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LCA for 100% Climate Neutral Buses – An Approach in IEA HEV Task 46

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Executive Summary

Reaching climate neutrality by GHG reduction is a societal challenge and Climate Neutrality is addressed by the methodology of dynamic Life Cycle Assessment (LCA), where GHG emissions and radiative forcing are calculated over the entire lifetime. In the Technology Collaboration Program (TCP) of the International Energy Agency (IEA) on Hybrid and Electric Vehicles (HEV) experts from 20 countries cooperate on LCA of electric vehicles since 2010, where Task 46 performed a case study for 100% climate neutral buses with a newly developed methodological framework, to compare buses with different propulsion & fuel combinations, e.g. battery & hydrogen electric city buses, diesel and e-diesel using wind energy. The Climate Neutrality Potential adds an additional environmental relevant category not covered yet in LCA. Based on the calculated radiative potential in year 2050 in W/m² of the GHG emission over time it became evident that climate neutrality can be reached for all buses in combination with a Carbon Capture & Storage (CCS) system only, which takes emitted CO_2 from air for very long-term underground storage. The additional energy needed for the CCS is only 10% more for the 100% climate neutral battery electric buses whereas the other buses need significant more energy for CCS compensation.

Keywords: Life Cycle Analysis, Environmental Impact, Climate Change, Heavy Duty electric Vehicles & Buses, International Networking, .

1 Goal and Scope

The goal and scope of this LCA are described.

1.1 Introduction

Reducing GHG emission to reach Climate Neutrality are major societal challenges for a sustainable development; and can only be addressed by the methodology of dynamic Life Cycle Assessment (LCA), where GHG emissions and primary energy demand are calculated and assessed over the life time from construction, operation until the end of life management of a product. In the Technology Collaboration Program (TCP) of the International Energy Agency (IEA) on Hybrid and Electric Vehicles (HEV) experts from 20 countries cooperate on LCA of electric vehicles since 2010, where currently in Task 46 (2022 - 2025) the focus is on LCA of city buses, buses and other vehicles. Base on a definition of "100% Climate Neutrality" a methodological assessment framework is developed and applied in a case study to compare city buses with different propulsion & fuel combinations. [1], [2]

2 Climate Neutrality and Circularity

Climate Neutrality and Circularity can be assessed in LCA based on the GHG emissions and the mass flows over the lifetime. Therefore, a LCA based definition of Climate Neutrality and Circularity is necessary, which is given in the following. To keep the wording appropriate to LCA nomenclature, in the impact assessment a "Climate Neutrality Potential (CNP)" and a "Circularity Potential (CPO) are applied. These definitions were initially developed in IEA HEV Task 46 (*https://ieahev.org/tasks/46/*) and applied for the first time in this LCA Case study on city buses.

A product or service is „climate neutral" and „circular", if its whole life cycle - production, operation and end-of-life uses only (Figure 1)

- reused components (reuse index)
- secondary/recycled material (recycled content)
- renewable energy

and makes

- zero waste and
- zero GHG emissions

In Figure 2 the wording and relations between "GHG reduction", "zero-GHG emissions" and "(towards) Climate Neutrality (radiative forcing)" is shown how it is used in this work.

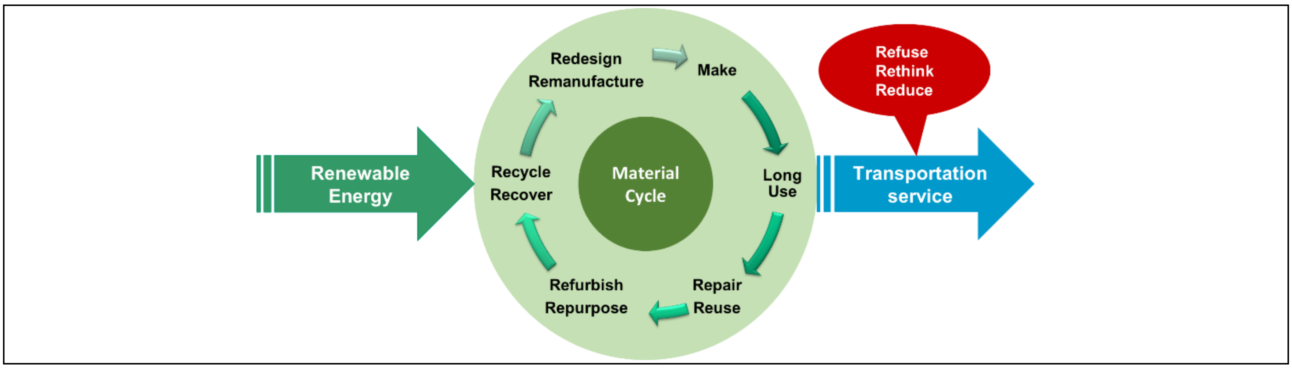

Figure 1: Circularity and Climate Neutrality for transportation services

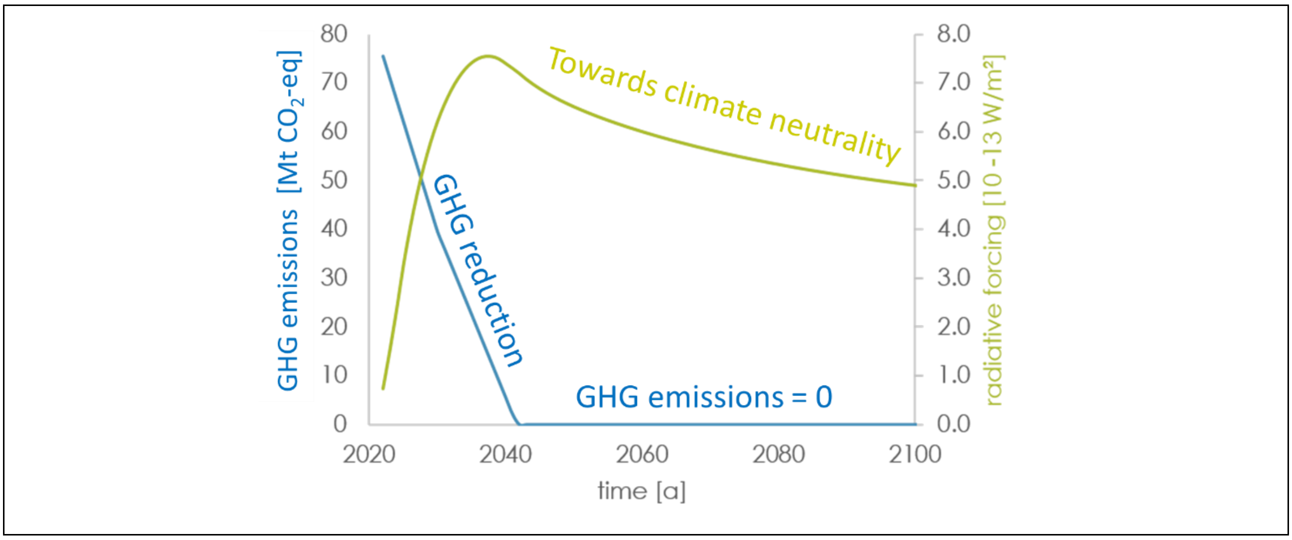

Figure 2: Relations between GHG reduction, zero-GHG emissions and Climate Neutrality (radiative forcing)

The indicators for the assessment in the LCA are

- Circularity Potential (CPO)

- Based on data of Inventory Analysis: mass flows in and out of the considered systems
- Material Circularity Index (MCI) based on mass flows over lifetime: 100% = circular (whereas: 0% = linear) [1]
  - Linear Flow Index of materials ($LFI_{material}$)
  - Utility Factor of product ($UF_{product}$): Utility = lifetime * intensitiy of use
  - MCI = $LFI_{materials}$ * $UF_{product}$
- Climate Neutrality Potential (CNP)
  - Based on GHG emissions for the impact assessment
  - Physical measure is the total top-of-atmosphere radiative forcing based on GHG emissions over lifetime: $RF \;=\; 0\,\mathrm{W/m^2}$
  - Every greenhouse gas emission increases the Climate Neutrality Potential, so Climate Neutrality is a visionary target, so at least the assessment helps to see if the systems is on a path „towards climate neutrality“ aiming for:
    - Zero GHG emissions in operation phase: e.g. 0 kg CO_2-eq/a
    - Small change in radiative forcing after system´s lifetime in 2050: $\Delta RF_{2050} \;=\; 0\,\mathrm{W/m^2}$

The calculation of the MCI is based on the methodology developed by the Ellen MacArthur Foundation [3], which is shown in Figure 3. The basis are the mass flows in and out of the system, whilst the most relevant factors are the amount of primary material used and the amount of non-recoverable waste that determines the LFI of a material and the MCI of a product.

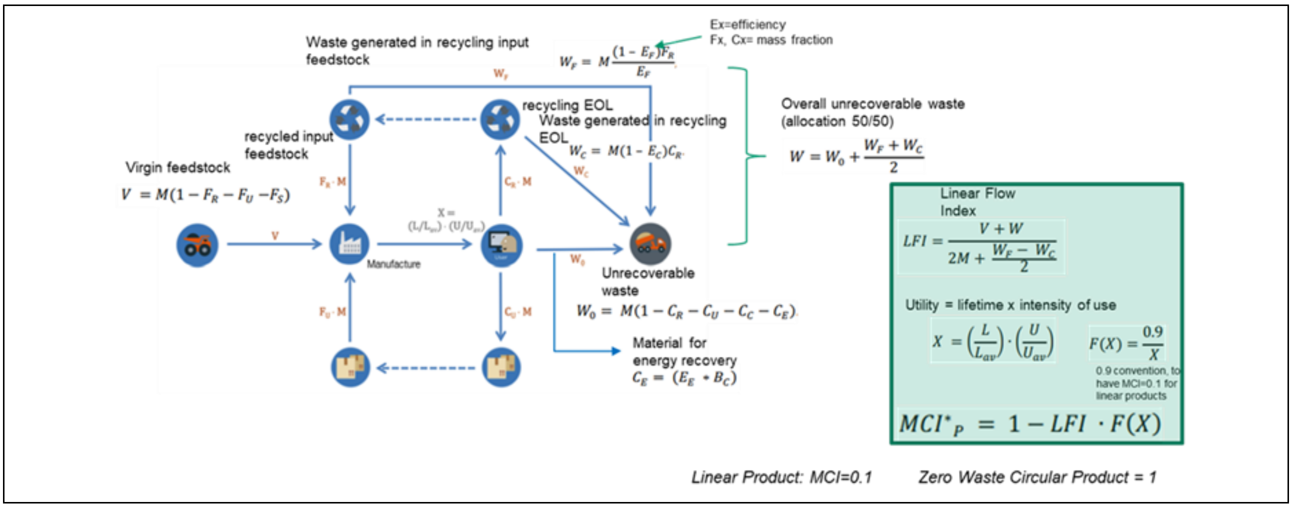

Figure 3: Calculation of the LFI of materials the MCI of products [3]

Taking theses definitions into account, it can be concluded that Climate Neutrality and Circularity are visionary and long term targets. In any case, all future products and services must be developed and assessed “towards” their Climate Neutrality Potential and Circularity Potential to address the global challenges.

2.1 Dynamic LCA

According to the definitions on Climate Neutrality it becomes clear that the approach of a dynamic LCA must be applied, in which the annual GHG emissions and the annual material demand is analysed during the whole life time of the transportation systems. [2]

The possible environmental effects of a system occur at different times during their lifetime. In LCA, the environmental effects are analysed for the three phases separately – production (for vehicles) or construction (for power plants), operation and end of life – over the whole lifetime of a system. Then the cumulated environmental effects over the lifetime are allocated to the service provided by the system during the operation phase, which is the functional unit in LCA, e.g. per passenger kilometre driven. Therefore, the functional unit gives the average environmental effects over lifetime by allocating the environmental effects for production and end of life over the lifetime to the service provided independent of the time when they occur. The approach considered in the Task is to reflect and keep the time depending course of the environmental effects in the life cycle and compare the absolute cumulated environmental effects in a dynamic LCA.

In Figure 4, the possible courses of the cumulated environmental effects of three systems in their lifetime are shown for the three phases – production, operation and end of life. All the three systems – A, B and C - have the same lifetime and provide the same service but the courses of the environmental effects are quite different. The system A has low environmental effects in the production/construction phase but high effects during the operation/use phase and again low effects in the end of life phase. By contrast, system B has average effects in the production phase, very low further effects in the operation phase and finally declining environmental effects in the end of life phase due to the recycling of materials and a credit given for the supply of secondary materials for substituting primary material. The system C has highest effects in production/construction phase, but during the operation phase the additional environmental effects decrease and the cumulated effects become more or less stable; e.g. an electric vehicle consumes more and more renewable electricity during its lifetime. In the end of life phase, the environmental effects significantly decline, which is due to the reuse of certain parts, facilities or materials for other further purposes. Therefore, with these effects, the system C sets initial possibilities *towards* Climate Neutrality. Additionally, if system C will be combined with a Carbon Capture and Storage (CCS) facility, that captured the GHG emission from system C at the same time as they are emitted, the total system C with CCSU will be "100% Climate Neutral".

So in a dynamic LCA the Climate Neutrality Potential in year 2050 can be assessed based on the GHG emissions over the lifetime of the system.

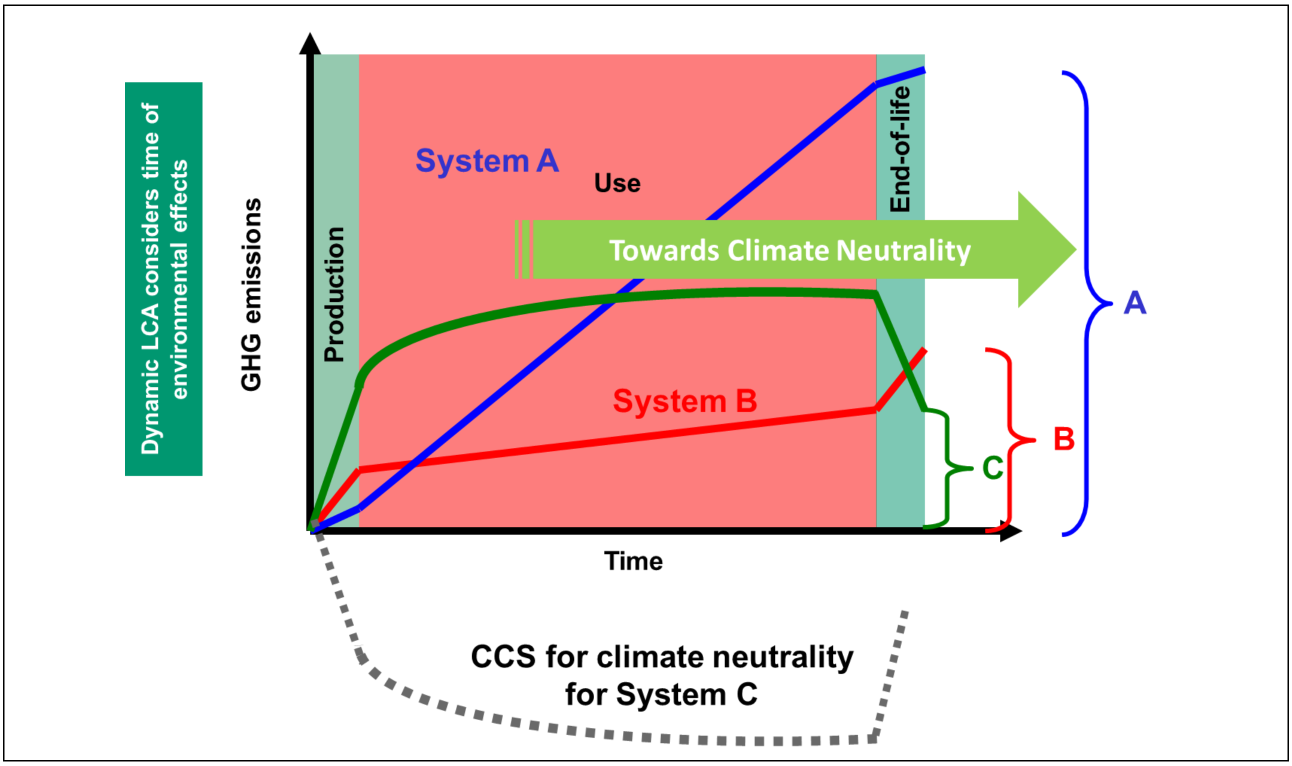

Figure 4: Timing of cumulated GHG emissions of three systems with the same lifetime and service

2.2 Analysed Systems

The goal of this LCA is to identify significant differences of environmental effects of city buses with different propulsion systems/fuels for current and future technology (2024&2036) based on the conclusions of a workshop on LCA of buses [7]. The applied methodology is a dynamic life cycle assessment using generic global production data for materials considering the cumulative effects over the lifetime of the city bus, for which typical urban driving cycles are considered.

The following transportation systems are analysed (Figure 5):

- diesel with ICE (Internal Combustion Engine)
- e-diesel from wind electricity and CO_2 from air with ICE
- electricity for BEV with depot (DC), opportunity (OC) and wireless charging (WC) with wind electricity
- H_2 with FC (Fuel Cell) from wind electricity: GH_2 @ 700 bar

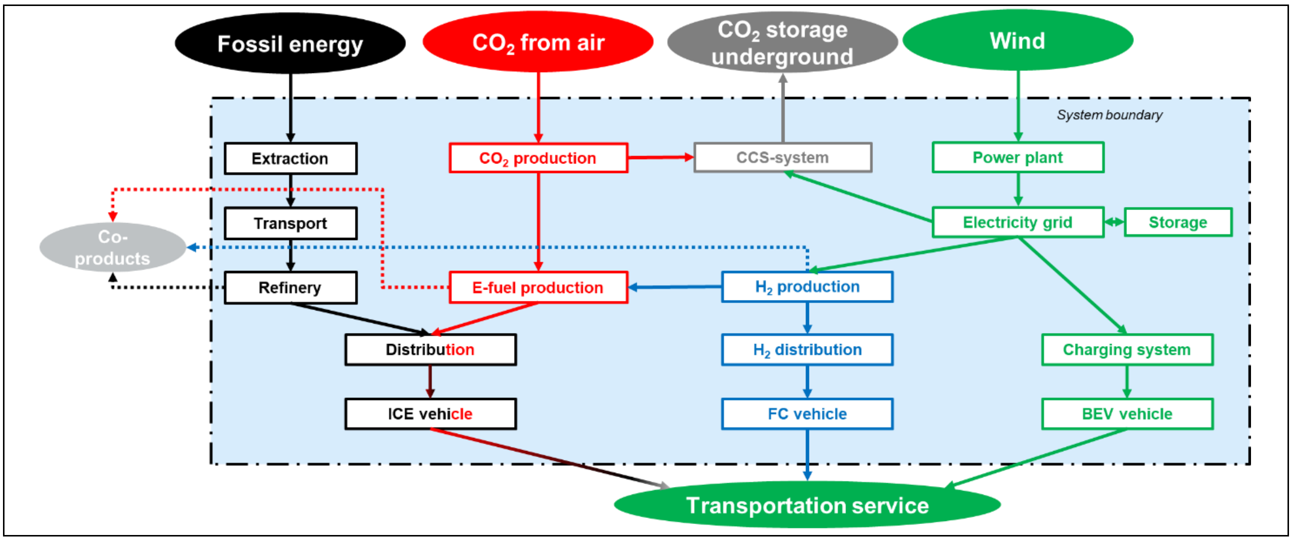

Figure 5: LCA comparison of "100% Climate Neutral" city bus systems using additional wind electricity and CCS

The functional unit is per passenger kilometer (P-km) due to the different passenger capacity of the city buses. The renewable electricity is generated in all cases in new wind power plants, which are considered in the production phase of the total system incl. city bus, and infrastructure for charging.

The considered impact categories are:

- GHG emissions covering CO_2, CH_4, N_2O and direct H_2 emissions in CO_2-eq
- towards climate neutrality: radiative forcing (in the year 2050) in mW_{2050}/m^2 to assess the Climate Neutrality Potential
- primary energy covering renewable and non-renewable energy carries in MWh

The GWP_{100} of hydrogen is 10.9 kg CO_2-eq per kg of hydrogen (range: 6.5- 15 kg CO_2-eq/kg_{H2}) based on [4] and [5]. The further specifications are

- Battery and fuel cell change after 6 years
- Consideration over lifetime of two buses for 24 years, same lifetime as wind power plant
- Duration of system construction: e-fuel= 3 years, H_2 = 2 years and BEV = 1 year
- "Climate Neutrality" of all systems
  - in combination with Carbon Capture & Storage (CCS) of CO_2 from air with wind power
  - Calculated based on CO_2eq also covering CH_4 and N_2O
  - CCS simplified with static LCA (no timing of GHG emissions, mainly relevant for construction phase).

The analysis is in accordance with ISO 14,040.

3 Database

The database for the LCA was developed to represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of the case study. The foreground data for the city buses are in Table 1.

The background data for the materials for city bus components and the material composition are from GREET 2022, the battery data are based on LCA Battery Model of JOANNEUM and the electricity & fuel supply are from the internal LCA database of JOANNEUM RESEARCH. The total lifetime mileage is 1.4 Mio. km in 24 years.

Table 1: Foreground data for city buses [6]

type class		city bus					
propulsion	[name]	ICE	ICE	BEV	BEV	BEV	FC
fuel	[name]	diesel	e-diesel	DC	OC	WC	GH2@700
weight	[kg]	19,500	19,500	19,500	19,500	19,500	19,500
Powertrain System (including BOP) ***)	[kg]	69	69	-	-	-	215
Transmission System	[kg]	677	677	338	338	338	338
Chassis (w/o battery)	[kg]	7,500	7,500	7,500	7,500	7,500	7,500
Traction Motor	[kg]	793	793	190	190	190	190
Generator	[kg]	-	-	-	-	-	-
Electronic Controller	[kg]	20	20	145	145	145	145
Hydrogen Tank Onboard Storage	[kg]	-	-	-	-	-	612
Van/Box	[kg]	-	-	-	-	-	-
Body: including BIW, interior, exterior, and glass	[kg]	3,500	3,500	3,500	3,500	3,500	3,500
Lift-gates	[kg]	-	-	-	-	-	-
Battery ***)	[kg]	100	100	3,000	1,100	850	900
total w/h battery	[kg]	12,559	12,559	11,673	11,673	11,673	12,500
total	[kg]	12,659	12,659	14,673	12,773	12,523	13,400
passenger capacity	[#]	105	105	84	95	101	100
payload	[%]	35%	35%	25%	34%	36%	31%
battery capacity	[kWh]	5.0	5.0	450.0	200.0	150.0	35.0
energy demand H2 without upstream losses	[kWh/km]						2.920
energy demand *)	[kWh/km]	5.050	5.050	1.900	1.700	1.680	3.044
CH4 emissions *)	[g/km]	0.001	0.001				
N2O-emissions *)	[g/km]	0.018	0.018				
H2 emissions **)	[g/km]						0.69
NOx emissions *)	[g/km]	0.084	0.084				
PM-emissions *)	[g/km]	0.002	0.002				
urea/AdBlue *)	[l/100 km]	2.061	2.061				
engine oil	[kg/100 km]	0.016	0.016				
driving range per charging (max SOC 90%)	[km]			213	106	80	

*) *average driving cycle*
**) *H_2 losses/emissions*
***) *2nd battery/fuel cell 10% less*

4 Results

In this chapter the results of the LCA are given by the GHG emissions, the Climate Neutrality Potential, the primary energy demand, the Circularity Potential and the overall assessment.

4.1 GHG Emissions

In Figure 6 the GHG emissions per passenger capacity kilometre for the buses 2024 are shown, where the diesel bus has the highest and the electricity buses have the lowest emissions. The ranges are due to sensitivity analysis on energy demand, annual mileage, electricity supply and battery.

In Figure 7 the Global Warming Potential of the GHG emissions over time for the city buses – bus 1: 2024 – 2035 and bus 2: 2036 – 2047 - are shown in t CO_2-eq in the total lifetime. The GHG emissions increase during the construction phase is due to the construction of the city bus and the power plants, and start in different years for the considered systems due to different assumed construction time. As the electricity demand for e-fuel and H_2 is higher than for electric city buses, the GHG emission are significantly higher, mainly in the construction phase. The systems using renewable electricity have nearly no additional GHG emission during operation except from spare parts and maintenance. In comparison, the GHG emissions of diesel rise significantly during operation due to the combustion of fossil fuel. The decrease of the GHG emissions in the EoL phase is due to the supply with secondary material from recycling of the city buses and the wind power plants for any other product. The changing of the fuel cell and the batteries after 6 years are visible but not significant in the total life cycle. Thus, all systems using renewable electricity have the potential to become climate neutral, but the GHG emissions are significantly higher during the whole lifetime of e-fuel and H_2 compared to electric city bus.

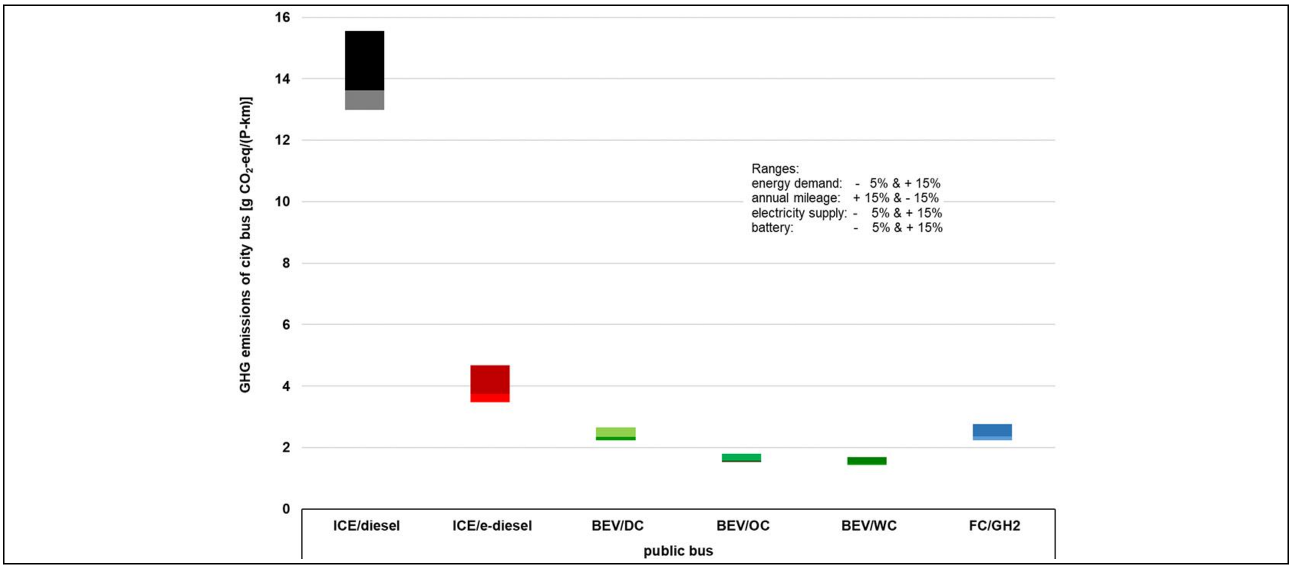

Figure 6: GHG emissions of the city buses 2024

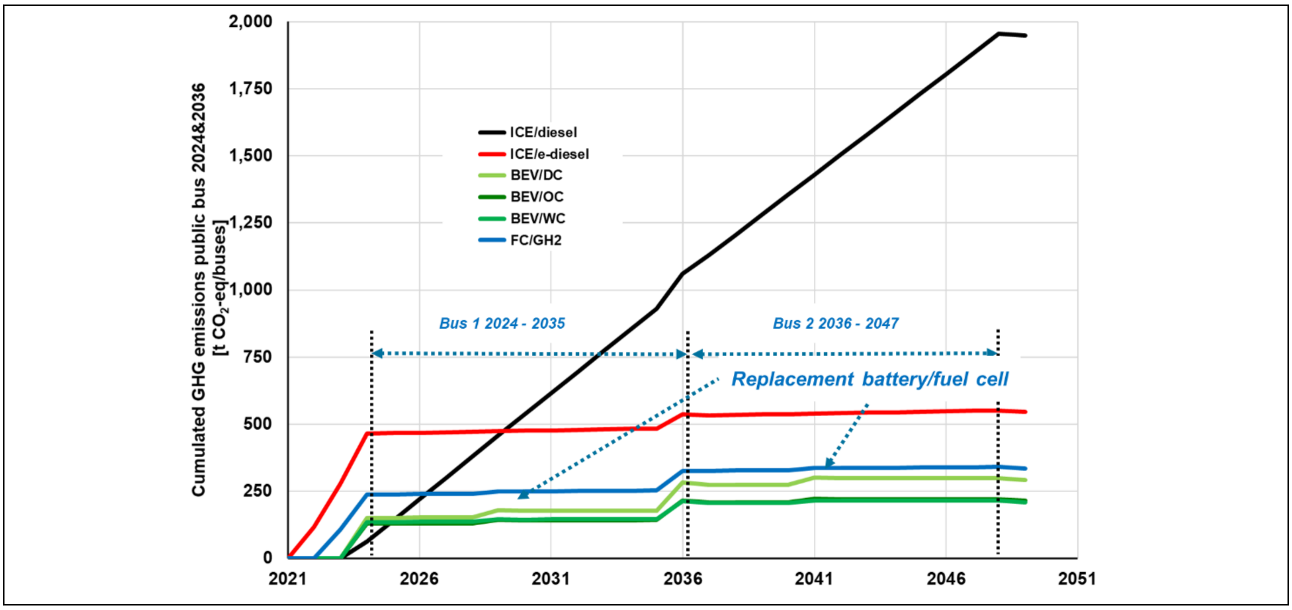

Figure 7: Global Warming Potential of the GHG emissions over time for the city buses

4.2 Radiative Forcing and Climate Neutrality Potential

In Figure 8 the Climate Neutrality Potential of the radiative forcing over time for the city buses is shown. It can be seen that due to the GHG emissions over time the electric buses has the lowest radiative forcing at the end of its lifetime. The Climate Neutrality Potential in 2050 delivers additional assessment information compared to the GHG emission over time.

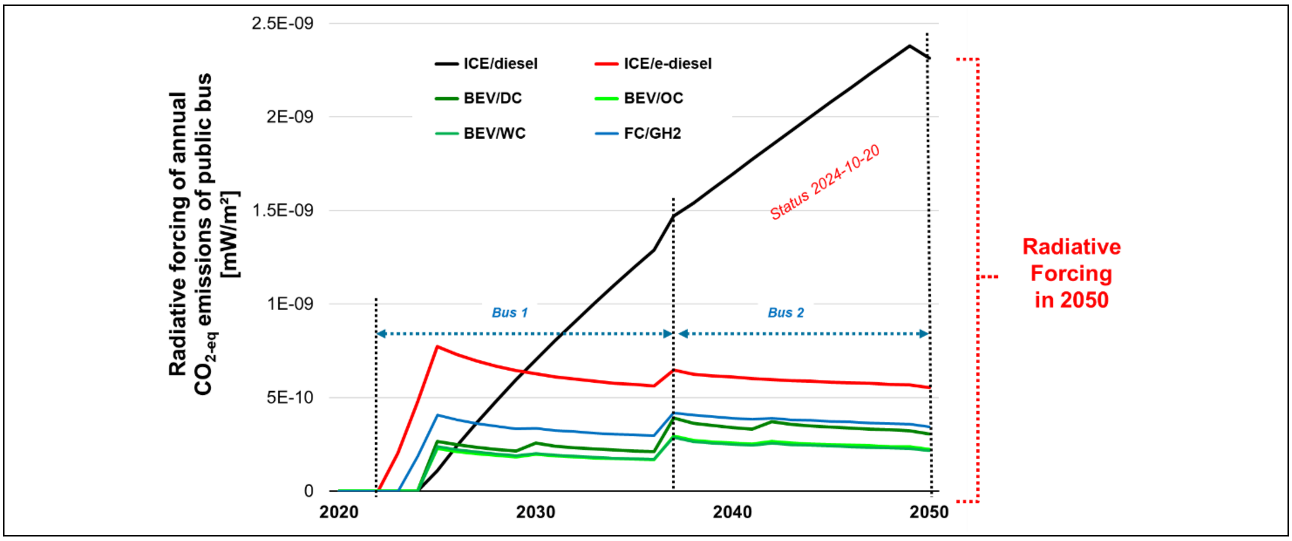

Figure 8: Climate Neutrality Potential of the radiative forcing over time for the city buses

4.3 Primary Energy Demand

Figure 9 shows the total and renewable primary energy demand over time for the city buses in MWh of the total lifetime without CCS, and in Figure 10 with CCS for the "100% climate neutral city buses". The total primary energy increases during the construction phase is due to the construction of the city bus and the power plants. As the electricity demand for e-fuel and H_2 is higher than for electric city buses, the primary energy demand is significantly higher. The primary energy demand of the diesel ICE-bus is about the same as for the H_2 FC-bus. The systems using renewable electricity have a strong increase in the renewable primary energy demand in the operation phase, which can even be higher than for the city buses using fossil fuels. The decrease of the primary energy demand in the EoL phase is due to the supply with secondary material from recycling of the city bus and the wind power plants for any other product.

The amount of renewable primary for the "100% climate neutral" city bus with diesel is about the same as for the "100% climate neutral" electric buses, whereas for H_2 and e-diesel it is significantly higher. It might be concluded that if CCS is technically and economically feasible in the future, significantly less additional renewable electricity would be needed for a "100% climate neutral" diesel bus than for a "100% climate neutral" e-diesel or H_2 bus.

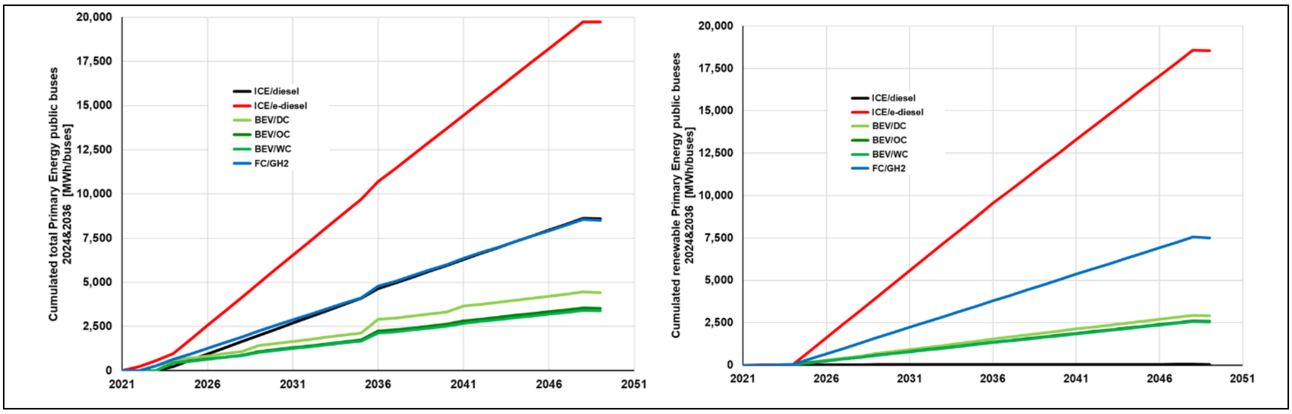

Figure 9: Total (left) and renewable (right) primary energy demand over time for the city buses without CCS

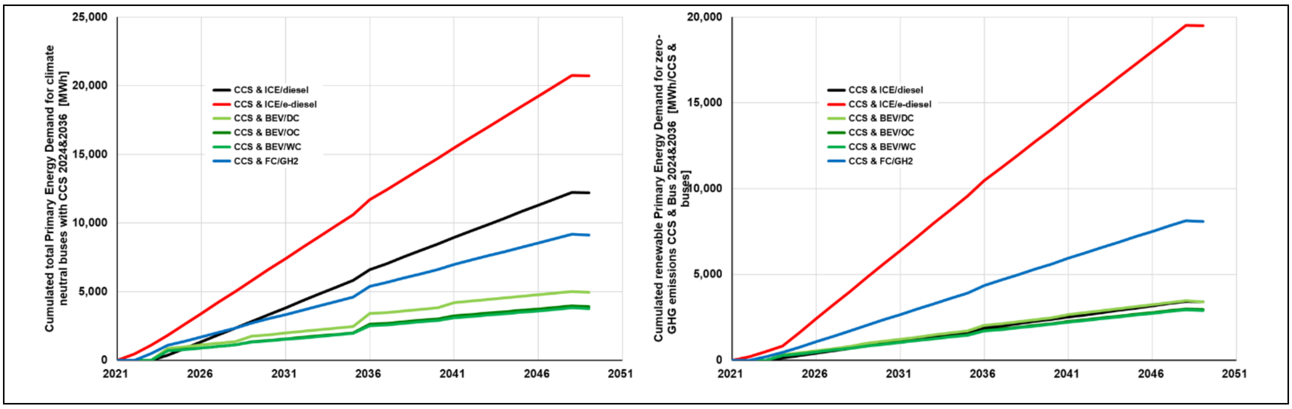

Figure 10: Total (left) and renewable (right) primary energy demand over time for the “100% climate neutral” city buses with CCS

4.4 Circularity Potential

As the basis for the calculation of the Material Circularity Index the total material demand in the lifetime of the city buses is calculated. In all systems, the mass of the city bus is significantly lower than the mass of the used fossil fuel and the mass needed for construction of renewable power plants as well as the catenary system.

In Figure 11 the Circularity Potential over time for the city buses is shown. All systems start in nature with an MCI of 100% before the construction phase. During the construction, phase the MCI decreases significantly, again for e-fuel and H_2 more than for electric city buses due to the higher demand of renewable power plants. In the operation phase the MCI for systems using renewable electricity nearly remains constant beside a small influence due to the spare parts and maintenance. For systems, using fossil energy the MCI is drastically reduced in the operation phase due to the non-circularity of fossil fuel combustion.

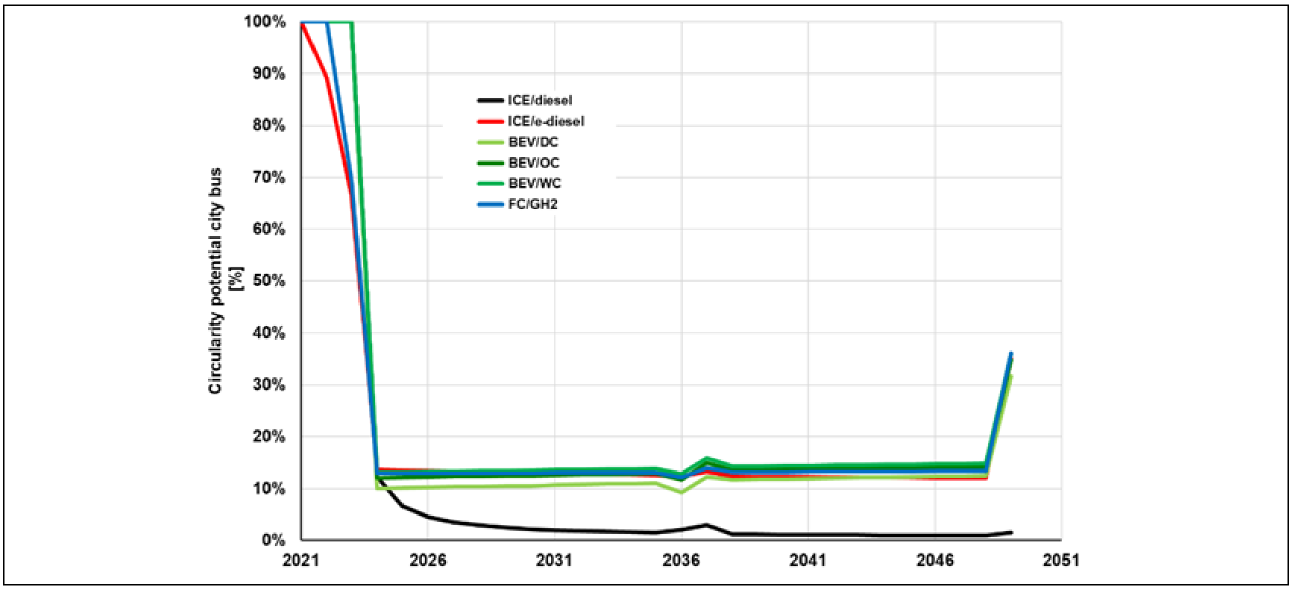

Figure 11: Circularity Potential over time for the city buses

4.5 Overall Results

Figure 12 shows the overall assessment of the different environmental effects of the city buses without CCS and “100% climate neutral” with CCS. In this overall summary, the reference is the diesel/ICE, which is set to 100%. The Circularity Potential is given in 1/MCI. One can observe that the Climate Neutrality Potential - measured in radiative forcing in the year 2050 – delivers different results than the GHG emissions. Additional to wellestablished categories in life cycle based assessment, the Circularity Potential as well as the Climate Neutrality Potential in 2050 delivers information covered neither in the primary energy demand nor in the GHG emissions.

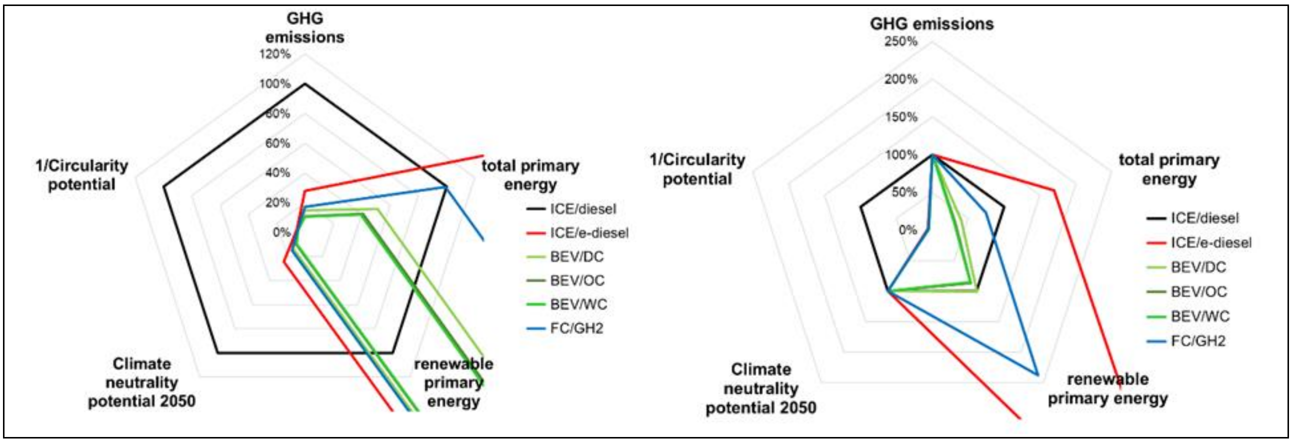

Figure 12: Overall assessment and comparison of the city buses without (right) / with CCS (left), diesel ICE = 100%

5 Conclusions

The following conclusions and observations can be drawn:

- Climate Neutrality Potential and Circularity Potential describe additional environmental effects not covered yet in the different LCA assessment categories.
- The Climate Neutrality Potential measures the radiative forcing in mW/m² in the year 2050. Thus, the timing of the GHG emissions during the lifetime of the system is relevant.
- The Circularity Potential is measured with the Material Circularity Index, which is between 0% (linear) and 100% (circular), which is mainly determined by the amount of primary material (incl. fossil fuels) and the non-recoverable waste.
- Systems using renewable energy have the potential to direct towards Climate Neutrality and Circularity.
- The assessment of circularity using MCI shows that material circularity is significantly determined by the amount and type of material used.
- The amount of material required for the renewable electricity power plants is significantly higher than the amount of material used in the city bus.
- Additional wind power: relevant in dynamic LCA to assess Circularity and Climate neutrality
- Further development of the approach for “Climate Neutrality Potential” and “Circularity Potential”: works well
- Battery and fuel cell change after 6 years: no significant influence on results
- Consideration over lifetime of two buses for 24 years: gives a better picture of circularity index at EoL
- Duration of system production: e-fuel= 3 years, H_2 = 2 years and BEV = 1 year: nice to have & argue
- “Climate Neutrality” with CCS of all systems:
    - more wind power needed
    - ICE/diesel needs about the same amount of electricity as for BEV systems
    - “it needs less additional renewable electricity to use fossil diesel with CCS than making e-diesel”
- Further issues
    - Reconsider methodology on recycling: e.g. GHG credits
    - Including criticality of materials in circularity assessment
- Battery electric buses have the lowest environmental effects in all environmental impacts
- Due to the higher necessary battery capacity of the depot charging strategy, the bus using depot charging has a little higher environmental impacts than the buses using (wireless) opportunity charging
- The e-diesel bus has the highest GHG emissions and the highest primary energy demand.
- The Circularity Potential of the electric, hydrogen and e-diesel bus a quite similar (31 – 36%). Due to the use of fossil diesel in the operation phase the circularity potential of the diesel bus is below 1.5%.

- In combination with CCS all buses can have zero GHG emissions and can be climate neutral throughout the total lifetime.
- The additional primary energy for CCS needed is
    - 30% for diesel bus and the absolute amount is the same as the electric buses needs in total
    - 5% for e-diesel bus
    - 10% for electric buses and the absolute amount is the lowest compared to all other buses
    - 7% for hydrogen bus

6 Acknowledgments

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8 Presenter Biography

Gerfried Jungmeier

Highlights of professional experiences: 1) life cycle assessment of energy systems, 2) greenhouse gas assessment of products and services. 3) sustainability assessment and scenarios for climate neutral transportation systems. Key researcher at JOANNEUM RESEARCH “Future Energy Systems and Lifestyles” and Lecturer at Vienna University of Technology, University of Applied Science in Kapfenberg and Danube University Krems". Task Manager in IEA TCP HEV Task 30 “Environmental Effects of Electric Vehicles”, Task 46 “LCA of Electric City buses, Buses, Two-wheelers and Other Vehicles”, Task 33 “Battery Electric Buses” and Task 52 “EVs and Circularity”