (production of consumed goods)
Waste management	Eco-friendly waste management with citizens participation	Eco-friendly waste management with citizens participation	Impact on scope 3 emissions (disposal of consumed goods)
	MSW incineration and energy recovery	MSW incineration and energy recovery	Impact on scope 3 emissions (disposal of consumed goods)
Other	Regeneration of neighborhoods	Regeneration and rehabilitation of neighborhoods	Depending on specific measure
	Climate change adaption	Bioclimatic renovation of public areas Re-naturalization measures	Depending on specific measure
	Reduction of other emission sources	Reduction of fireworks	Depending on specific measure

The measures identified in WP5 have been analyzed with regard to activities and processes that cause significant changes in life cycle emissions. Measures related to transport mainly address a switch of transportation modes to car-independent lifestyles (walking, cycling, and public transport) as well as the promotion of fuel alternative vehicles such as e-cars and hybrids. The measures in the building and household sector mainly focus on energetic renovation, energy efficiency and energy savings as well as the promotion of alternative heating techniques. The domestic sector also has an important role for indirect emissions through electricity use. Especially measures including a fuel switch in transport and electrification in both transport and heating sector are addressed by the cities. Given that these measures result in a shift from emissions at the point of use (e.g. tailpipe emissions of vehicle, stationary fuel combustion in households) to emissions related to fuel production, it becomes obvious that a comprehensive assessment of options requires the inclusion of full life cycle emissions.

In accordance with the findings of WP5 and the expected effect on life cycle emission changes, emphasis has been placed on the sectors transport, buildings and households as well as the electricity generation sector. Data for different transportation services (such as private cars, metro and trams, buses) has been gathered for all relevant processes in order to provide emission factors for the scope 3 perspective. The same holds true for measures in the buildings and households sector, where data on different heating technologies and insulation materials has been collected. Emission factors for district heating have not been provided since they depend strongly on the local mix and need to be calculated for each case study city separately. Emission factors for indirect emissions due to electricity use in both consumption sectors have been separately calculated based on different scenarios for the future European energy system. They represent scope 2 emissions of the cities activities. Life cycle factors for measures related to waste and industry have been excluded for this study and can be calculated for local plants and facilities in WP5.The mainly affected activities and processes in the WP2 activities emissions factor database have been identified as follows:

Table 5 Affected activities in WP2 database

Measure sector (WP5)	AEFDB[7] Sector (WP2)	Activity unit (functional unit)	LCDB[8] processes and factors
Transport	Road (all vehicle types)	vkm (vehicle kilometer) (converted to pkm for comparisons between different modes)	Electricity and heat consumption in transport, buildings and households (scope 2) Production, maintenance and disposal in transport, buildings and households (scope 3)
Transport	Rail (metro&tram)	vkm (vehicle kilometer) (converted to pkm for comparisons between different modes)	
Buildings and households/ Tertiary	Domestic (heating technologies)	PJ (final energy consumption) (to be converted to useful energy for comparisons between different heating technologies)	
Energy supply	taken into account as indirect scope 2 emissions in energy consumption sectors like transportation and buildings		

[7] AEFDB: Activity emission factor database (developed in ICARUS Task 2.1, 2.2)
[8] LCDB: Life cycle database (developed in ICARUS Task 2.3)

4 Data collection and satellite system

As described in the previous section, life cycle emission factors were collected in order to enrich the activity emission factor databases developed in ICARUS Task 2.1 and Task 2.2. Main sources for life cycle data are the Ecoinvent database and results of the NEEDS[9] project.
Ecoinvent version 2.0 database was compiled in 2007 by the Swiss Centre for Life Cycle Inventories and contains about 4000 datasets for products, services and processes often used in life cycle analysis case studies (Frischknecht R. 2007). Information is available about the outputs of these processes, including emissions to air. Leuenberger (2010 a) and Leuenberger (2010 b) were used to complete the life cycle database for transport processes. Electricity processes have been modelled using the Ecoinvent database and especially for future years (2020, 2030, 2050) the NEEDS database. Life cycle emission factors relative to electricity, buildings and transport are available for the following pollutants:

- Ammonia
- Arsenic
- Benzo(a)pyrene
- Cadmium
- Carbon monoxide, biogenic
- Carbon monoxide, fossil
- Carbon monoxide, fossil and biogenic
- Carbon dioxide, biogenic
- Carbon dioxide, fossil
- Carbon dioxide, land transformation
- Carbon dioxide, fossil and biogenic
- Carbon dioxide
  fossil and land transformation
- Carbon dioxide
  fossil, biogenic and land transformation
- Dinitrogen monoxide
- Dioxins, measured as
  2,3,7,8-tetrachlorodibenzo-p-dioxin
- Furan
- Hydrocarbons, aromatic
- Lead
- Particulates, < 2.5 µm
- Particulates, > 2.5 µm, and < 10 µum
- Particulates, < 10 µm
- Sulfur dioxide
- Methane, biogenic
- Methane, bromo-, Halon 1001
- Methane, bromochlorodifluoro-, Halon 1211
- Methane, bromotrifluoro-, Halon 1301
- Methane, chlorodifluoro-, HCFC-22
- Methane, dichloro-, HCC-30
- Methane, dichlorodifluoro-, CFC-12
- Methane, dichlorofluoro-, HCFC-21
- Methane, fossil
- Methane, monochloro-, R-40
- Methane, tetrachloro-, CFC-10
- Methane, tetrafluoro-, CFC-14
- Methane, trichlorofluoro-, CFC-11
- Methane, trifluoro-, HFC-23
- Methane, fossil and biogenic
- Mercury
- Nitrogen oxides
- NMVOC, non-methane volatile organic compounds, unspecified origin

4.1 Data collection scope 2: Electricity

Following the methodology as described by Itten et al. (2014), a LCA of country specific electricity mixes (high voltage, medium voltage, low voltage) considering country specific production mixes as well as

[9] http://www.needs-project.org/needswebdb/search.php [cited 2018-09-11]

electricity imports as given by TIMES PanEU was performed based on existing life cycle inventory databases. The functional unit of the study is 1 kWh of electricity at low, medium and high voltage. Two scenarios presenting different renewable energy shares in the gross final energy consumption are used to generate the life cycle emission factors.

4.1.1 The energy system model TIMES PanEU

The Pan-European TIMES energy system model *TIMES PanEU* is built with the TIMES model generator (Loulou et al. 2016), developed and maintained within the Energy Technology System Analyses Program (ETSAP) of the International Energy Agency (IEA). *TIMES PanEU* is a bottom-up linear partial equilibrium model reflecting the complete European energy system with a time horizon from 2010 up to 2050. The aim of the model is to minimize the energy system cost according to given energy demands, energy technologies and policy requirements (Remme 2006, Loulou et al. 2016). All costs are discounted to the reference year which is used to calibrate the energy balances and technology stocks based on statistical data. *TIMES PanEU* covers all European Union member states as well as Norway and Switzerland. Each country is modelled as a single region with implemented trading mechanisms enabling exchanges and interactions between these. The model horizon is divided in 5-year intervals, with one year comprising twelve time slices (four seasonal and 3 day levels). The reference energy system of the model represents all energy and material flows across the entire energy system, starting from the supply of resources and ending with fulfilling different energy demand services. It is split into seven main sectors (supply, electricity and heat production, industry, commercial, residential, agriculture and transport) reflecting different demand structures and transformation steps. All sectors can interact with each other and different indicators (e.g. energy use) are calculated through each step in the reference system. To be able to analyse environmental policies, GHG (CO_2, CH_4, N_2O) are included in the model (Blesl 2014, Blesl et al. 2010, Blesl et al. 2012).

4.1.2 Data description and scenario assumptions

To derive future electricity mixes, two distinct transformation pathways to a European low-carbon society as developed within the EU Horizon 2020 project REEEM[10] are used: the BASE pathway and the HighRES pathway. The pathways provide a consistent description of a possible future, decarbonisation targets and further technological, social and environmental developments (Gardumi et al. 2018).

Both pathways are placed within the same possible future which corresponds to the “Those Who Want More Do More” scenario as discussed in the ‘White paper on the future of Europe’ at the State of the Union 2017 (European Commission 2017a). It is assumed that energy policies within the EU will have more parallels within clusters of member states, with some setting more ambitious targets than others. Countries are clustered based on their socioeconomic situation, availability of resources and their geographical location (Gardumi et al. 2018).

The BASE pathway takes into account all existing EU-wide GHG-reduction goals as set in the 2020 Climate and Energy Package (EU 2009a) and the 2030 Climate and Energy Framework (European Commission 2014) as well as ambitious targets in 2050. This means all GHG under the EU Emissions Trading System (ETS) (European Commissions 2017b) have to be reduced by 20% in 2020 and by 43% in 2030 compared to 2005 levels. For non-ETS GHG country-specific reduction levels according to the

[10] http://www.reeem.org/

binding effort sharing decisions (EU 2009a, EU 2018) are considered for 2020 and 2030. (Gardumi et al. 2018) Reduction targets for 2050 are chosen in line with the Energy Roadmap 2050 (European Commission 2012), leading to an EU-wide 83% reduction compared to 2005 levels for ETS GHG. For non-ETS GHG, the concept of effort sharing is applied to defined country clusters with an EU-wide reduction of 75% relative to 2005 levels (Table 1).

In the HighRES pathway, additional targets for the share of renewable energy sources in gross final energy consumption (RES) following the Renewable Energy Directive (EU 2009b) are set (Gardumi et al. 2018). Following the country clusters, national targets are chosen for 2050 to match a 75% share across the EU as laid out in the Energy Roadmap 2050 (European Commissions 2012). The country clusters and respective targets are depicted in Table 1.

Table 6 Country clusters and targets for 2050

Country Cluster	GHG non-ETS (2050 rel. to 2005)	RES (2050)
Austria, France, Italy, Portugal, Spain, United Kingdom	-80%	85%
Belgium, Germany, Luxembourg, Netherlands	-80%	65%
Denmark, Finland, Ireland, Sweden	-80%	85%
Czech Republic, Poland	-50%	45%
Bulgaria, Croatia, Cyprus, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Romania, Slovakia, Slovenia	-60%	75%

For the current year 2015 (only BASE pathway), electricity production technologies as given by TIMES PanEU were matched to existing technologies in the Ecoinvent database. For future years (2020, 2030, 2050), the NEEDS[11] database was applied to also reflect possible developments in production efficiency and new evolving technologies. The NEEDS project covered three different scenarios, which differ in terms of optimism towards technological improvements, cost reductions and market growth rates of the technologies under investigation:

- pessimistic (PE): Socio-economic framing conditions do not stimulate market uptake and technical innovations.
- realistic-optimistic (RO): Strong socio-economic drivers support dynamic market uptake and continuous technology development.
- very optimistic (VO): A technological breakthrough makes the respective technology on the long term a leading global electricity supply technology.

In addition to the technology scenarios, three different future electricity mixes were developed, namely business as usual, 440 ppm CO_2 and enhanced renewables. Through the combination of technology and electricity mix scenarios, consistent scenario families have been created: realistic optimistic/440 ppm CO2, very-optimistic/enhanced renewables. Both consistent scenarios for

[11] http://www.needs-project.org/needswebdb/search.php [cited 2018-09-11]

technology development (realistic optimistic/440ppm and very optimistic/enhanced renewables) were applied to both TIMES PanEU pathways.

The NEEDS factors are only available for 2025 and 2050. To still be able to model 2020 and 2030 electricity mixes as needed in ICARUS, the 2025 NEEDS factors were applied to both years. In the case of missing processes in the NEEDS database, existing processes from Ecoinvent were used instead. Two different electricity storage technologies are modelled. Future battery storages are modelled as Lithium-ion-batteries with an energy density of 250 Wh/kg, as indicated by Thielmann et al. (2013) and Darmani et al. (2017) and an efficiency of one. Hydro-pump-storages are modelled based on the existing Ecoinvent process. In both cases electricity consumption (input) is considerable high due to the high efficiencies. To also reflect future developments in the energy system in this case, both technologies are modelled with the electricity mix of the respective country, year and scenario.

Depending on the need and availability of TIMES PanEU results, additional future scenarios may be added if these reflect ICARUS visions and their assumptions better than the existing TIMES PanEU results. Life cycle emission factors of all scenarios and countries can be found in the life cycle database. The structure of the database is as follows:

Table 7 Structure of electricity life cycle emission factor database (LCDB_Electricity)

Country	all EU28 countries + NO + CH and one average factor for Europe
Scenario	Base, HighRES
Scenario_technology	realistic– optimistic, very– optimistic
Year_	2015, 2020, 2030, 2050
Grid	low voltage, medium voltage, high voltage
Functional_unit	1 kWh
Pollutant	Considered pollutants are listed in section 4.
Category	Emission to air
Sub_ category	high population density, low population density, low population density long-term, lower stratosphere + upper stratosphere, unspecified
Emission_unit	kg

4.2 Data collection scope 3: Materials and production chain emissions

Scope 3 emission factors have been collected and calculated for two main consumption sectors: transport including road and rail and buildings and households including heating and insulation.

4.2.1 Data description and disaggregation: Buildings and Households

Heating

Life cycle emission factors for different heating systems were gathered through the Energy section of the Ecoinvent 2.0 database. The emission factors were grouped to represent different phases of the life cycle:

- Production of the infrastructure,
- Transport related to the infrastructure,
- Disposal of the infrastructure,
- Refrigerant cycle,
- Fuel cycle (apart from electricity),
- Operation direct emissions,
- Electricity during operation (has been replaced by factors calculated with the electricity scenarios, cf. section 4.1).

Factors for all scenarios and countries can be found in the life cycle database. The structure of the database is as follows:

Table 8 Structure of heating life cycle emission factor database (LCDB_Buildings_heating)

Heating_type_LC	Boiler, Furnace/boiler, Geothermal, Heat pump, Stove
Fuel_Type_LC	Natural gas, Oil, Wood, Electricity, Hard Coal, briquette
Technology_LC	at boiler atmospheric condensing modulating less 100kW, at boiler atmospheric condensing modulating more 100kW, …
Pollutant	Considered pollutants are listed in section 4.
Compartment	Air
Emission_unit	kg
Functional_unit	1 MJ heating energy
Production_infrastructure	Scope 3 emission factor
Transport_infrastructure	Scope 3 emission factor
Disposal_infrastructure	Scope 3 emission factor
Fuel_cycle	Scope 3 emission factor
Refrigerant_cycle	Scope 3 emission factor
Total_up_down	Scope 3 emission factor (complete)
Operation_electricity**	Scope 2 emission factor
Electricity_kWh/MJ **	Electricity consumption per functional unit
Operation_direct	Scope 1 emission factor (for comparison with AEFDB)
Conversion_MJ_finalEnergy_2_usefulEnergy*	Conversion factor

*The conversion factor provides the link to the AEFDB and the factor between activity unit and functional unit.

**Both columns provide the link to the electricity database; emission factors in column operation_electricity are calculated based on the generated life cycle emissions per kWh for the different energy system scenarios and the electricity consumption of the heating type.

Insulation

Life cycle emission factors for different insulation materials were added from the Insulation section of the Ecoinvent 2.0 database. These emission factors are related to the production of the different insulation materials. They were gathered in three different phases:

- Production,
- Transport related to production,
- Disposal related to production.

The insulation materials database has the following structure:

Table 9 Structure of insulation life cycle emission factor database (LCDB_Buildings_insulation)

Material	Cellulose fibre, inclusive blowing in, at plant Cork slab, at plant Foam glass, at plant Foam glass, at regional storage Foam glass, at regional storage Glass wool mat, at plant Polystyrene foam slab, at plant Polystyrene, extruded (XPS), at plant Rock wool, at plant Rock wool, packed, at plant Tube insulation, elastomere, at plant Urea formaldehyde foam, in situ foaming, at plant Urea formaldehyde foam slab, hard, at plant
Pollutant	Considered pollutants are listed in section 4.
Compartment	Air
Emission_unit	kg
Functional_unit	1 kg
Production	Emission factor
Transport	Emission factor
Disposal	Emission factor
Total_up_down	Emission factor (complete)

4.2.2 Data description and disaggregation: Transport

Life cycle emission factors were mainly obtained from the Rail and Road Transport sections of the Ecoinvent 2.0 database, which provide air emissions for the different life cycle processes related to transport. The following life cycle stages have been included in the database:

- Vehicle production,
- Maintenance of the vehicle,
- Disposal of the vehicle,
- Construction of the infrastructure (track and road),
- Maintenance of the infrastructure (track and road),
- Disposal of the infrastructure (track and road),
- Fuel production and transport.

Similar data were gathered for electric cars and two wheel vehicles thanks to the study realized by ESU-services in 2010 (Leuenberger M. 2010a, Leuenberger M. 2010b) and whose results were implemented in the Ecoinvent 2.0 database.
The air emissions were provided for one ton-kilometer for lorries and for one person-kilometer for other road vehicles which must be converted to vehicle kilometers to match the activity emission factor database. Therefore conversion factors taken from the Evoinvent 2.0 database have been added to the life cycle database (Frischknecht et al., 2007). The occupancy factor for passenger cars is about 1.59. The considered occupancy factors for buses are based on Swiss data, which refers values of 14 passengers for urban buses and 21 for coaches. For mopeds and motorcycles an occupancy factor of 1 was assumed. The average occupancy factor for trains was assumed to be 114 (Zampori et al. 2017).

The Ecoinvent database provides emission factors for the different type of vehicles, fuels and emission standards. Moreover, lorries are also divided according to their size. Emissions are available for the emission standards Euro3, Euro 4 and Euro 5 but also for a mix of them representing an average fleet. Some data represent the Swiss conditions while others represent European conditions.

The different categories from the activity emission factor database were matched with the categories from the life cycle database. The road transport section of the activity emission factor database has an additional level of disaggregation compared to the life cycle database, the “driving mode”, so the same life cycle data was applied for the activity emission factor database entries differing in driving modes. This approach is reasonable, since the driving mode only affects the operation emission factors that are taken from the more differentiated activity emission factor database.
The size disaggregation for the trucks is similar in both databases. For passenger cars, the activity emission factor database has different engine size categories while there is not this level of disaggregation in the life cycle database, the generic passenger car data was applied for passenger cars with different engine sizes.
The “motorcycles” and “mopeds” categories from the activity emission factor database were matched with “scooters” from the life cycle database. Emission factors for categories from activity emission factor that do not have a match in the life cycle emission factors database yet may be calculated from other relevant vehicle categories and fuels. More information can be found in Annex 1.

Table 10 Structure of Road transport life cycle emission factor database (LCDB_Transport)

Vehicle_type_LC	Coach, Electric bicycle, Electric scooter, Passenger car, Regular bus, Scooter, Tram, Trolleybus, Van
Size_LC	<3.5t, <32t, 16t-32t, 3.5t-7.5t, 7.5t-16t, not specified
Fuel_LC	Diesel, Electric, Hybrid , Natural gas, Petrol Propane/butane
Technology_LC	EURO 3, 4, 5, not specified
Pollutant	Considered pollutants are listed in section 4.
Compartment	Air
Emission_unit	kg
Functional_unit	pkm, tkm
Production_Vehicle	Scope 3 emission factor
Operation_Maintenance_Vehicle	Scope 3 emission factor
Disposal_Vehicle	Scope 3 emission factor
Production_Road	Scope 3 emission factor
Operation_Maintenance_Road	Scope 3 emission factor
Disposal_Road	Scope 3 emission factor
Fuel_cycle	Scope 3 emission factor
Total_up_down	Scope 3 emission factor (complete)
Operation_electricity**	Scope 2 emission factor
Electricity_kWh/pkm**	Electricity consumption per functional unit
Conversion_vkm*	Conversion factor

*The conversion factor provides the link to the AEFDB and the factor between activity unit and functional unit

**Both columns provide the link to the electricity database; emission factors in column operation_electricity are calculated based on the generated life cycle emissions per kWh for the different energy system scenarios and the electricity consumption of the transport type

Table 11 Structure of Rail transport life cycle emission factor database (LCDB_Transport)

Vehicle_type_LC	Freight Rail, ICE, Long distance train, Regional train, tram
Fuel_LC	Electricity, diesel
Pollutant	Considered pollutants are listed in section 4.
Compartment	Air
Emission_unit	kg
Functional_unit	pkm, tkm
Production_Vehicle	Scope 3 emission factor
Operation_Maintenance_Vehicle	Scope 3 emission factor
Disposal_Vehicle	Scope 3 emission factor
Production_Track	Scope 3 emission factor
Operation_Maintenance_Track	Scope 3 emission factor
Disposal_Track	Scope 3 emission factor
Fuel_cycle	Scope 3 emission factor
Total_up_down	Scope 3 emission factor (complete)
Operation_electricity**	Scope 2 emission factor
Electricity_kWh/pkm**	Electricity consumption per functional unit
Conversion_vkm*	Conversion factor
*The conversion factor provides the link to the AEFDB and the factor between activity unit and functional unit. **Both columns provide the link to the electricity database; emission factors in column operation_electricity are calculated based on the generated life cycle emissions per kWh for the different energy system scenarios and the electricity consumption of the transport type.	

4.3 Satellite system for automated calculation of emission changes

To allow an automated calculation of direct and indirect emissions through urban activities, a satellite system has been developed that can be linked to the activity emission factor databases generated in ICARUS Task 2.1 and Task 2.2. The satellite system consists of scope 2 and scope 3 emission factors and supplements the scope 1 emission factors in the current databases. Generally, changes in emissions result either from changes in activities or emission factors. The life cycle factors are provided in such a way that they refer to the activities in the existing activity emission factor database. Therefore, factors for the conversion of activity units (existing activity emission factor databases) and functional units (life cycle database) are included in the life cycle database. Linking the life cycle database/emission factors to the activity emission database makes it possible to simultaneously estimate the effect of emission reduction measures on direct and indirect emissions.

The conversion factors for transport (occupancy factor) and heating (utilization rate and annual coefficient of performance) are taken from Ecoinvent 2.0 database (Frischknecht et al., 2007). They may depend on city specific characteristics such as seat occupancy rates, but the European wide default values given in the LCDB can be used as a first estimate. For linking the electricity database to the scope 3 database, the electricity consumption per functional unit has been provided.

The structure of the satellite system and link to the current activity emission factor databases is shown in Figure 2. It follows three main principles:

- Scope 1 emission factors (i.e. operational emission factors) are taken from the current activity emission factor databases in WP2. For road transport and railways, a unified allocation, which is based on the European/top down emission inventory structure, can be used. Since the European/top down structure for heating is rather aggregated and bottom up city databases and life cycle database show a more disaggregated structure a provisional allocation has been introduced, but a flexible linkage depending on the specific structure of the bottom up database can be developed.
- Scope 2 emission factors (i.e. electricity use during the operation stage) have been calculated for two scenarios representing different renewable energy shares in the gross final energy consumption and two different technology sub-scenarios to also reflect possible developments in production efficiency and new evolving technologies. The emission factors for the specific scenarios have been included in the life cycle database for transport and building heating. The electricity consumption of the specific activities/processes has been taken from Ecoinvent 2.0 database.
- Scope 3 emission factors for production and construction, deconstruction and disposal of the infrastructure per functional unit have been collected using the Ecoinvent 2.0 database.

Scope 2 and scope 3 life cycle data as well as allocation tables are provided in 4 separate excel-files:

1. LCDB_Electricity (including the spreadsheet LCDB_EF_Electricity)
2. LCDB_Transport (including the spreadsheets LCDB_EF_Road and LCDB_EF_Rail)
3. LCDB_Buildings_heating (including the spreadsheet LCDB_EF_heating)
4. LCDB_Buildings_insulation (including the spreadsheet LCDB_EF_insulation)

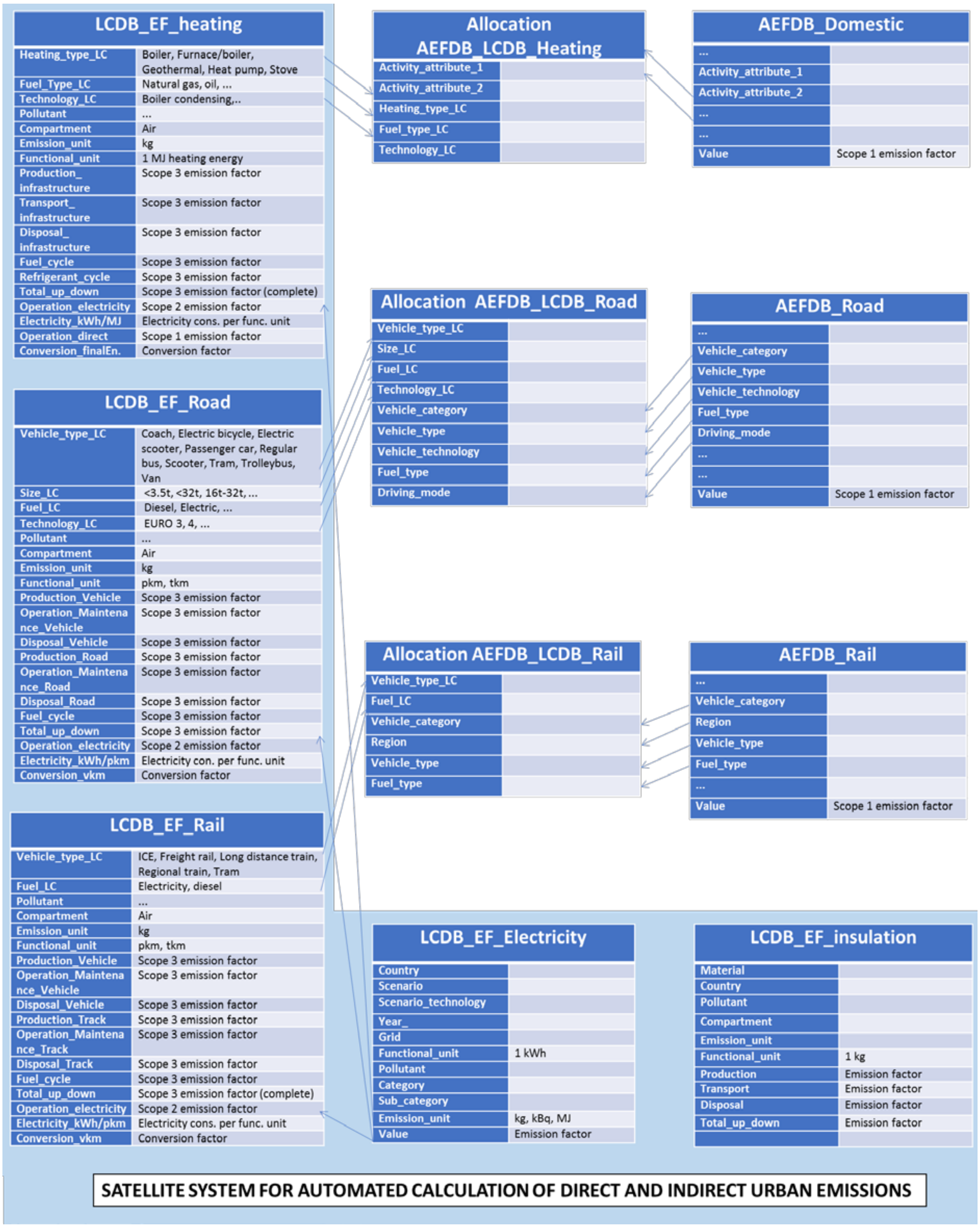

Figure 2 Structure of the satellite system and integration in existing databases

5 Application of the satellite system

Main objective of the collection of life cycle data is to quantify the changes in emission factors and emissions resulting from different European and urban measures, e.g. use of efficient and low carbon heating or switch from private transport to public transport.

5.1 Method

Generally, changes in emissions are caused by modifications either of activities or emission factors. The consumer or city oriented point of view leads to the fact that changes in the activity structure of the energy system manifest as changes in scope 2 emission factors. Therefore, emission factor changes are especially relevant for grid supplied electricity and district heat consumption. Since emissions of district heating are strongly dependent on the local heat generation, emphasis has been placed on electricity provision and estimated emission factor changes will be discussed in the next section. Scope 3 emission factors for considered activities in transport and heating do not show a yearly variation, since technological development and improvements (for example a higher share of condensing boilers or electric vehicles) are modelled through the disaggregated activity structure and not through an average emission factor as for scope 2 emissions. Therefore, the applicability of the satellite system has been verified by calculating two different measure scenarios with altering activity levels. Results are presented in section 5.3.

Generally, existing activity emission factor databases include all anthropogenic emission sources within the specified area (European or city level). This leads to the fact that upstream/downstream emissions of one activity might already be included in the operation emissions of another activity: e.g. emissions due to electricity consumption can be added as life cycle scope 2 emissions, but a small proportion of these emissions might also be included in the direct emissions of power plants within the city area. It is reasonable to assume this effect negligible for small urban areas and most of the considered activities like electricity consumption. However, an analysis of interdependencies between the scopes of emissions is required for other sectors as well, such as provision of district heating and waste management. To avoid a possible double counting when adding life cycle data to the emission inventories, it is therefore not feasible to calculate total city emissions by simply adding life cycle emissions to the operation emissions of all sectors, but to analyze the sectors separately. It is further recommended to make comparisons between different scenarios (with and without measure) by subtracting the emissions of the measure-scenario from the non-measure-scenario. The current method of linking scope 2 and scope 3 emission factors to single sectors and activities of the existing databases allows this with minimum effort.

The analysis of impacts on emissions for single measures has been done by comparing the emissions of the reference scenario with emissions of the measure scenario. In order to estimate the effect of the measures the following scheme has been adopted:

1. Calculating the baseline (business as usual) scenario for a future year (2020 and/or 2030)

2. Estimating the effect of short- and mid-term measures by comparing the measure scenarios against the baseline scenario

Emissions for the baseline and the measure scenario will be calculated by multiplying the activity level and (life cycle) emission factors for all pollutants. The emission analysis comprises the assessment of impacts at three different stages, as follows:

1. Direct emissions, **scope 1:** Operation (combustion processes and abrasion in transport)
2. Indirect emissions, **scope 2:** Electricity used for operation
3. Indirect emissions, **scope 3**: Upstream and downstream emissions due to construction/deconstruction or production/disposal of infrastructure, material and goods, maintenance of the infrastructure and fuel supply

$$Emission = Activity * (EFscope1/operation\_direct + EFscope2/operation\_electricity + EFscope3)$$

The resulting emissions include all direct and indirect emission releases caused by a specific activity. Direct emissions occur during the operation phase and are covered by the current activity emission factor databases. They not only include combustion related emissions, but also abrasion processes in transport. To calculate these emissions, the emission factors of the activity emission factor databases have been used. Indirect emissions occur during maintenance of infrastructure as well as construction and deconstruction processes at the up- and downstream level of the process. Furthermore, emissions related to the consumed electricity for each process have been considered as scope 2 emissions.

In summary, the calculation of emission changes is performed based on a comparison of the baseline scenario to those scenarios where specific measures have been implemented. The application of the above described approach shows changes in urban emissions for each process/activity relevant for the measure and avoids a double counting of emissions.

5.2 Electricity – future emission factor changes

Indirect emissions due to electricity use in households and transport are an important part not only of the total city carbon footprint, but also because they affect the "air pollution footprint" of a city. Furthermore the actual benefit of measures focusing at an increased share of electricity depends strongly on the electricity generation mix in the respective country, e.g. several studies show that the composition of power plants has a major influence on the life cycle emission balance for electric vehicles and buildings (Helms et al. 2010; Cabeza et al. 2014). The effect of fuel switching in electricity production is further complicated by different abatement technologies used at power plants. Thus, direct emission changes of the electricity production sector due to different shares of fuels and future technologies have an influence on emission changes of measures aiming at an increasing electrification and alter the global effect of these measures.

To be able to take this effect into account when calculating measures in transport and household sector, different scenarios for the future electricity system have been examined. The generated life cycle emission factors are scenario and country specific and available for all European countries as well as Norway and Switzerland. They are available for a base scenario (BASE) and a scenario with a higher target share of renewable energies (HighRES). For both scenarios, two sub-scenarios (realistic-optimistic and very optimistic) with different assumptions regarding technological development have been generated. In addition to the scenarios a differentiation of the grid in high, medium and low voltage has been introduced. The scenarios cover the years 2015, 2020, 2030 and 2050. The functional unit of the calculated emission factor is 1 kWh.

Figure 3 - Figure 5 show the development of emission factors from 2015 to 2050 for all ICARUS countries. As an example the emission factors for fossil CO_2, NO_x, and PM_{10} at a low voltage grid are shown. The generated emission factors include all relevant life cycle stages such as the operational (fuel combustion) phase of energy production and the upstream and downstream processes of construction and deconstruction of power plants, fuel supply, maintenance and grid. Reductions or in some cases increases of emission factors depend on country and scenario. Differences between technological sub-scenarios (realistic-optimistic and very-optimistic) are rather small. The respective emission factor changes compared to the base year 2015 can be found in Annex 2.1. Emission factor reductions for medium and high voltage grids and further pollutants can be calculated with the help of the life cycle database.

The BASE scenario takes into account all existing EU-wide GHG-reduction goals as set in the 2020 Climate and Energy Package (EU 2009a) and the 2030 Climate and Energy Framework (European Commission 2014) as well as ambitious targets in 2050. For non-ETS GHG country-specific reduction levels according to the binding effort sharing decisions (EU 2009a, EU 2018) are considered for 2020 and 2030. Reduction targets for 2050 are chosen in line with the Energy Roadmap 2050 (European Commission 2012), leading to an EU-wide 83% reduction compared to 2005 levels for ETS GHG. In the HighRES scenario, additional targets for the share of renewable energy sources in gross final energy consumption (RES) following the Renewable Energy Directive (EU 2009b) are set.

The binding EU targets regarding the share of renewable energy sources in gross final energy consumption in 2020 and 2030 are also achieved in the BASE pathway due to general decarbonisation. The additional renewable targets in the HighRES pathway, still lead to a lower carbon intensity of final energy consumption in all considered years compared to the BASE pathway. However, since the targets are set as national shares in gross final energy consumption, this does not automatically lead to less carbon intensive electricity production. The complex interactions of national renewable targets and Europe-wide decarbonisation targets in the electricity sector as part of the ETS as well as availability of renewable energy sources, secure energy supply conditions and electricity trade between neighbouring countries can, indeed, result in a slower decarbonisation of electricity production in some countries. Without any fixed renewable targets in the BASE pathway, nuclear power is utilized as a carbon-neutral technology as long as there is no fixed exit strategy, e.g. in France. With the ambitious renewable targets in the HighRES pathway in 2050, the share of renewables has to be increased also in electricity production which leads to less investments in nuclear power even if a country allows new investments. Due to the perfect foresight characteristic of the TIMES PanEU model, this also results in less utilization of nuclear power in earlier years. To balance this out and to account for secure electricity supply, this results in a slower coal and lignite exit in countries with less ambitious renewable targets. In Germany, for example, overall electricity production is higher in the HighRES pathway with a higher share in electricity from coal as Germany exports more electricity in this scenario, especially to France which utilizes less nuclear power due to their ambitious renewable targets. Additionally, the renewable targets reduce the utilization of natural gas in the combined power and heat plants, which acts as a transition technology in the BASE pathway. As the model takes the ambitious RES targets in 2050 into account, it rather utilizes additional capacities in 2030 to provide secure electricity in the case of low availability of renewable energy sources then to invest into low-carbon transition technologies as it is the case in the BASE pathway. Overall these kind of interactions between decarbonisation and national renewable energy targets on final energy consumption, the specific availability factors and the chosen country clusters result in a faster decarbonisation of electricity production in some countries, in others the decarbonisation appears to be slower with a peak in 2030 as most of decarbonisation happens after 2040 in this case due to the ambitious targets in 2050. This slower decarbonisation can then also lead to higher direct emissions of electricity production in the HighRES pathway compared to the BASE pathway if a the decommissioning of coal and lignite power plants is affected, which is then also reflected in the Life Cycle Emission factors (compare DE 2030 CO_2 and PM_{10} emissions).

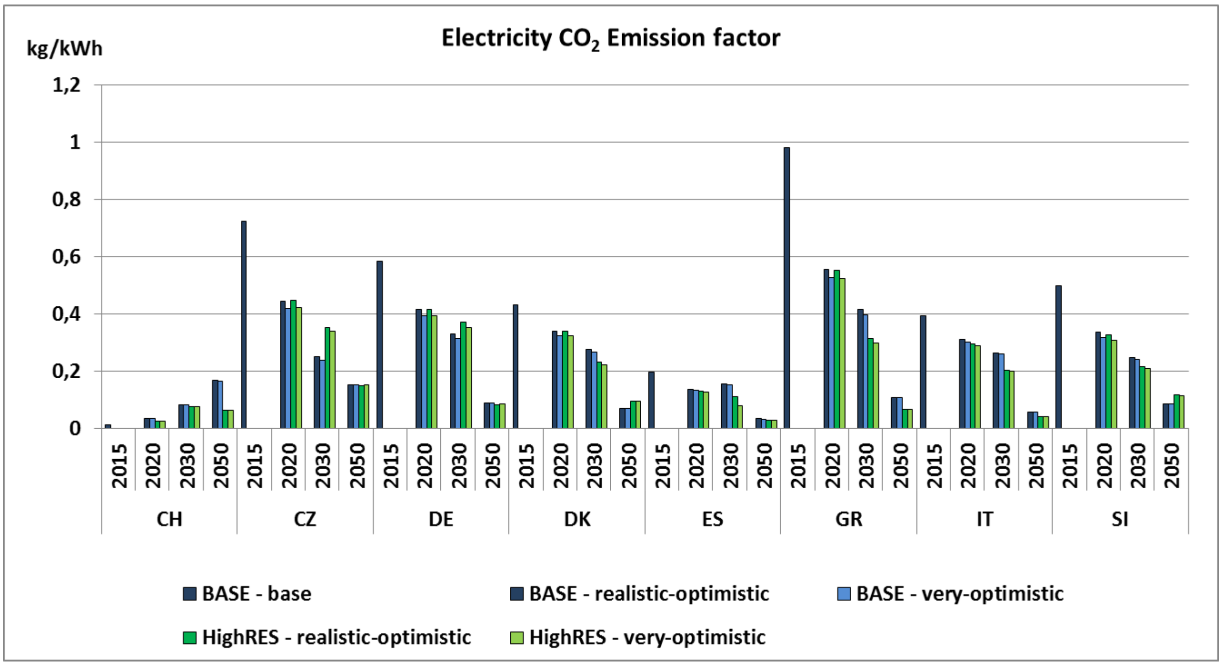

Figure 3 Development of CO_2 emission factors for different scenarios, low voltage grid

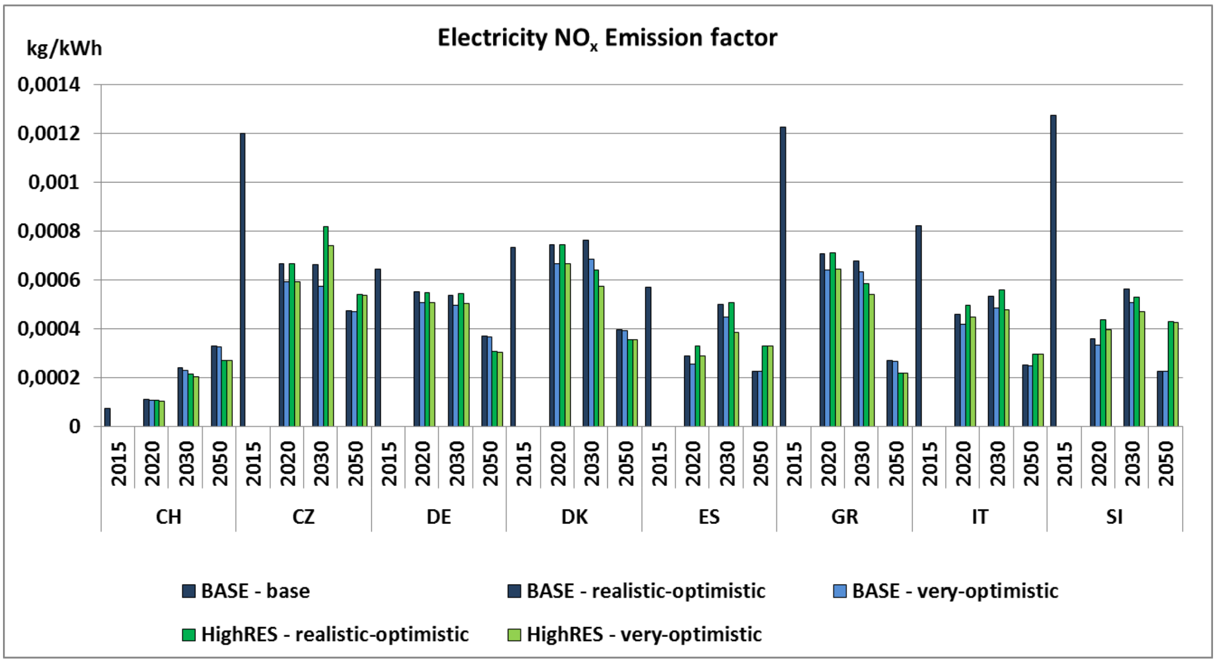

Figure 4 Development of NO_x emission factors for different scenario, low voltage grid

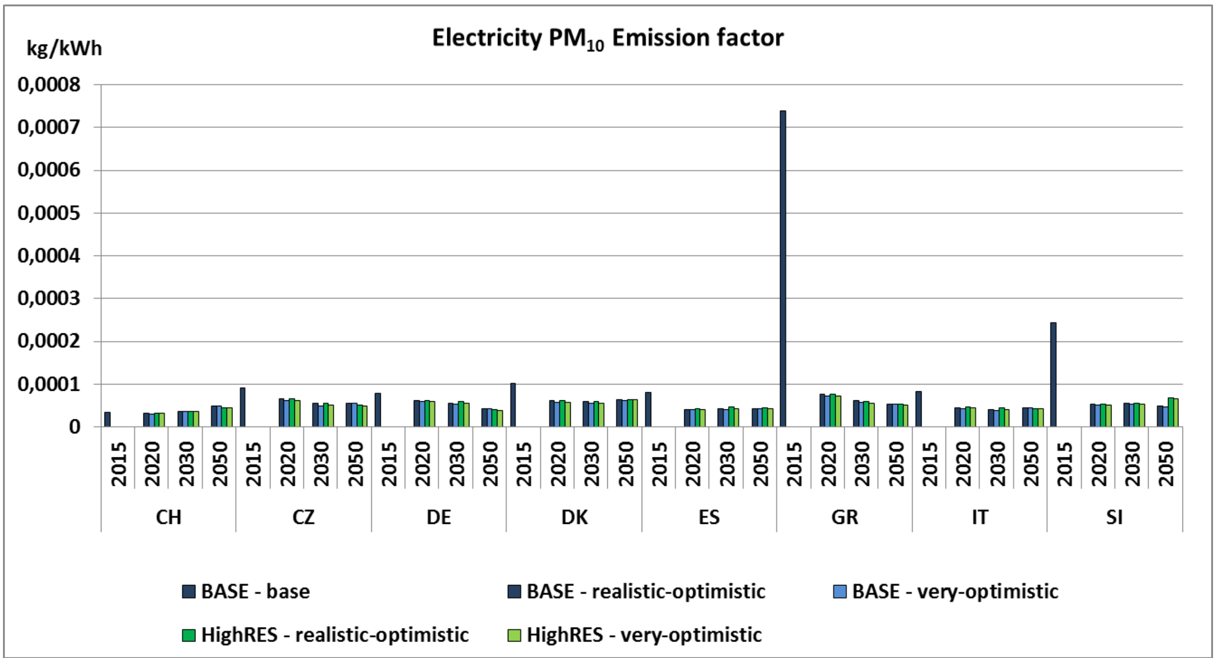

Figure 5 Development of PM_{10} emission factors for different scenarios, low voltage grid

5.3 Measure examples – emission reductions

The following section briefly presents the most relevant measures in the buildings and transport sector as selected by the city partners and the importance of the life cycle perspective. These measures can be modelled as activity changes and with the help of the life cycle database direct and indirect emission changes can be automatically estimated. Respective (life cycle) emission changes in each ICARUS city will be simultaneously estimated with the calculation of effect and costs of measures in WP5. This procedure aims at using a coherent measure calculation method for the estimation of emissions with and without life cycle perspective and makes it possible to compare the effect of one measure at different levels. Therefore, the life cycle database and satellite system have been made available for direct use in ICARUS WP5. In order to test the applicability of the life cycle database, two scenarios have been identified for exemplary usage of the satellite system. The scenario analysis has been conducted for the years 2020 and 2030 depending on the timeframe of the considered measure. The first scenario (H 2020/2030) concerns the switch of heating technologies in the case study city Stuttgart and has been calculated for the years 2020 and 2030. A second scenario in the transport sector concerns the fostering of car independent lifestyles in European-wide urban areas (T 2020). The presentation of results will focus on CO_2, NO_x and PM_{10}.

5.3.1 Buildings and households

Emission causing activities related to buildings are the use of the dwelling by its inhabitants; especially due to electricity and water use for space heating, appliances, cooking, cooling, domestic hot water, lighting, water and the maintenance of the buildings including the replacement of building components and renovation activities. Therefore, life cycle emission factors have been provided for two different purposes: Heating technologies and insulation materials. Measures of the buildings and households sector discussed in WP5 include especially:

1) Enhanced energy conscious behavior and efficiency improvements of appliances

2) Increase of building renovation and energy efficient building design

3) Environmentally friendly heating technologies (switch to electricity heat pumps/ district heating)

1) Due to electricity use in households, the residential sector is an important indirect emission source. Measures aiming at reduced energy consumption through **enhanced energy conscious behavior and efficiency improvements in the use of appliances and lighting** will reduce indirect emissions due to electricity consumption (scope 2 emissions). For example, in 2015 households account for 25-30 % of the city's electricity use in Stuttgart and thus for an equal share of scope 2 emissions. After assuming a target value of electricity savings in kWh, avoided emissions can be calculated using the provided electricity emission factors for country specific scenarios. The achieved emission savings will decrease in future years as the scope 2 emission factor decreases (cf. Table 12).

Table 12 Emission savings for reductions of the German electricity factor: BASE – realistic-opt.

	CO_2	NO_x	PM_{10}
2015	0%	0%	0%
2020	29%	14%	22%
2030	43%	17%	29%
2050	84%	43%	46%

2) Measures aiming at an **increase in the buildings renovation rate** and energy efficient design lead to a decrease of space heating demand. This results, on the one hand, in less energy demand for the buildings operation, but on the other hand increases energy demand and emissions for the buildings production/maintenance phase. After estimating the amount of avoided heating demand, saved emissions can be calculated by reducing the amount of final energy for heating in the activity emission factor database. This procedure results in a decrease of scope 1 emissions. Relevant for the estimation of scope 3 emissions is the material used for constructing the buildings insulation. A study by Gustavsson and Joelsson (2010) shows that 45 – 60 % of the primary energy production of a low-energy building can be attributed to the production phase with higher variations for conventional buildings. Furthermore, it has been highlighted that CO_2 emissions and energy use depend mainly on the energy supply. Compared to fuel-based electricity, biomass based district heating with cogeneration accounted for 70 % lower operational primary energy use for conventional single-family houses and 40 % for a passive row house. In the future the share of energy use in the operation phase will most likely decrease while the buildings construction phase will gain influence when considering the energy demand and resulting emissions of the building (Cabeza et al. 2014). Measures fostering the increase of the renovation rate will be calculated in WP5 since they strongly depend on the cities renovation rate and selection of the insulation material. For this purpose, a database with life cycle factors for different insulation materials has been set up.

3) Environmentally friendly heating technologies for buildings include for example solar thermal, combined heat and power, heat pumps, but also efficient fossil fuel technologies, such as condensing boilers, biomass and biofuels. The life cycle emission factor database for heating comprises different boiler technologies for natural gas and oil (condensing/non-condensing, modulating/non-modulating), heat pumps, and wood boilers. The emissions of district heating depend on the local energy mix, which is why no national life cycle factor has been provided.

Figure 6 shows the fossil CO_2 emission factors for different heating technologies and years in Europe. Emission factors for PM_{10} and NO_x can be found in Annex 2.2. The emission factors are aggregated according to the energy carrier and give the average for all ICARUS countries. In this case the baseline realistic-optimistic scenario has been used to calculate the average emission factors for heating. The link to different energy scenarios as described in 4.3 allows also the calculation of country specific factors. Emission factors for heat pumps decrease by about 70% from 2015 to 2050, while emission factors for combustion related heating technologies do not significantly decrease.

Figure 7 shows that scope 1 emission factors account for the major share of total CO_2 life cycle emissions when considering combustion related heating technologies like oil and gas boilers. The contribution of each life cycle stage can be found in Annex 2.2, Table 30. The contribution ranges from 85% for oil boilers to 92% for coal. On the contrary, emission factors for heat pumps are mainly dominated by the electricity related emissions (scope 2). Depending on the considered year the share of scope 2 emission factors ranges from 86% in 2015 to 56% in 2050. The decreasing absolute scope 2 emissions of heat pumps lead to an increasing importance of scope 3 emissions in future years. Scope 3 emissions play an important role for wood firings, as biomass combustion is assumed to be carbon neutral and electricity is not needed for operation. The high share of scope 2 and scope 3 emissions in wood boilers and heat pumps highlights the importance of life cycle analysis when calculating measures for future heat supply.

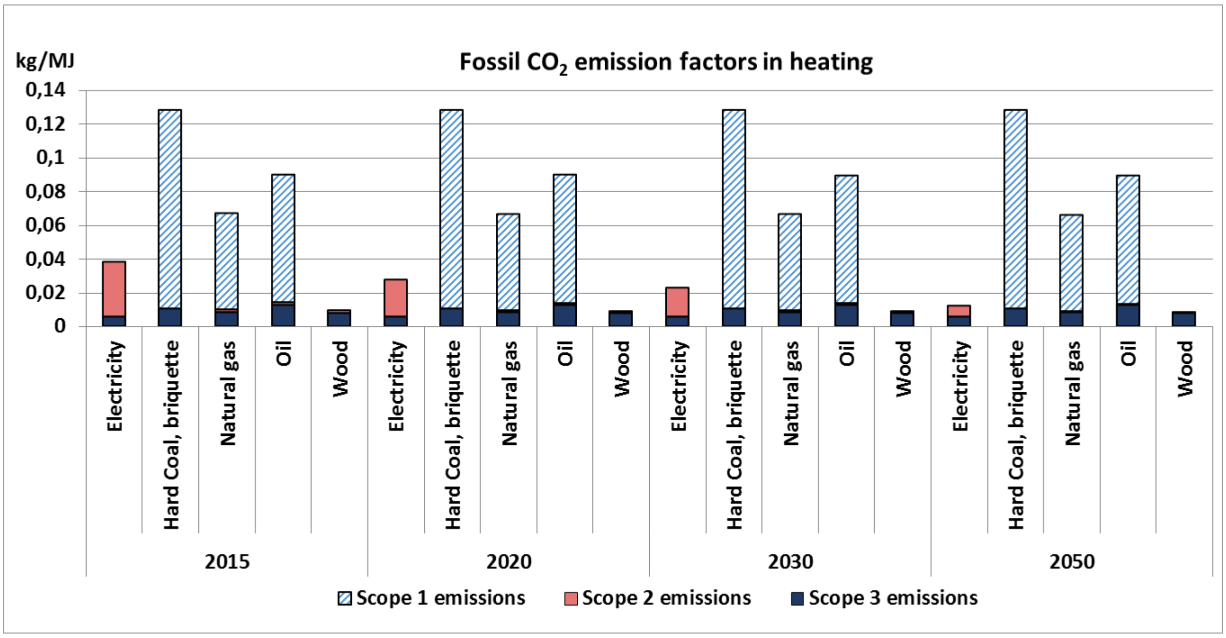

Figure 6 Average fossil CO_2 emission factors for different heating types in the BASE – realistic optimistic scenario (electricity: heat pumps, oil/wood/natural gas: boilers, hard coal: stoves)

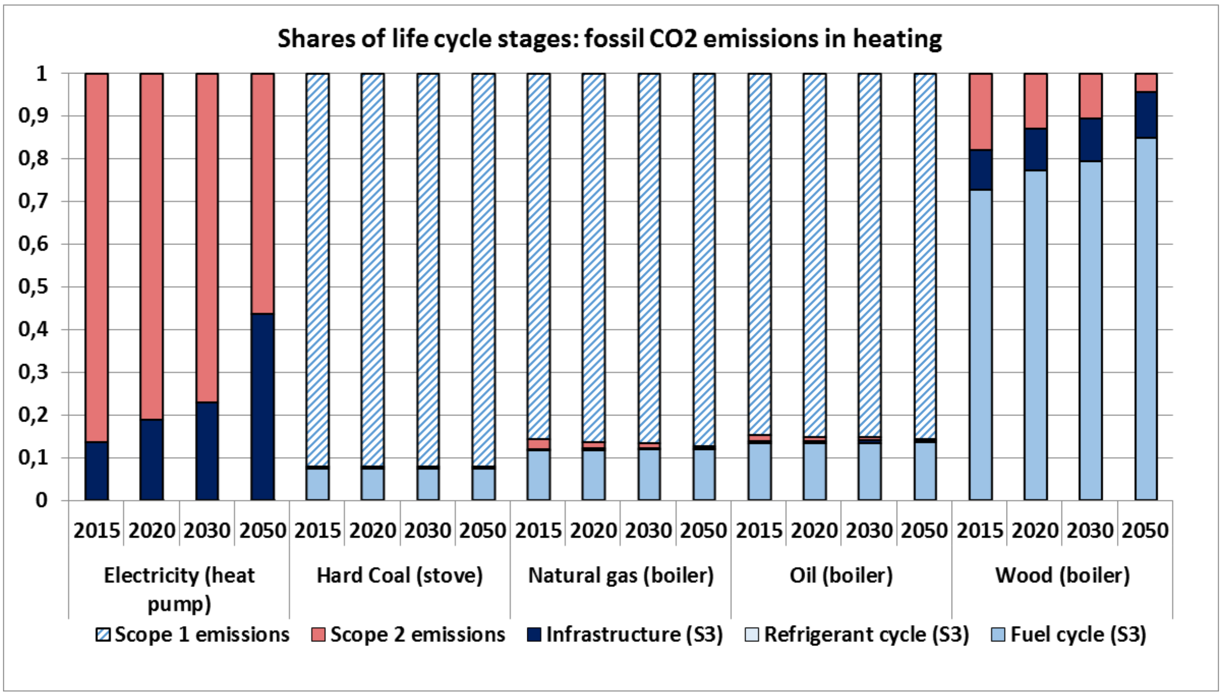

Figure 7 Shares of life cycle stages for fossil CO_2 emissions of different heating technologies and years (BASE – realistic optimistic scenario)

A study by Greening and Azapagic (2012) comparing gas boilers with heat pumps in the UK shows that heat pumps can have higher environmental impacts due to the use of electricity. In this study the total CO_2 life cycle emission factor for heat pumps is lower than for natural gas for all years and countries except for Greece in 2015. The decrease of the absolute emission factor for heat pumps from 2015 to 2050 reflects the change in the energy system as described in section 4.1. The averaged emission factor for conventional heating technologies does not change significantly over the years due to the high share of direct emissions, which is assumed to be constant in this scenario. A future development of boiler technologies can be modelled using the activity disaggregation of the database so that future emissions scenarios with varying technology mixes can be calculated. The emission factors are therefore provided for different technologies as shown in Figure 8.

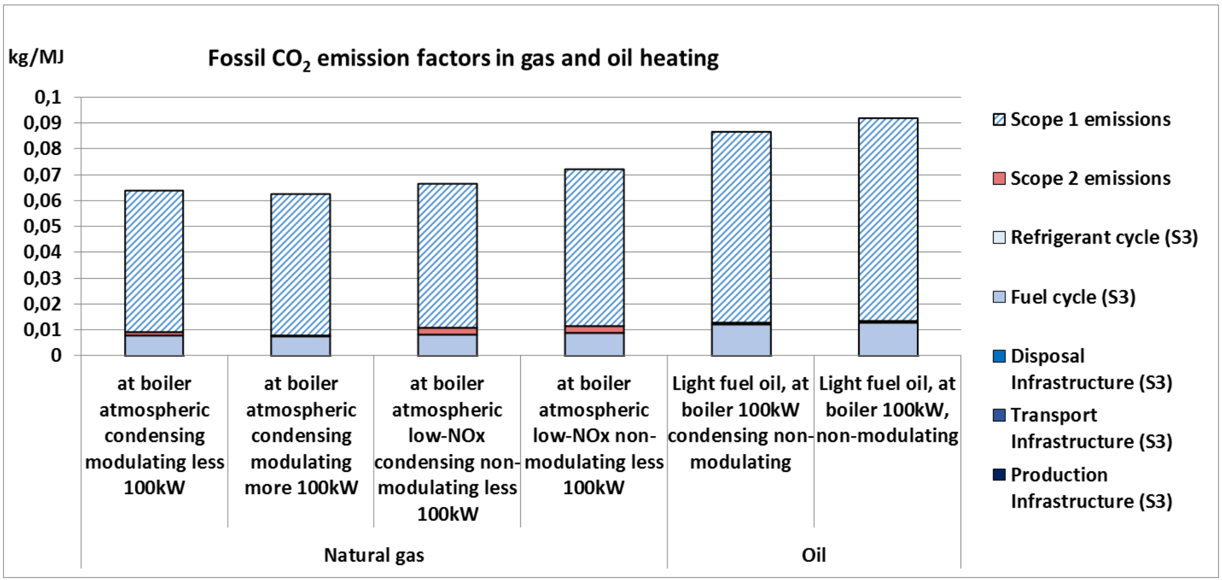

Figure 8 Fossil CO_2 emission factors for different gas and oil heating types in the BASE – realistic optimistic scenario (S3: scope 3)

According to the above mentioned impact parameters, the following scenario has been considered for an analysis of emission changes in the case study city Stuttgart:

Measure example – Stuttgart: Replacement of oil fired heating by electric heat pumps (H2020/2030)

The example measure considers the complete exchange of oil fired heating systems in the residential and commercial sector by heat pumps in Stuttgart by the year 2020 and 2030. Emission factors for different heating technologies have been calculated with life cycle scope 2 electricity factors for Germany. The considered scenarios are Base and HighRES with a realistic-optimistic technology sub-scenario. German emission factors can be found in Annex 2.2, Figure 18. Scope 3 emission factors have been taken from the life cycle database for heating and linked to the bottom up structure of the activity emission factor database for Stuttgart. Oil fired plants provide about 2 PJ/a heating in 2015, about 1.7 PJ in 2020 and 1 PJ in 2030 and thus contribute 16% to 10% to the heating energy provision. A switch to heat pumps would reduce the direct emissions of CO_2 by about 130kt in 2020 and 80kt in 2030 (cf.

Figure 9). This is about 20 % of the CO_2 emissions caused by all heating activities in 2020 and 16 % in 2030 (2020: 665kt, 2030: 492kt CO_2).

The total life cycle emissions of the heat pumps compared to the oil fired heating systems account only for 28% in 2020 and 22-25% in 2030 depending on the electricity scenario. The smaller share in 2030 is caused by a less CO_2 intense electricity mix. Emissions related to the infrastructure play a minor role in the total emissions when comparing CO_2 emissions of both heating systems. Results for PM_{10} and NO_x can be found in Annex 2.2. The results show that the fuel cycle and therefore scope 3 emissions account for a larger share of total emissions when considering NO_x and especially PM_{10} instead of CO_2 emissions. However, the general trend between BAU and H2020/2030 scenario remains unchanged and the H2020/2030 shows fewer emissions for all pollutants. The impact of the different energy scenarios on the absolute emissions in 2020 and 2030 is negligible.

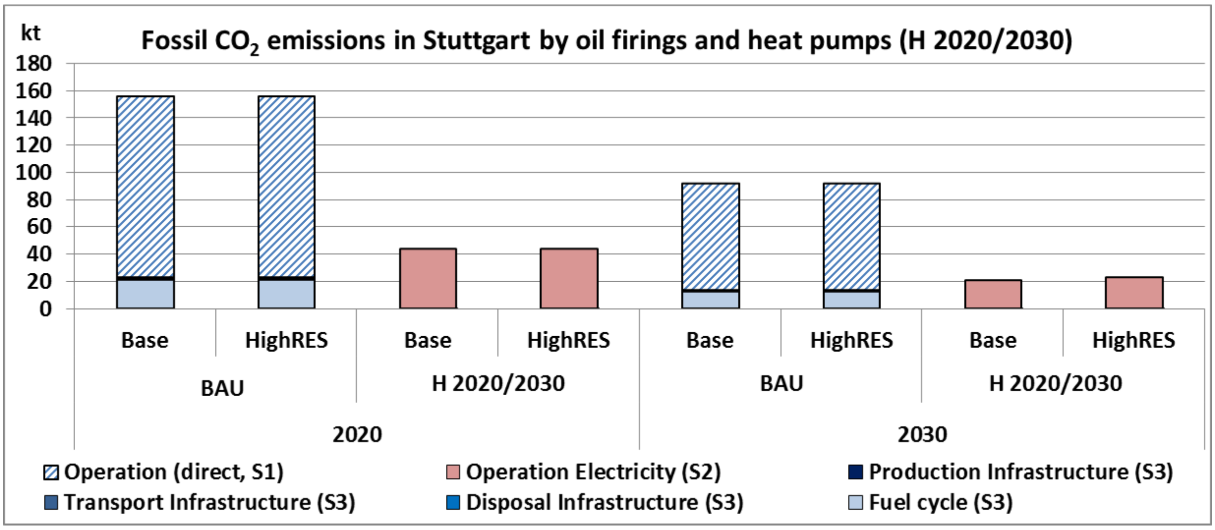

Figure 9 H2020/2030 – Fossil CO_2 emissions in Stuttgart by oil firings and heat pumps

5.3.2 Transport

Emissions of the transport sector are caused by vehicle engines, abrasion processes, electricity consumption (mainly in rail-bound public transport), and provision of infrastructure and transport means. Transport measures discussed in WP5 concern:

1) a switch from conventionally fueled vehicles to hybrid/e-cars or alternative fuels

2) a switch of transport modes (mainly from private cars to public transport or to slow modes like walking and cycling)

1) A life cycle perspective should be conducted when comparing the emissions due to **electric and hybrid vehicles and alternative fuels**. Kugler (2012) estimates that a higher share of electric vehicles in urban areas in 2020 (5-10 %) causes emissions up to 14.000 t CO_2, 230 t NO_x, 10 t PM_{10} and 10 t SO_2. These emissions mainly depend on the assumed electricity mix, which is why different scenarios for scope 2 emission factors have been provided. Several studies show that the composition of power plants has a major influence on the life cycle emission balance for electric vehicles (Helms et al. 2010; Lane 2006; Pötscher et al. 2014; Aguirre et al. 2012). Tessum et al. (2014) show that vehicles using corn ethanol or the grid average electricity increase monetized environmental health impacts by 80% or more relative to conventional gasoline. Conversely, electric vehicles powered by renewable energy sources like natural gas, wind, water, or solar power reduced environmental health impacts by 50% or more.

The current emission inventories in WP2 consider a business as usual scenario, which reflects a rather conservative development with stagnating shares of alternative driving technologies. In order to allow the modelling of scenarios with a higher share of electric and hybrid vehicles**,** a new vehicle category (hybrid) has been introduced into the activity emission factor databases and linked to the life cycle database emission factors. Operation emission factors for hybrid cars are taken from the COPERT 5[12] model, while life cycle factors are modelled as described in Annex 1. It was assumed that hybrid cars operate 69% in electric mode and the electricity consumption has been calculated accordingly. The electricity consumption for each vehicle type (hybrid and electric) can be linked to the electricity life cycle database. Figure 10 – 12 show the shares of different life cycle stages on total emissions for diesel, petrol and hybrid vehicles. The emission factors have been calculated for the European BASE realistic-optimistic scenario. It can be seen that diesel scope one emissions have with 80-90% a major influence on total CO_2 and NO_x emissions, while scope 3 emissions account for 40-50% of PM_{10} emissions. Gasoline vehicles show a similar distribution for CO_2 and PM_{10} and a comparably high impact of the fuel cycle on total NO_x emissions. Emissions of battery electric vehicles and hybrids are dominated by scope 3 and scope 2 emissions. Scope 1 emissions from hybrids are caused by the combustion driving mode and scope 1 PM_{10} emissions of battery electric vehicles result from tire and brake abrasion.

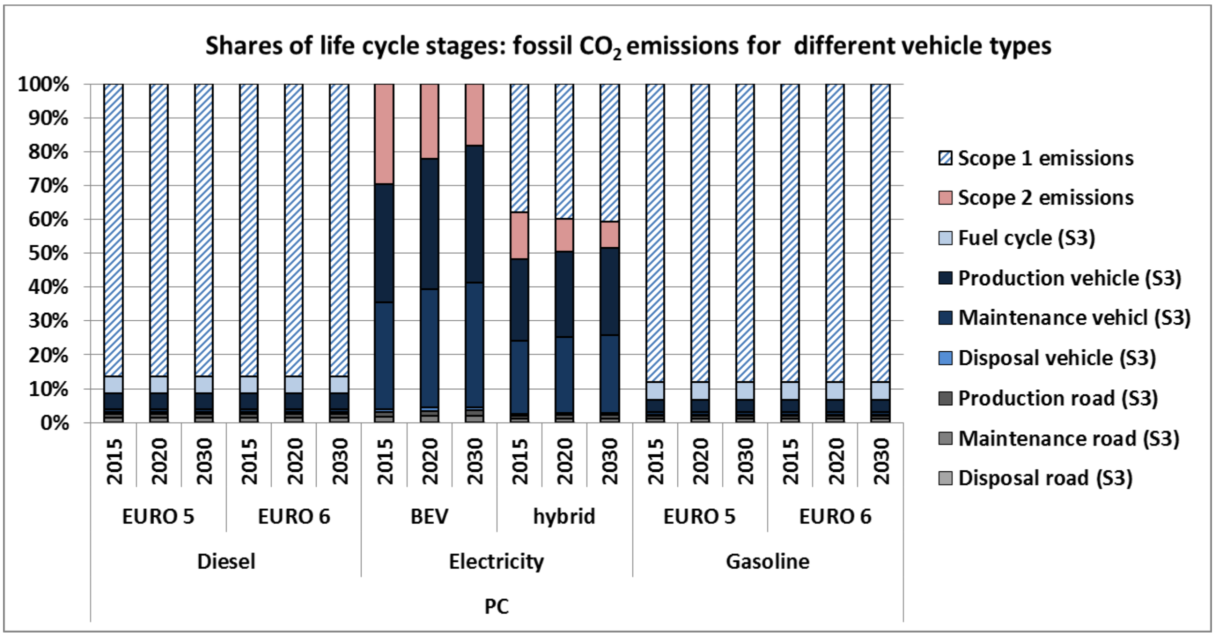

Figure 10 Shares of life cycle stages for fossil CO_2 emissions of different vehicle types and years (BASE – realistic optimistic scenario)

[12] http://emisia.com/products/copert/copert-5 (last accessed: 12.10.2018)

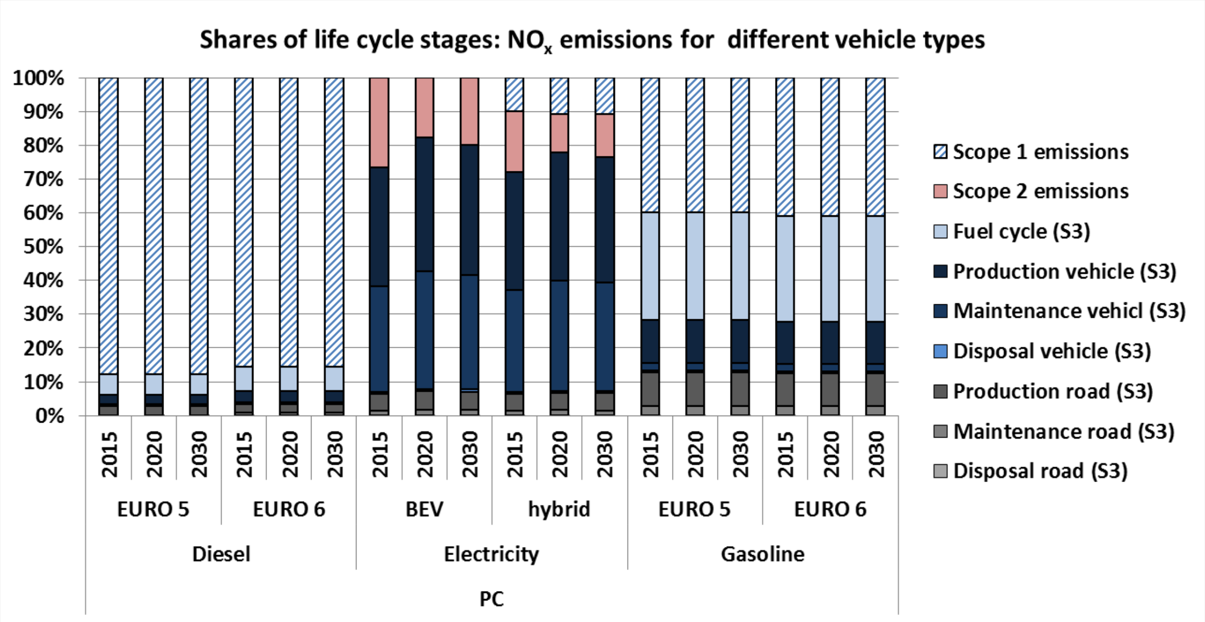

Figure 11 Shares of life cycle stages for NO_x emissions of different vehicle types and years (BASE – realistic optimistic scenario)

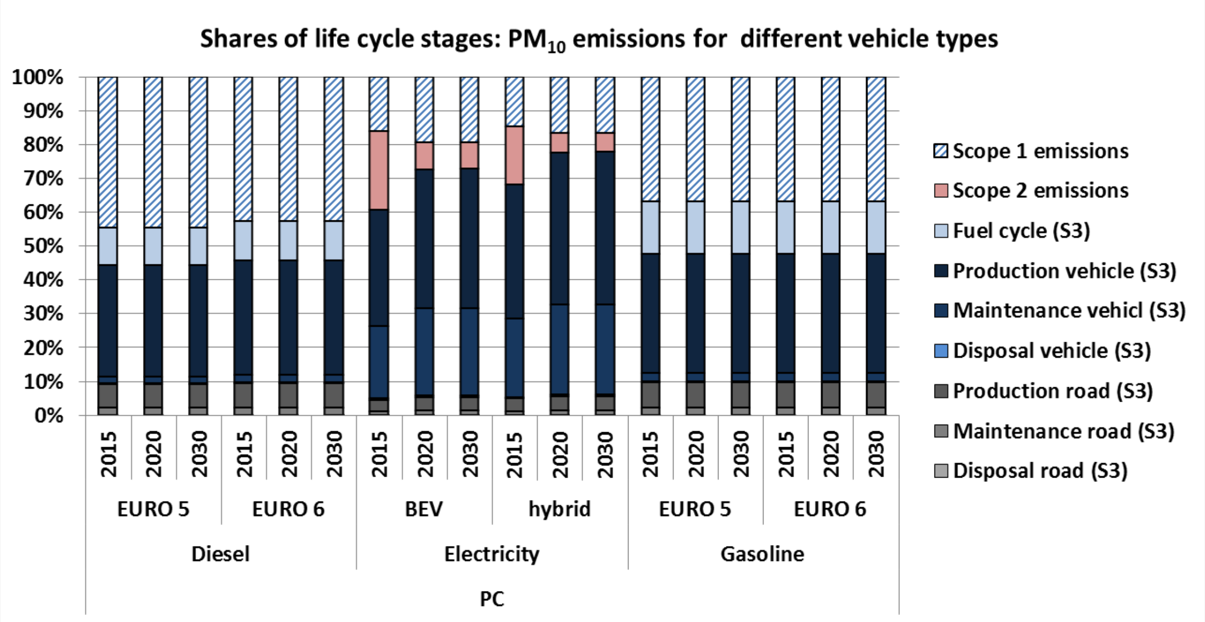

Figure 12 Shares of life cycle stages for PM_{10} emissions of different vehicle types and years (BASE – realistic optimistic scenario)

2) The comparison of **different transport modes** and alternatives makes it especially crucial to consider life cycle emissions (Chester et al. 2013). An electric powered tram or metro emits no tailpipe emissions, but the electricity it uses causes a significant amount of upstream emissions. In contrast, a natural gas powered bus emits emissions from both tailpipe and upstream. The need to consider the whole life cycle perspective becomes even more important when evaluating options leading to increased public transport, as for public transport systems the electricity used for infrastructure operation is a high impact component in the whole life cycle (Air quality expert group 2007). According to the above mentioned impact parameters and in order to test the applicability of the life cycle database, the following scenario has been considered for detailed analysis of emission changes:

Measure example – Urban areas in Europe: Switch of transport modes, car independent lifestyles (T1 2020)

This scenario concerns a modal shift from private passenger cars in favor of public transport and slow transport modes like cycling and walking. The switch from private cars to public transport can be fostered by many different measures, as for example the introduction of low emission zones. Kugler (2012) has estimated that the introduction of a low emission zone in all European urban areas and the resulting increase in the use of electrified transport modes (metro&tram) would lead to additional emissions by about 107 t CO_2, 115 t NO_x, 40 t PM_{10}, and 639 t SO_2. Other measures aiming at a switch of transport modes are the introduction of express bus lines and more frequent and extended services. The options chosen by ICARUS city partners show a variety of specific measures ranging from zone specific measures to infrastructure changes, so that the effect on the emission changes can be estimated only for individual cases.

In order to still show the potential effect of different measures fostering a change of transport modes, scenario T1 2020 assumes a default reduction of private passenger car vehicles kilometres by 10%. This scenario acts only on the vehicle kilometres travelled in urban areas, which account for about 20% of the total vehicle kilometres in Europe according to the activity emission factor database developed in ICARUS Task 2.1. Since detailed information about the kilometer share travelled by different kinds of urban public transport like metro, tram and buses are not provided by the European database, is has been assumed that all kilometers substituted by public transport are covered by urban buses. Scenarios considering a shift to electrically driven transport modes like metro and tram will be further evaluated at the city level.

In detail, it has been assumed that 90% of the travelers shift to urban buses (diesel EURO 6) and 10% substitute the trips by walking and cycling. The vehicle kilometers of urban buses have been increased coherently with this assumption.

Figure 13 - Figure 15 show the comparison between the baseline scenario and scenario T1 in terms of absolute emissions. It can be seen that the decrease of private transportation and subsequent increase of kilometers travelled by public transport, i.e. urban buses, leads to a slight reduction in emissions ranging from 0.8% for PM_{10} to 1.22% for NO_x and 1.25% for CO_2. Emission reductions can be found in Annex 2.3. The influence of the individual life cycle stages on the total emissions follows the general relations as shown in Figure 10 - Figure 12. The higher emission reduction potential for CO_2 comes from the higher share of direct operation emissions on the total life cycle emissions. The fuel cycle particulate matter emissions of buses are relatively high, which leads to a part-compensation in the measure scenario. The reduction can be expected to be proportional to the share of modal shift assumed in the scenario.

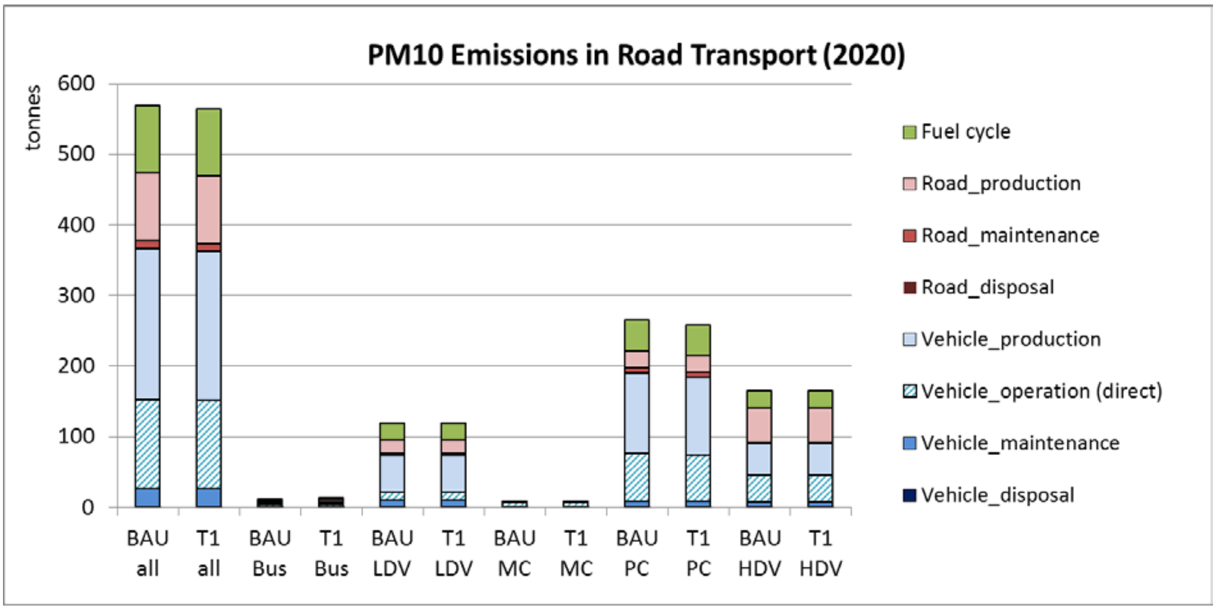

Figure 13 T1 2020 – PM_{10} emissions in Road Transport in European cities

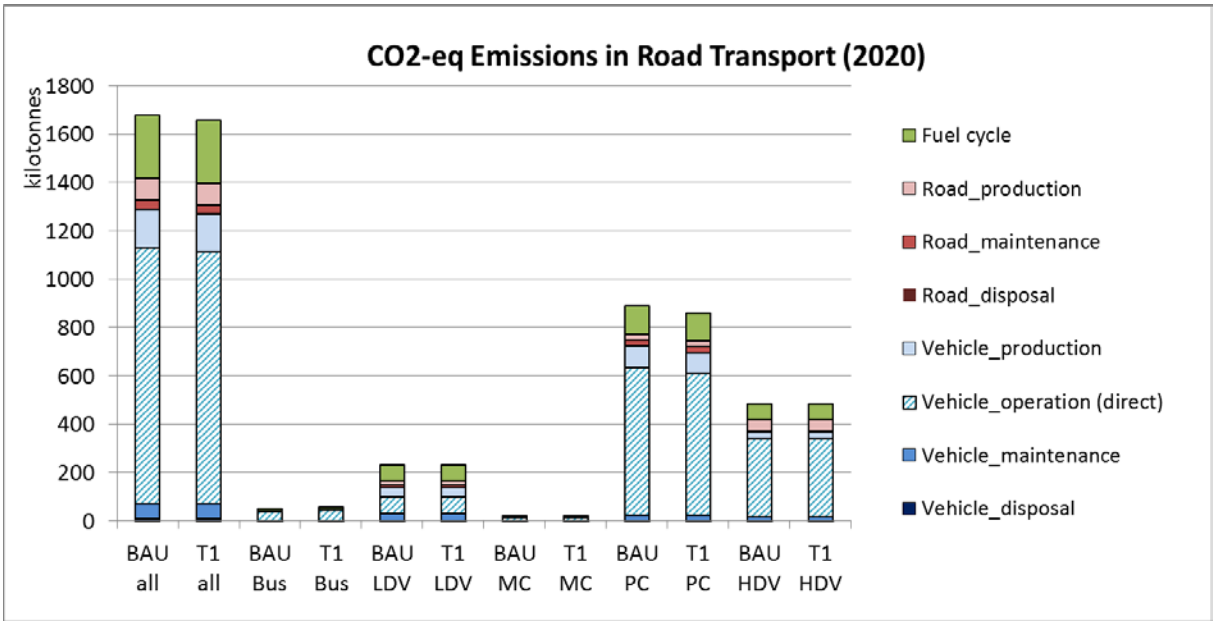

Figure 14 T1 2020 – CO_2-eq emissions in Road Transport in European cities

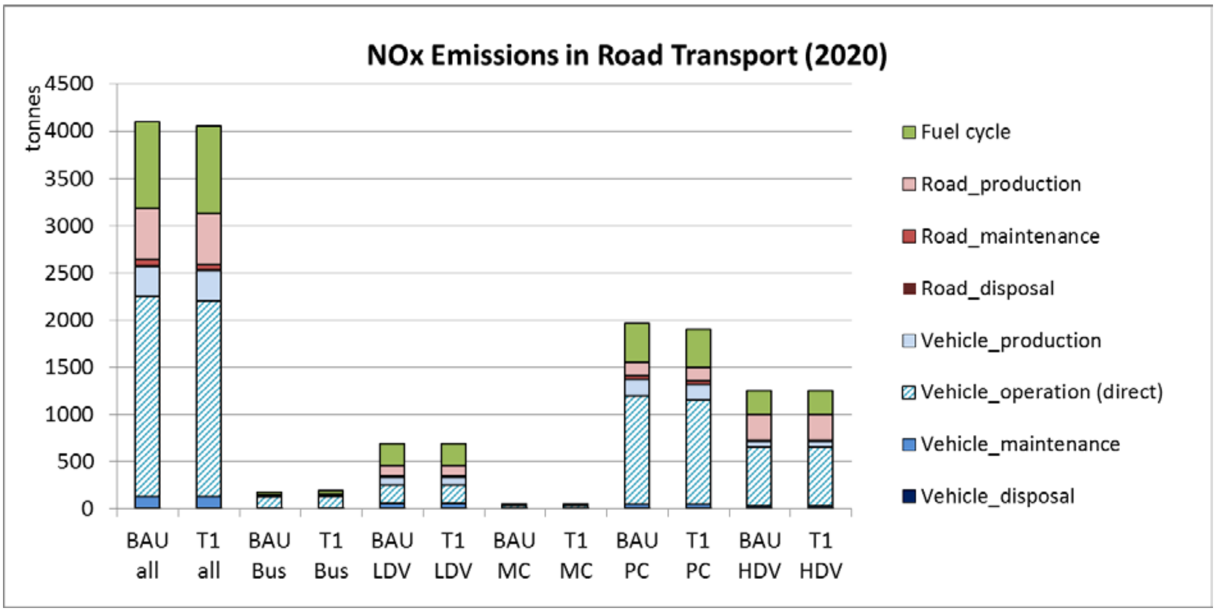

Figure 15 T1 2020 – NO_x emissions in Road Transport in European cities

Both the considered scenarios verify the applicability of the life cycle database for the simultaneous calculation of direct and indirect urban emissions for relevant activities and sectors. The heating scenario shows that life cycle emission factors can be linked to single activities in the bottom up databases and therefore allow estimating the emission reduction potential of different heating technologies. The transport scenario shows that direct and indirect emissions caused by modified activities can be simultaneously calculated for one complete sector. Based on the combination of activity emission factor database and life cycle database, the influence of the life cycle emissions on emission changes can be demonstrated and main emission causing life cycle stages can be identified.

6 Conclusions

There is an increasing need to look beyond the end of pipe emissions as they are currently indicated in conventional emission inventories to allow for a more consistent comparison of measures. This concerns emissions at various stages of the life cycle and especially highlights the importance of the fuel cycle emissions.

To allow an automated calculation of direct and indirect emission through urban activities, a satellite system has been developed that can be linked to the activity emission factor databases generated in ICARUS Task 2.1 and Task 2.2. Indirect emissions origin on the one hand from the cities consumption of grid supplied electricity, heat and cooling, that causes emissions at power plants outside the city area (scope 2) and out of boundary production chain emissions due to embodied emissions from food and materials consumed in the city and their disposal (scope 3). The satellite system consists of scope 2 and scope 3 emission factors and supplements the scope 1 emission factors in the current databases. Scope 2 emission factors (i.e. electricity use during the operation stage) have been calculated for two scenarios representing different renewable energy shares in the gross final energy consumption and two different technology sub-scenarios to also reflect possible developments in production efficiency and new evolving technologies. Scope 3 emission factors have been provided for different transportation services and means, building heating and insulation materials. In this context scope 2 has a particular importance as a lot of city specific measures lead to an increased use of electricity. The assessment of these options depends strongly on the fuel mix and abatement technologies to generate electricity, which is why different energy scenarios have been calculated and directly linked to the consumption sectors heating and transport. This allows the scenario specific assessment of electricity based heating systems like heat pumps and the use of electricity in the transport sector. For the transport sector, a switch from conventionally fueled vehicles to hybrid/ electric cars directly leads to higher electricity consumption while measures aiming at a switch from private cars to public transport can cause the enhanced use of electricity due to an increased use of urban metros and trams. Measures that go along with a high material consumption like the exchange of cars and the insulation of buildings or new appliances show a high importance of the production phase to the overall emissions.

Linking the life cycle database to the activity emission databases makes it possible to simultaneously estimate the effect of emission reduction measures on direct and indirect urban emissions. A lot of measures that will be important in the future result in a shift from emissions at the point of use to other life cycle stages and emissions related to electricity production. Since for air pollutants the location of emission release is crucial this needs to be considered when evaluating measures. The holistic approach of a life cycle assessment allows the early identification of measure induced problem-shifting from one life cycle phase to another, from one region to another, or from one environmental problem to another. Thus, when aiming at a comparative and long-term evaluation of policy interventions, it is of utmost importance to consider emissions of the full life cycle.

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Annexes

1 Additional transport processes

I-Additional vehicles

1) Electric cars

Electric cars were designed using “Life Cycle Assessment of Battery Electric Vehicles and Concept Cars”.

2) Scooter, electric scooter, electric bicycle

Scooter, electric scouter and electric bicycle were designed using “Life Cycle Assessment of Two Wheel Vehicles”.

3) Hybrid petrol, electric cars

Hybrid petrol, electric cars were derived from electric cars with some changes.

a) Vehicle production

Relatively to electric cars, the fuel tank, the catalyst and the internal combustion engine that were subtracted from petrol cars to design electric cars were added.

From (Leuenberger M., 2010a) :

“According to Röder (2001), the specific weight of a tank is 0.55kg/ per litre capacity. We assume an average tank volume of 50 litres. This assumption leads to the material input outlined in Tab. 1.10. These amounts of aluminium and epoxy fibres are subtracted from the total amounts recorded in the original ecoinvent dataset of passenger car manufacture.

Table 13 Material weight and composition of a fuel tank (Röder 2001)

Material	Percentage	Weight in a 27.5 kg tank
Aluminium	36%	9.9 kg
Epoxy fibres	64%	17.6 kg

The weight of the electric motor is assumed to be equal to the electric motor used in a Toyota Prius. The composition of a combustion engine is roughly described in the LCI of a VW Golf. The main component is aluminium (42 kg), some parts are made of steel (15 kg) (Schweimer & Levin 2002). These values are subtracted from the total aluminium and total steel demand of the conventional car as modelled in the ecoinvent dataset v2.01.
Because no three-way catalyst is needed all inputs of platinum group metals are set to zero.”

As a consequence, the differences between hybrid cars and electric cars are the following.

Table 14 Differences between electric and hybrid cars for production

	Electric car	Hybrid car
Steel, low-alloyed, at plant (kg)	84	99
Aluminium, production mix at plant (kg)	0	51.8
Platinum, at regional storage (kg)	0	0.0016
Palladium, at regional storage (kg)	0	0.0003

b) Vehicle maintenance

Maintenance is the same as for electric cars.

c) Vehicle disposal

Disposal is the same as for electric cars.

d) Fuel

The electric part of the fuel for 1 km driven is obtained by multiplying the utility factor to the electricity consumption of an electric car: 0.69*0.2=0.138 kWh.
The petrol part of the fuel for 1 km driven is obtained by multiplying 1-utility factor to the petrol consumption of a petrol car: 0.31* 0.060003= 0.0186009 kg.

4) Hybrid diesel, electric cars

The process was designed the same way as hybrid petrol electric cars, the only difference is the fuel part.

a) Fuel

The electric part of the fuel for 1 km driven is obtained by multiplying the utility factor to the electricity consumption of an electric car: 0.69*0.2=0.138 kWh.
The diesel part of the fuel for 1 km driven is obtained by multiplying 1-utility factor to the diesel consumption of a diesel car: 0.31* 0.060973= 0.01890163 kg.

5) LPG car

LPG cars were derived from petrol car. The only difference is the fuel part.

a) Fuel

Petrol was replaced by Propane, butane. With assumed volumic masses of 0.54 kg/L for LPG and 0.74 kg/L for gasoline and 1.35 gasoline gallon equivalent from "Gasoline Gallon Equivalents (GGE)"[13], the LPG consumption for 1 km driven is: 0.060003/0.74*0.54*1.35= 0.059111 kg.

6) Petrol vans

The vans in Ecoinvent are defined with a mix of petrol and diesel .Petrol vans were derived from petrol, diesel Swiss vans, only the fuel part was changed.

a) Fuel

The proportions for Swiss vans are 0.372 petrol, 0.628 diesel.
The petrol consumption for 1 km driven is: 0.032568/0.372=0.0875484 kg.

7) Diesel vans

Diesel vans were derived from petrol, diesel Swiss vans, only the fuel part was changed.

a) Fuel

The proportions for Swiss vans are 0.372 petrol, 0.628 diesel.
The diesel consumption for 1 km driven is: 0.05498/0.628= 0.08754777 kg.

8) Electric vans

Electric vans were mainly derived from petrol, diesel Swiss vans. The modifications were done in analogy with the design of electric cars "Life Cycle Assessment of Battery Electric Vehicles and Concept Cars".

a) Vehicle production

The fuel tank, internal combustion engine, catalyst and lead battery were subtracted and an electric motor and an electric battery was added.

A fuel tank capacity of 70L was assumed from a Peugeot van[14].
From "Life Cycle Assessment of Battery Electric Vehicles and Concept Cars", a weight of 0.55*70=38.5 kg was deduced.

An internal combustion engine of 208kg was assumed from the Mercedes-Benz_OM642_engine[15].

Using the same proportions as in (Leuenberger M., 2010a), 15/57*208=55 kg of steel were subtracted.

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[13] https://www.thoughtco.com/fuel-energy-comparisons-85636 (last accessed: 05.10.2018)
[14] http://www.vanleasingmadesimple.com/data/peugeot/expert/fuel-tank-capacity-2/ (last accessed: 05.10.2018)
[15] https://en.wikipedia.org/wiki/Mercedes-Benz_OM642_engine (last accessed: 05.10.2018)

Aluminium, lead, sulphuric acid were also subtracted.

An electric motor and a lithium battery were added with the same weight as for electric cars.

Table 15 Differences between petrol, diesel vans and electric vans for production

	Petrol, diesel van	Electric van
Steel, low-alloyed, at plant (kg)	1040	985
Aluminium, production mix at plant (kg)	84	0
Lead, at regional storage (kg)	13	0
Sulphuric acid, liquid, at plant (kg)	0.8	0
Electric motor, electric vehicle, at plant (kg)	0	104
Battery, LiIo, rechargeable, prismatic, at plant (kg)	0	312

b) Vehicle maintenance

Lead and sulphuric acid were suppressed compared to petrol, diesel vans and a lithium-ion battery was added.

Table 16 Differences between petrol, diesel vans and electric vans for maintenance

	Petrol, diesel van	Electric van
Lead, at regional storage (kg)	13	0
Sulphuric acid, liquid, at plant (kg)	1.4	0
Battery, LiIo, rechargeable, prismatic, at plant (kg)	0	312

c) Vehicle disposal

A lithium-ion battery was added compared to petrol, diesel vans.

Table 17 Differences between petrol, diesel vans and electric vans for disposal

	Petrol, diesel van	Electric van
Disposal, LiIo batteries, mixed technology (kg)	0	312

d) Fuel

The electricity consumption for 1km driven was calculated from petrol vans with an analogy with passenger cars: 0.2/0.060003* 0.0875484= 0.291813366 kWh.

9) Hybrid petrol, electric vans

Hybrid petrol, electric vans were derived from electric vans with some changes.

a) Vehicle production

Relatively to electric vans, the fuel tank, the catalyst and the internal combustion engine that were subtracted from petrol cars to design electric cars were added.

Table 18 Differences between electric vans and hybrid vans for production

	Electric van	Hybrid van
Steel, low-alloyed, at plant (kg)	985	1040
Aluminium, production mix at plant (kg)	0	84

b) Vehicle maintenance

Maintenance is the same as for electric vans.

c) Vehicle disposal

Disposal is the same as for electric vans.

d) Fuel

The electric part of the fuel for 1 km driven is obtained by multiplying the utility factor to the electricity consumption of an electric van: 0.69* 0.291813366= 0.201351223 kWh.

The petrol part of the fuel for 1 km driven is obtained by multiplying 1-utility factor to the petrol consumption of a petrol van: 0.31* 0.0875484=0.02714 kg.

10) Hybrid diesel, electric vans

The process was designed the same way as hybrid petrol electric vans, the only difference is the fuel part.

a) Fuel

The electric part of the fuel for 1 km driven is obtained by multiplying the utility factor to the electricity consumption of an electric van: 0.69* 0.291813366= 0.201351223 kWh.
The diesel part of the fuel for 1 km driven is obtained by multiplying 1-utility factor to the diesel consumption of a diesel van: 0.31* 0.08754777= 0.02713981 kg.

11) Electric buses

Electric vans were mainly derived from diesel buses. The modifications were done in analogy with the design of electric cars (Leuenberger M., 2010a).

a) Vehicle production

The fuel tank, internal combustion engine, catalyst and lead battery were subtracted and an electric motor and an electric battery was added.

A fuel tank capacity of 310L was assumed from Urbino 12[16].
From (Leuenberger M., 2010a), a weight of 0.55*310=170.5 kg was deduced.

An internal combustion engine of 522kg was assumed from Cummins ISB6.7[17].

Using the same proportions as in (Leuenberger M., 2010a), 15/57*522=137 kg of steel and 42/57*522+0.36*170.5=446 kg of aluminium were subtracted.

Lead and sulphuric acid were also subtracted.

An electric motor of 350kg was added from PEM-Motor 1DB2016–WS54[18].

Lithium-ion batteries of 1400 kg were added from Solaris Urbino 8,9 LE electric[19].

Table 19 Differences between diesel and electric buses for production

	Diesel bus	Electric bus
Reinforcing steel, at plant (kg)	4540	4403
Aluminium, production mix at plant (kg)	1670	1224
Lead, at regional storage (kg)	90	0
Sulphuric acid, liquid, at plant (kg)	34	0
Electric motor, electric vehicle, at plant (kg)	0	350
Battery, LiIo, rechargeable, prismatic, at plant (kg)	0	1400

b) Vehicle maintenance

[16] https://www.solarisbus.com/en/vehicles/conventional-drives/urbino (last accessed: 05.10.2018)
[17] https://westernstar.com.au/cummins-isb6-7/ (last accessed: 05.10.2018)
[18] https://www.industry.usa.siemens.com/drives/us/en/electric-drives/hybrid-drives/automotive/Documents/elfa-components-data-sheets.pdf (last accessed: 05.10.2018)
[19] https://en.wikipedia.org/wiki/Solaris_Urbino_8,9_LE_electric (last accessed: 05.10.2018)

Lead was suppressed compared to diesel buses and lithium-ion batteries were added.

Table 20 Differences between diesel and electric buses for maintenance

	Diesel bus	Electric bus
Lead, at regional storage (kg)	17.9	0
Battery, LiIo, rechargeable, prismatic, at plant (kg)	0	1400

c) <u>Vehicle disposal</u>

Lithium-ion batteries were added compared to diesel buses.

Table 21 Differences between diesel and electric buses for disposal

	Petrol, diesel van	Electric van
Disposal, LiIo batteries, mixed technology (kg)	0	1400

d) <u>Fuel</u>

The electricity consumption for 1km driven was calculated from diesel buses with an analogy with passenger cars: 0.2/ 0.060973*0.34981= 1.14742591 kWh.

12) Hybrid diesel, electric buses

Hybrid diesel, electric buses were derived from electric buses with some changes.

a) <u>Vehicle production</u>

Relatively to electric buses, the fuel tank, the catalyst and the internal combustion engine that were subtracted from diesel buses to design electric buses were added.

Table 22 Differences between electric and hybrid buses for production

	Electric bus	Hybrid bus
Reinforcing steel, at plant (kg)	4403	4540
Aluminium, production mix at plant (kg)	1224	1670

b) <u>Vehicle maintenance</u>

Maintenance is the same as for electric buses.

c) <u>Vehicle disposal</u>

Disposal is the same as for electric buses.

d) Fuel

The electric part of the fuel for 1 km driven is obtained by multiplying the utility factor to the electricity consumption of an electric bus: 0.69* 1.14742591= 0.791723878 kWh.

The petrol part of the fuel for 1 km driven is obtained by multiplying 1-utility factor to the petrol consumption of a diesel bus: 0.31* 0.34981= 0.1084411 kg.

13) Natural gas bus

Natural gas buses were derived from diesel buses. The only difference is the fuel part.

a) Fuel

Diesel was replaced by Natural gas. The natural gas consumption for 1km driven was calculated from diesel buses with an analogy with passenger cars: 0.2/ 0.06409*0.34981= 0.367692633 kg.

14) Hybrid petrol, electric scooters

Hybrid petrol, electric cars were derived from petrol and electric scooters.

a) Vehicle production

Relatively to electric scooters, the platinum and palladium were added.

Table 23 Differences between electric and hybrid scooters for production

	Electric scooter	Hybrid scooter
Platinum, at regional storage (kg)	0	0.000107
Palladium, at regional storage (kg)	0	0.0000201

b) Vehicle maintenance

Maintenance is the same as for electric scooters.

c) Vehicle disposal

Disposal is derived from petrol and electric scooters.

Table 24 Differences between ICE, electric and hybrid scooters for disposal

	ICE scooter	Electric scooter	Hybrid scooter
Transport, lorry 20-28t, fleet average	1.45E+01	1.12E+02	1.45E+01
Disposal, Li-ion batteries, mixed technology	0	3.20E+01	3.20E+01
Disposal, zinc, in car shredder residue, 0% water, to municipal incineration	3.95E-01	6.77E-01	6.77E-01

d) Fuel

The electric part of the fuel for 1 km driven is obtained by multiplying the utility factor to the electricity consumption of an electric scooter: 0.69* 0.03= 0.0207 kWh.

The petrol part of the fuel for 1 km driven is obtained by multiplying 1-utility factor to the petrol consumption of a petrol scooter: 0.31* 0.0252= 0.007812 kg.

15) ICE

ICE were derived from german ICE, the difference is that the average European electricity mix was used in the fuel part instead of the german one.

16) Diesel ICE

Diesel ICE were derived from electric ICE. The only difference is the fuel part.

a) Fuel

The electricity consumption for 1pkm driven was calculated from electric ICE with an analogy with freight trains: 0.010023/ 0.0478* 0.0811= 0.017006 kWh.

17) Long distance train

Long distance trains were derived from long distance trains with the SBB electric mix, the difference is that the average European electricity mix was used in the fuel part instead of the SBB mix.

18) Diesel long distance train

Diesel long distance trains were derived from electric long distance trains. The only difference is the fuel part.

a) Fuel

The electricity consumption for 1pkm driven was calculated from electric long distance trains with an analogy with freight trains: 0.010023/ 0.0478* 0.084185= 0.017652 kWh.

19) Regional train

Regional trains were derived from regional trains with the SBB electric mix, the difference is that the average European electricity mix was used in the fuel part instead of the SBB mix.

20) Diesel regional train

Diesel regional trains were derived from electric regional trains. The only difference is the fuel part.

a) Fuel

The electricity consumption for 1pkm driven was calculated from electric regional trains with an analogy with freight trains: 0.010023/ 0.0478* 0.176= 0.03690477 kWh.

II-Utility factor and fuel consumption

The electric ranges of different hybrid cars were gathered from a list of different plug-in hybrid electric vehicles[20]. The utility factors of the vehicles were deduced from “Too low to be true? How to measure fuel consumption and CO2 emissions of plug-in hybrid vehicles, today and in the future”[21], except for BMW i3 Rex, for whom it was taken from “Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends:1975 Through 2017”[22]

A utility factor was finally deduced as an average of the different utility factors weighted with the sales in Europe in 2017[23].

[20] https://en.wikipedia.org/wiki/List_of_modern_production_plug-in_electric_vehicles (last accessed 05.10.2018)
[21] https://www.theicct.org/sites/default/files/publications/EU-PHEV_ICCT-Briefing-Paper_280717_vF.pdf (last accessed 05.10.2018)
[22] http://www.indiaenvironmentportal.org.in/files/file/Light-Duty%20Automotive%20Technology_0.pdf (last accessed 05.10.2018)
[23] http://carsalesbase.com/european-sales-2017-ev-phev-segments/ (last accessed 05.10.2018)

Table 25 Calculation of an average utility factor

	Sales 2017 in Europe	Electric range (km)	Approximate utility factor	UFxSales
Mitsubishi Outlander	19189	60	0.8	15351.2
Volkswagen Passat GTE	13599	50	0.75	10199.25
Mercedes-Benz GLC350e	11249	31	0.6	6749.4
BMW 225xe Active Tourer	10805			
BMW 330e	10117	23	0.49	4957.33
Volkswagen Golf GTE	9267	50	0.75	6950.25
Audi A3 e-Tron	8356	50	0.75	6267
Volvo XC90 T8 Twin Engine	7847	43	0.72	5649.84
BMW i3 REx (est.)	6934	116	0.89	6171.26
Mercedes-Benz C350e	6861	31	0.6	4116.6
BMW 530e	6143	30	0.58	3562.94
BMW X5 40e	5944	23	0.49	2912.56
Porsche Panamera PHEV (est.)	4251	32	0.61	2593.11
Hyundai Ioniq PHEV	1900	50	0.75	1425
BMW i8	988			
Total without i8 and Tourer	111657			76905.74
Total UF*Sales divided by total sales	0.688767744			

Table 26 Vehicles fuel consumption

	Petrol (kg)	Diesel (kg)	Electricity (kWh)	Natural gas (kg)	LPG(kg)
Passenger car, petrol	0.060003				
Passenger car, diesel		0.060973			
Passenger car, electric			0.2		
Passenger car, LPG					0.059111
Passenger car, natural gas				0.06409	

	Petrol (kg)	Diesel (kg)	Electricity (kWh)	Natural gas (kg)	LPG(kg)
Passenger car, hybrid, electric, petrol	0.0186009		0.138		
Passenger car, hybrid, electric, diesel		0.01890163	0.138		
Bus, diesel		0.34981			
Bus, electric			1.14742591		
Bus, natural gas				0.367692633	
Bus, hybrid, electric, diesel		0.1084411	0.791723878		
Van, mix, petrol, diesel	0.032568	0.05498			
Van, petrol	0.0875484				
Van, diesel		0.08754777			
Van, electric			0.291813366		
Van, hybrid, electric, petrol	0.02714		0.201351223		
Van, hybrid, electric, diesel		0.02713981	0.201351223		
Scooter, petrol	0.0252				
Scooter, electric			0.03		
Scooter, hybrid, electric, petrol	0.007812		0.0207		
Freight, electricity			0.0478		
Freight, diesel		0.010023			
Regional train, electricity			0.176		
Regional train, diesel		0.03690477			

	Petrol (kg)	Diesel (kg)	Electricity (kWh)	Natural gas (kg)	LPG(kg)
Long distance train, electricity			0.084185		
Long distance train, diesel		0.017652			
ICE, electricity			0.0811		
ICE, diesel		0.017006			
Utiliy factor	0.69				
1-UF	0.31				
Van petrol factor	0.372				
Van diesel factor	0.628				

2 Emission factor and emission reductions

2.1 Electricity

Table 27 PM10 Emission factor reduction for different energy scenarios compared to the base year 2015

	PM10	BASE % from 2015		HighRES % from 2015
	realistic-optimistic	very-optimistic	realistic-optimistic	very-optimistic
CH				
2020	94%	93%	94%	93%
2030	111%	110%	109%	108%
2050	149%	148%	136%	134%
CZ				
2020	72%	67%	72%	67%
2030	59%	54%	61%	56%
2050	60%	59%	55%	54%
DE				
2020	78%	74%	78%	74%
2030	71%	67%	74%	71%
2050	54%	53%	50%	49%
DK				
2020	60%	56%	60%	56%
2030	59%	55%	58%	54%
2050	61%	60%	61%	61%
ES				
2020	50%	49%	52%	49%
2030	52%	50%	56%	51%
2050	53%	52%	55%	53%
GR				
2020	10%	10%	10%	10%
2030	8%	8%	8%	8%
2050	7%	7%	7%	7%
IT				
2020	55%	53%	56%	53%
2030	49%	47%	54%	49%
2050	55%	54%	53%	52%
SI				
2020	22%	21%	22%	21%
2030	23%	22%	23%	22%
2050	20%	20%	28%	27%

Table 28 CO_2 Emission factor reduction for different energy scenarios compared to the base year 2015

	CO2	BASE % from 2015		HighRES % from 2015
	realistic-optimistic	very-optimistic	realistic-optimistic	very-optimistic
CH				
2020	255%	254%	195%	195%
2030	614%	611%	557%	554%
2050	1243%	1217%	468%	471%
CZ				
2020	61%	58%	62%	58%
2030	35%	33%	48%	47%
2050	21%	21%	21%	21%
DE				
2020	71%	67%	71%	67%
2030	57%	54%	64%	61%
2050	16%	15%	14%	15%
DK				
2020	78%	75%	78%	75%
2030	64%	61%	54%	51%
2050	16%	16%	22%	22%
ES				
2020	70%	68%	67%	65%
2030	79%	78%	57%	41%
2050	17%	17%	15%	15%
GR				
2020	57%	54%	57%	53%
2030	42%	41%	32%	31%
2050	11%	11%	7%	7%
IT				
2020	79%	77%	75%	73%
2030	67%	66%	52%	51%
2050	15%	15%	11%	11%
SI				
2020	68%	64%	66%	62%
2030	50%	48%	44%	42%
2050	17%	17%	24%	23%

Table 29 NOx Emission factor reductions for different energy scenarios compared to the base year 2015

NOx	BASE % from 2015		HighRES % from 2015	
	realistic-optimistic	very-optimistic	realistic-optimistic	very-optimistic
CH				
2020	149%	143%	147%	138%
2030	321%	306%	287%	276%
2050	441%	438%	364%	362%
CZ				
2020	55%	49%	55%	49%
2030	55%	48%	68%	62%
2050	39%	39%	45%	45%
DE				
2020	86%	79%	85%	78%
2030	83%	77%	84%	78%
2050	57%	57%	48%	47%
DK				
2020	102%	91%	102%	91%
2030	104%	94%	87%	79%
2050	54%	54%	49%	49%
ES				
2020	50%	45%	58%	50%
2030	88%	78%	89%	68%
2050	40%	39%	58%	57%
GR				
2020	58%	52%	58%	53%
2030	55%	52%	48%	44%
2050	22%	22%	18%	18%
IT				
2020	56%	51%	60%	54%
2030	65%	59%	68%	58%
2050	31%	30%	36%	36%
SI				
2020	28%	26%	34%	31%
2030	44%	40%	42%	37%
2050	18%	18%	34%	33%

2.2 Buildings

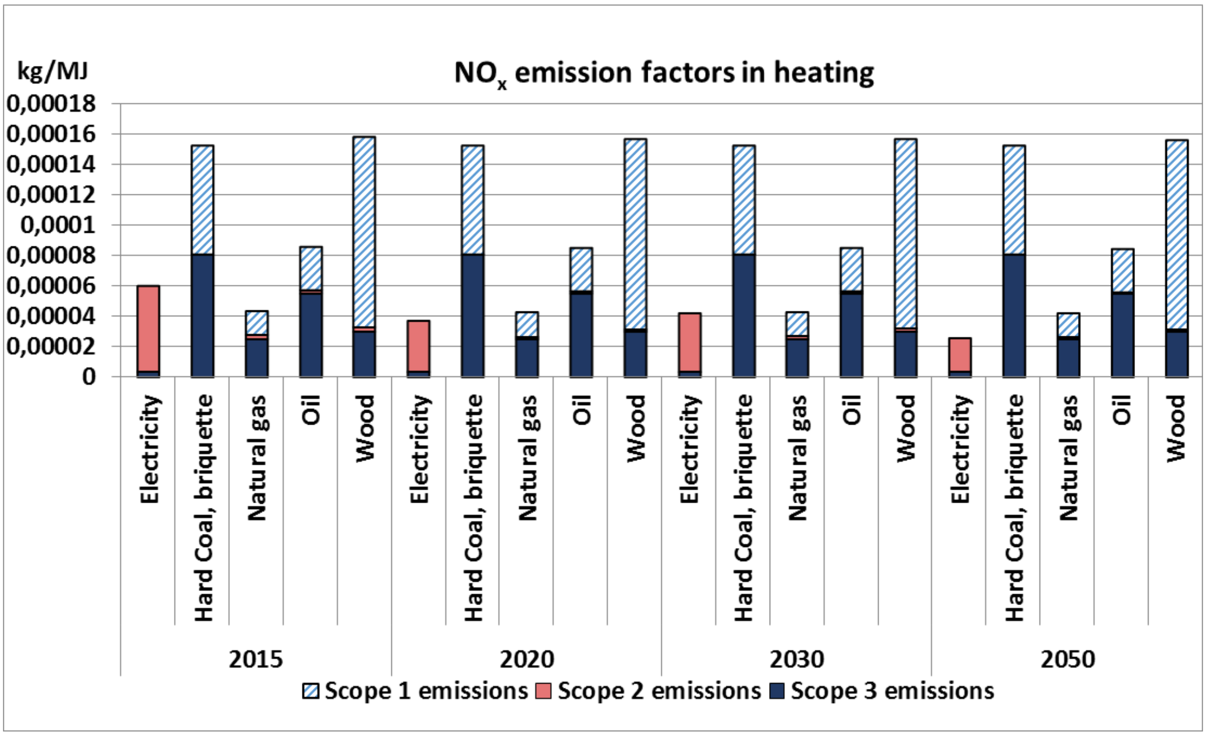

Figure 16 Average NO_x emission factors for different heating types in the BASE – realistic optimistic scenario (electricity: heat pumps, oil/wood/natural gas: boilers, hard coal: stoves)

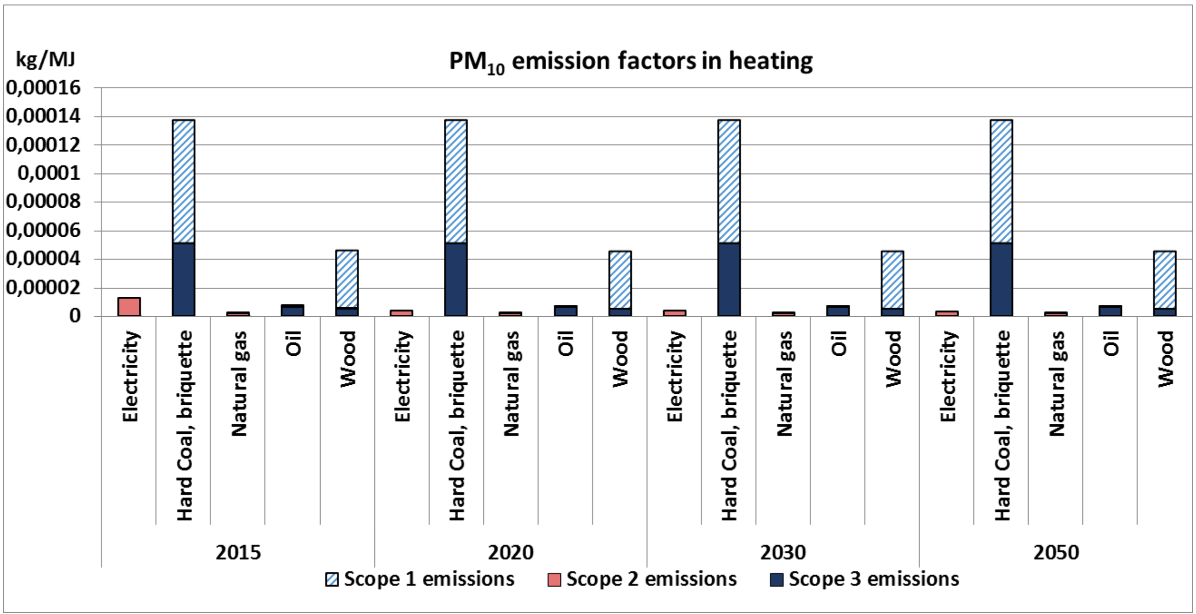

Figure 17 Average PM_{10} emission factors for different heating types in the BASE – realistic optimistic scenario (electricity: heat pumps, oil/wood/natural gas: boilers, hard coal: stoves)

Table 30 Shares of life cycle stages on total fossil CO2 emissions for different heating technologies

Year	Heating type	Infrastructure (S3)	Fuel cycle (S3)	Refrigerant cycle (S3)	Scope 2 emissions	Scope 1 emissions
2015	Electricity (heat pump)	13,6%	0,0%	0,0%	86,4%	0,0%
2015	Hard Coal (stove)	0,4%	7,4%	0,0%	0,0%	92,2%
2015	Natural gas (boiler)	0,3%	11,8%	0,0%	2,4%	85,5%
2015	Oil (boiler)	0,5%	13,5%	0,0%	1,4%	84,6%
2015	Wood (furnace)	9,3%	72,7%	0,0%	18,0%	0,0%
2020	Electricity (heat pump)	18,9%	0,0%	0,0%	81,0%	0,0%
2020	Hard Coal (stove)	0,4%	7,4%	0,0%	0,0%	92,2%
2020	Natural gas (boiler)	0,3%	11,9%	0,0%	1,6%	86,2%
2020	Oil (boiler)	0,5%	13,5%	0,0%	0,9%	85,0%
2020	Wood (furnace)	9,9%	77,3%	0,0%	12,9%	0,0%
2030	Electricity (heat pump)	22,9%	0,0%	0,0%	77,1%	0,0%
2030	Hard Coal (stove)	0,4%	7,4%	0,0%	0,0%	92,2%
2030	Natural gas (boiler)	0,3%	11,9%	0,0%	1,3%	86,5%
2030	Oil (boiler)	0,5%	13,5%	0,0%	0,7%	85,2%
2030	Wood (furnace)	10,1%	79,5%	0,0%	10,4%	0,0%
2050	Electricity (heat pump)	43,8%	0,0%	0,1%	56,2%	0,0%
2050	Hard Coal (stove)	0,4%	7,4%	0,0%	0,0%	92,2%
2050	Natural gas (boiler)	0,3%	12,0%	0,0%	0,5%	87,2%
2050	Oil (boiler)	0,5%	13,6%	0,0%	0,3%	85,6%
2050	Wood (furnace)	10,8%	84,9%	0,0%	4,2%	0,0%

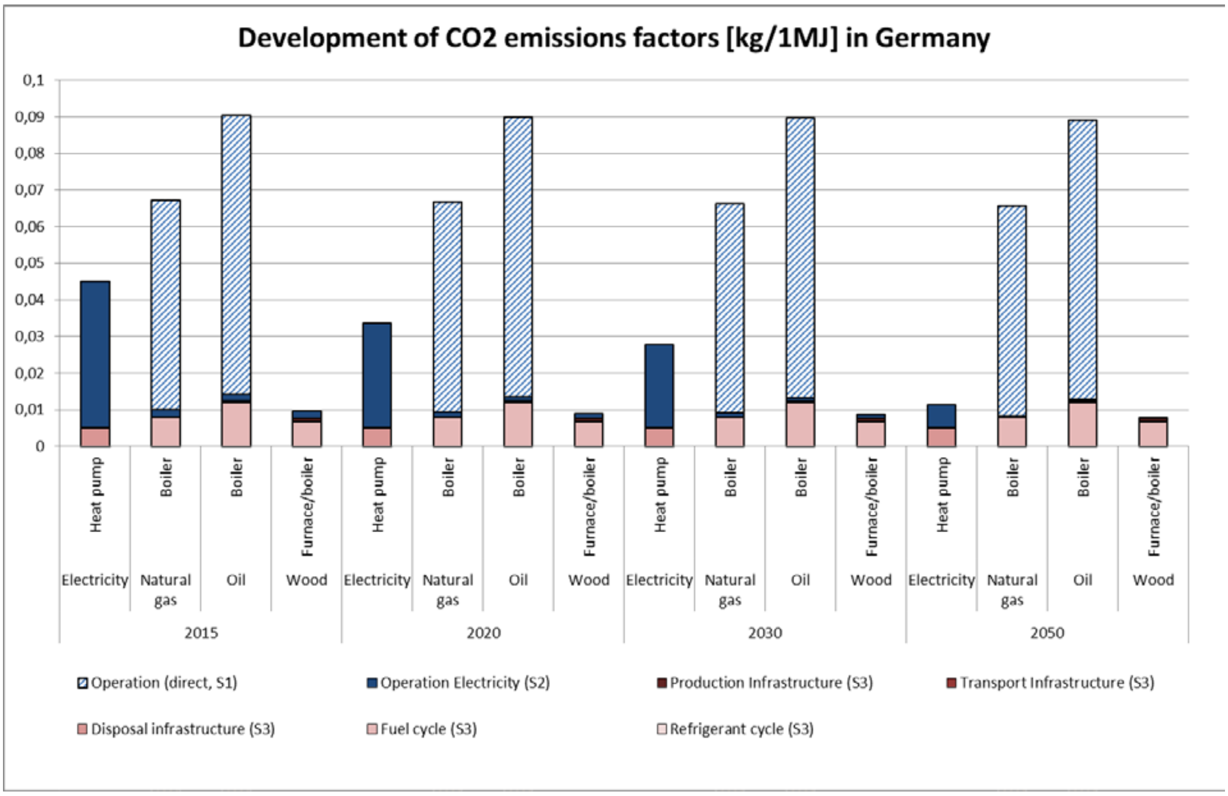

Figure 18 Fossil CO_2 emission factors for different heating technologies in the BASE – realistic optimistic scenario; in Germany (S1: scope 1, S2: scope 2, S3: scope 3)

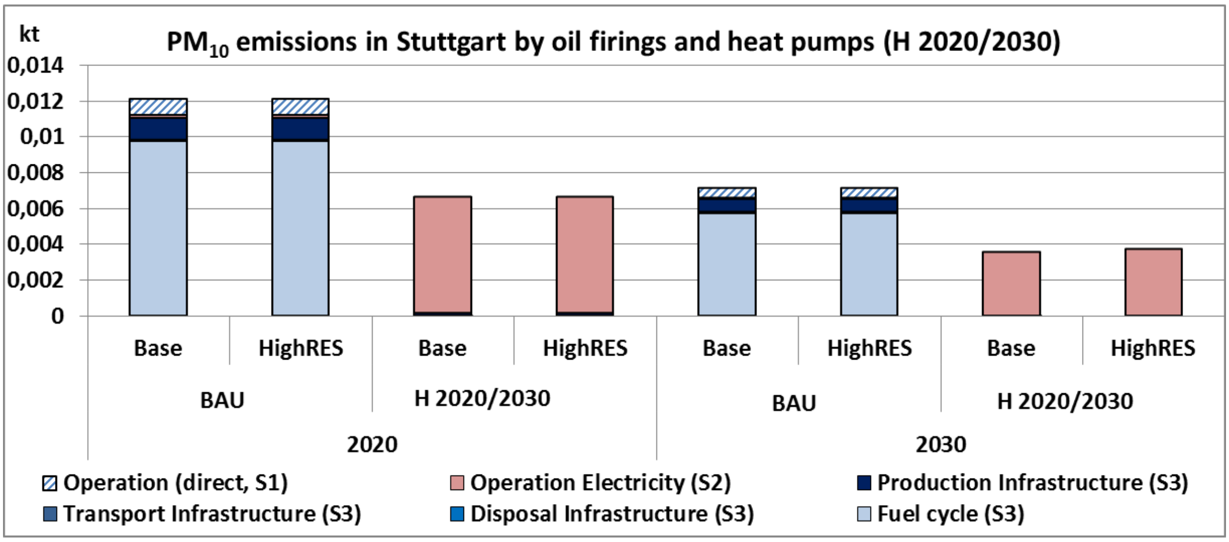

Figure 19 H2020/2030 – PM_{10} emissions in Stuttgart by oil firings and heat pumps

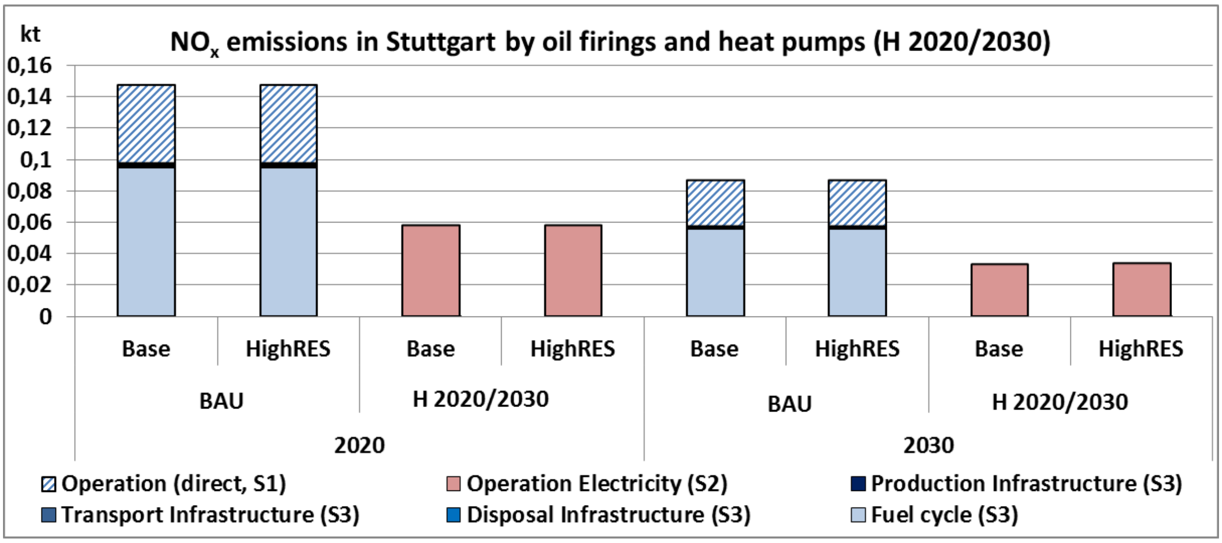

Figure 20 H2020/2030 – NO_x emissions in Stuttgart by oil firings and heat pumps

2.3 Transport

Table 31 PM10 emission reductions compared to the T1 2020 BAU scenario

Scenario	Pollutant	Vehicle type	Vehicle_disposal	Vehicle_maintenance	Vehicle_operation (direct)	Vehicle_production	Road_disposal	Road_maintenance	Road_production	Fuel cycle	Total_emissions
T1	PM10	All types	2,0%	0,6%	1,5%	1,0%	0,0%	1,3%	0,0%	0,4%	0,8%
T1	PM10	Bus	-16,9%	-17,5%	-18,4%	-17,8%	-17,8%	-17,8%	-17,8%	-30,0%	-20,2%
T1	PM10	LDV	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
T1	PM10	MC	0,0%	0,0%	0,0%	0,0%	0,0%	-	0,0%	0,0%	0,0%
T1	PM10	PC	2,3%	2,3%	3,6%	2,3%	2,3%	2,3%	2,3%	2,3%	2,6%
T1	PM10	HDV	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%

Table 32 CO_2-eq. emission reductions compared to the T1 2020 BAU scenario

Scenario	Pollutant	Vehicle type	Vehicle_disposal	Vehicle_maintenance	Vehicle_operation (direct)	Vehicle_production	Road_disposal	Road_maintenance	Road_production	Fuel cycle	Total_emissions
T1	CO2-eq	All types	1,8%	0,4%	1,6%	1,1%	0,0%	1,3%	0,0%	0,4%	1,2%
T1	CO2-eq	Bus	-17,8%	-17,6%	-18,0%	-17,7%	-17,8%	-17,8%	-17,8%	-17,3%	-17,9%
T1	CO2-eq	LDV	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
T1	CO2-eq	MC	0,0%	0,0%	0,0%	0,0%	0,0%	-	0,0%	0,0%	0,0%
T1	CO2-eq	PC	2,3%	2,3%	3,9%	2,3%	2,3%	2,3%	2,3%	2,3%	3,4%
T1	CO2-eq	HDV	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%

Table 33 NO_x emission reductions compared to the T1 2020 BAU scenario

Scenario	Pollutant	Vehicle type	Vehicle_disposal	Vehicle_maintenance	Vehicle_operation (direct)	Vehicle_production	Road_disposal	Road_maintenance	**Road_production**	**Fuel cycle**	**Total_emissions**
T1	NOx	All types	1,8%	0,5%	1,9%	1,1%	0,0%	1,3%	0,0%	0,4%	1,2%
T1	NOx	Bus	-17,6%	-17,5%	-2,7%	-17,7%	-17,8%	-17,8%	-17,8%	-24,1%	-7,8%
T1	NOx	LDV	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
T1	NOx	MC	0,0%	0,0%	0,0%	0,0%	0,0%	-	0,0%	0,0%	0,0%
T1	NOx	PC	2,3%	2,3%	3,9%	2,3%	2,3%	2,3%	2,3%	2,3%	3,2%
T1	NOx	HDV	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%