

ASSESSING THE CIRCULARITY POTENTIAL IN LCA AS A NEW IMPACT CATEGORY - A CASE STUDY ON BUSES

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Abstract

In the IEA Technology Collaboration Program experts from 20 countries focus on LCA of EVs since 2010. The IEA Task 46 developed a new methodology to assess the Circularity Potential using a dynamic LCA approach and applied it in a case study to city buses using electricity, hydrogen, diesel and e-diesel. For LCA Circularity is defined by Task 46: *A product or service is “100% circular”, if its whole life cycle - production, operation and end-of-life - uses only reused components, secondary/recycled material, renewable energy and makes no waste and GHG emissions.* The Circularity Potential is assessed based on the mass flows of the buses during their lifetime using data of the Inventory Analysis for the Material Circularity Index (MCI) - 100% = circular and 0% = linear – applying the Linear Flow Index of materials (LFI_{material}) and the Utility Factor of product (UF_{product}).

Figure 1 shows the Circularity Potential over 24 years life time for the city buses. All systems start in nature with an MCI of 100% before the construction phase. During the construction phase the MCI decreases significantly, for e-fuel and H₂ 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.

The main conclusions are: (1) Systems using renewable energy have the potential to direct towards Circularity. (2) The assessment of circularity using MCI shows that material circularity is significantly determined by the amount and type of material used. (3) The amount of material required for the renewable electricity power plants is significantly higher than the amount of material used in the city bus. (4) The Circularity Potential of the electric, hydrogen and e-diesel bus is quite similar (31 – 36%), whereas for e-diesel (35%) and hydrogen (36%) it is a lower compared to electric buses (31 – 36%) due to the higher demand of renewable electricity. (5) For diesel bus due to the use of fossil diesel the circularity potential is below 1.5%. (6) The Circularity Potential is a new indicator in LCA not yet covered by other impact categories.

1 Goal and Scope

The goal and scope of this LCA are described.

1.1 Introduction

Reducing GHG emissions 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 Electric Vehicles (EV) 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. Based on a definition of “100% Climate Neutrality” in [1] and [2] a methodological assessment framework is developed and applied in a case study to compare city buses with different propulsion & fuel combinations

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 EV Task 46 (<https://ieaev.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.

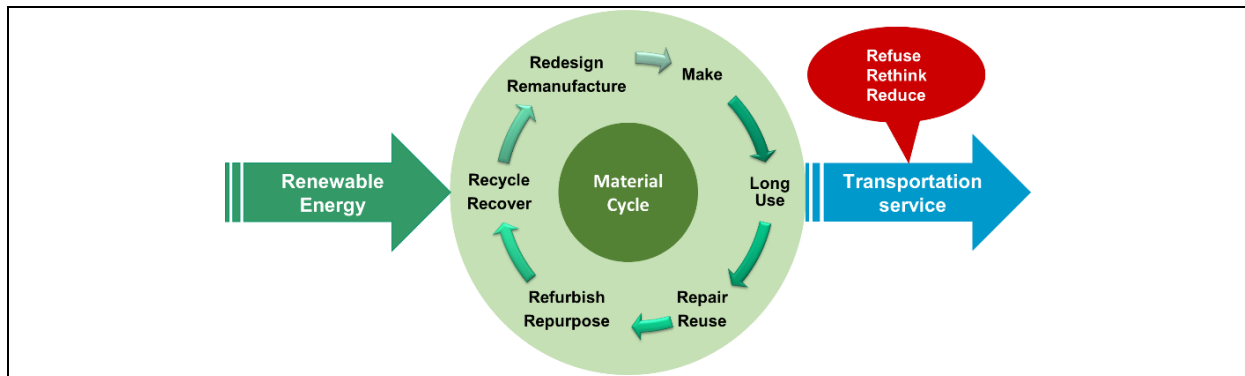


Figure 1: Circularity and Climate Neutrality for transportation services

The indicators for the assessment in the LCA are

- Circularity Potential (CPO) is based on data of Inventory Analysis of the mass flows in and out of the considered systems. The Material Circularity Index (MCI) is calculated based on mass flows over lifetime based on [3] with additional aspects on fossil energy use, where 100% means full circularity. The use of fossil energy is not circular. The Linear Flow Index of the materials (LFI_{material}) - including fossil energy as material in the operation phase - is used together with the Utility Factor of the product (UF_{product}): Utility = lifetime * intensity of use:

$$MCI = LFI_{\text{materials}} * UF_{\text{product}}$$

- Climate Neutrality Potential (CNP) is based on GHG emissions of the impact assessment. The physical measure is the total top-of-atmosphere radiative forcing based on GHG emissions over lifetime: $RF = 0 \text{ W/m}^2$. Every greenhouse gas emission increases the Climate Neutrality Potential, so Climate Neutrality is a visionary target. At least this assessment helps to see if the systems is on a path „towards climate neutrality“ aiming for zero GHG emissions in operation phase: e.g. $0 \text{ kg CO}_2\text{-eq/a}$ and a small change in radiative forcing after system's lifetime in 2050: $\Delta RF_{2050} = 0 \text{ W/m}^2$.

The calculation of the MCI is based on the methodology developed by the Ellen MacArthur Foundation [3], which is shown in Figure 2 but fossil energy in operation phase is considered in addition. 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. The MCI is split in the production, operation and EoL phases.

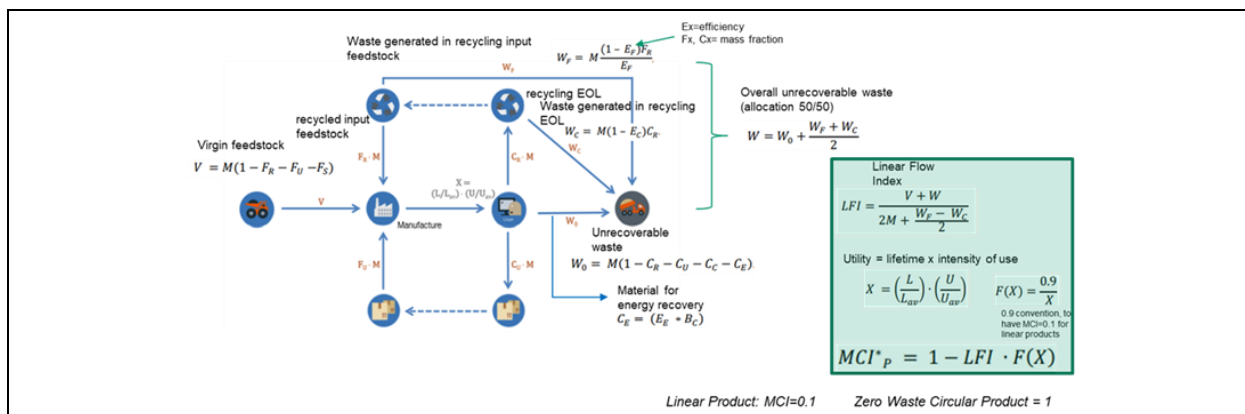


Figure 2: Calculation of the LFI of materials the MCI of products based on [3]

Taking these 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 3, 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.

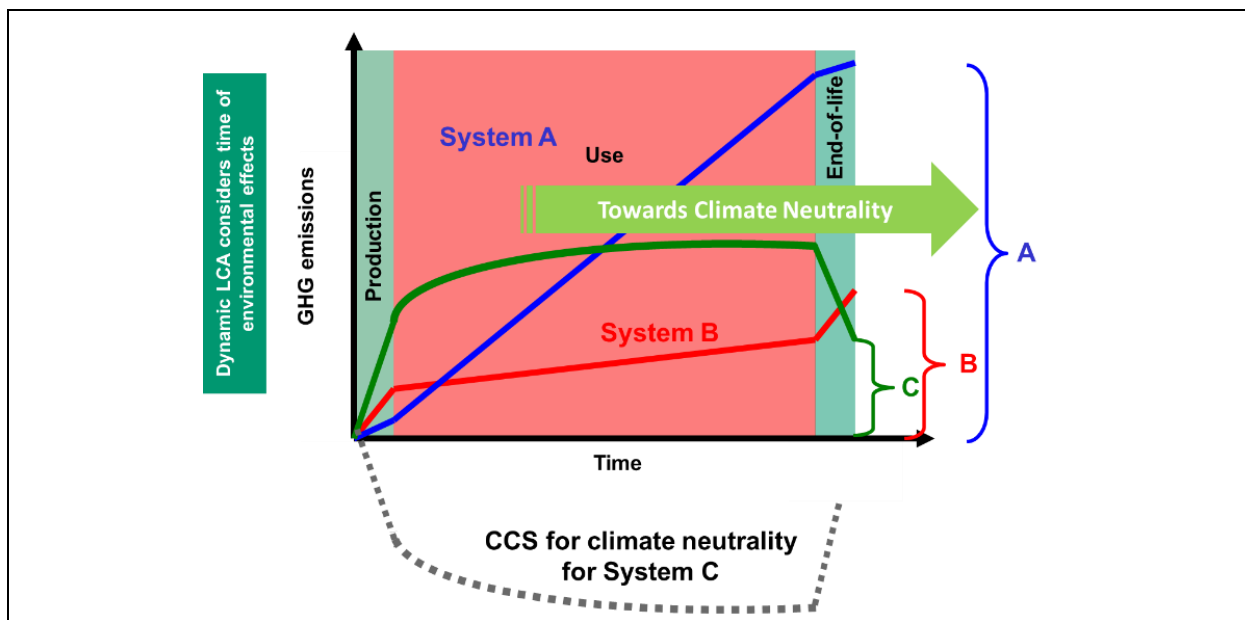


Figure 3: Timing of cumulated GHG emissions of three systems with the same lifetime and service

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 4):

- diesel with ICE (Internal Combustion Engine)
- e-diesel from wind electricity and CO₂ from air with ICE
- electricity for BEV with depot (DC), opportunity (OC) and wireless charging (WC) with wind electricity
- H₂ with FC (Fuel Cell) from wind electricity: renewable GH₂ @ 700 bar

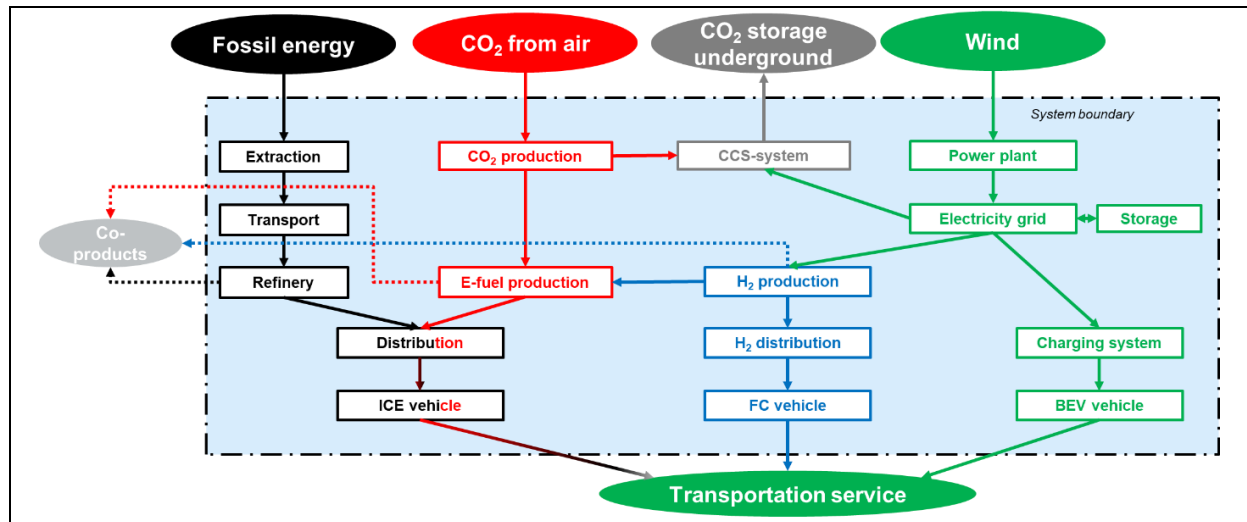


Figure 4: LCA comparison of “100% Climate Neutral” bus systems using additional wind electricity and CCS

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 CO₂, CH₄, N₂O and direct H₂ emissions in CO₂-eq
- towards climate neutrality: radiative forcing (in the year 2050) in mW₂₀₅₀/m² to assess the Climate Neutrality Potential
- primary energy covering renewable and non-renewable energy carries in MWh

The GWP₁₀₀ of hydrogen is 10.9 kg CO₂-eq per kg of hydrogen (range: 6.5- 15 kg CO₂-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, H₂ = 2 years and BEV = 1 year
- “Climate Neutrality” of all systems in combination with Carbon Capture & Storage (CCS) of CO₂ from air with wind power. It is calculated based on CO₂eq also covering CH₄ and N₂O. The CCS simplified with static LCA with no timing of GHG emissions.

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 and for relevant infrastructure in Table 2. E.g. the BEV DC bus needs annually about 120 MWh of electricity incl. charging and distribution losses, so the construction material demand of the wind power plant - 0.5 t/(MWh/a) - for this bus is about 60 t.

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	[name]	city bus						
		ICE diesel	ICE e-diesel	BEV DC	BEV OC	BEV WC	FC GH2@700	
propulsion	[name]	19,500	19,500	19,500	19,500	19,500	19,500	
fuel	[name]							
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
 **) H₂ losses/emissions
 ***) 2nd battery/fuel cell 10% less

Table 2: Foreground data for infrastructure city buses [8]

	Construction					
	GHG [gCO ₂ e/(kWh/a)]	PED [kWh/(kWh/a)]	PEDfossil [kWh/(kWh/a)]	mass [kg/(kWh/a)]	lifetime [a]	full load hours [h/a]
electr. / wind	551	1.00	0.99	0.5	24	2,200
(e-)fuel supply	17	0.03	0.03	9	35	8,500
	[t CO ₂ -eq/point]	[MWh/point]	[MWh_fossil/point]	[t/point]	[a]	[h/a]
charging station	13	20	19	3	15	4,000

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 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 5 the Circularity Potential over time for the city buses is shown. In the construction phase the total infrastructure (e.g. wind power plants, fossil energy supply) and the buses are considered, and in the operation phase also the fossil energy. All systems start in nature with an MCI of 100% before the construction phase. As the e-fuel and hydrogen buses need significantly more electricity than the battery bus, more wind power plants have to be built, so it was assumed that the wind power plant construction for the e-fuel and hydrogen bus must start 1 or 2 years before the battery bus. During the construction, phase the MCI decreases significantly, again for e-fuel and H₂ 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. In the EoL-phase the MCI increases due to the recycling of materials. The Circularity Potential of the electric, hydrogen and e-diesel bus a quite similar (31 – 36%), whereas for e-diesel (35%) and hydrogen (36%) it is a lower compared to electric buses (31 – 36%) due to the higher demand of renewable electricity. For diesel bus due to the use of fossil diesel the circularity potential is below 1.5%.

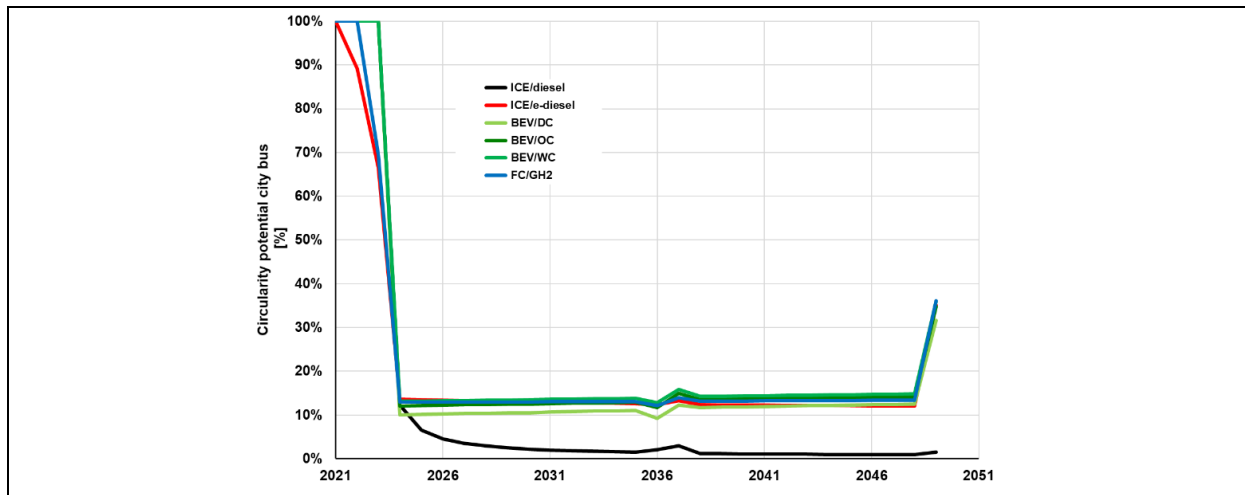


Figure 5: Circularity Potential over time for the city buses

4.2 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 CO₂-eq in the total lifetime. The GHG emissions increase during the construction phase is due to the construction of the city bus and the wind power plants, and start in different years for the considered systems due to different assumed construction time. For the bus 2 the energy supplying infrastructure is already existing from bus 1, so only the construction of bus 2 is relevant. As the electricity demand for e-fuel and H₂ 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, where a GHG credit is given based on avoided burden approach. 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 H₂ compared to electric city bus.

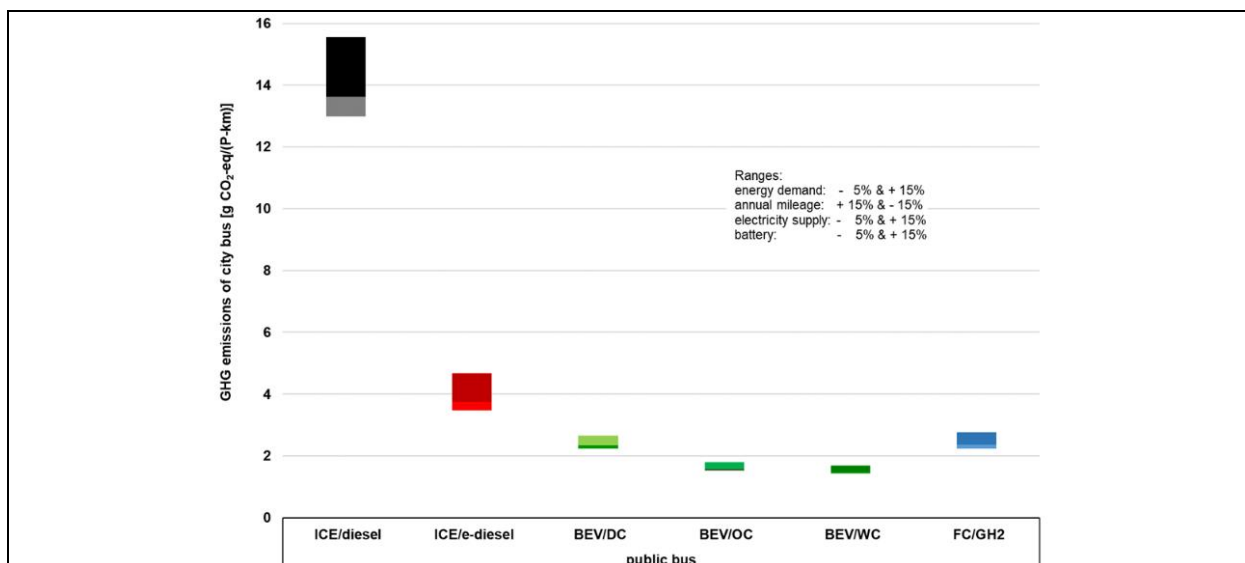


Figure 6: GHG emissions of the city buses 2024

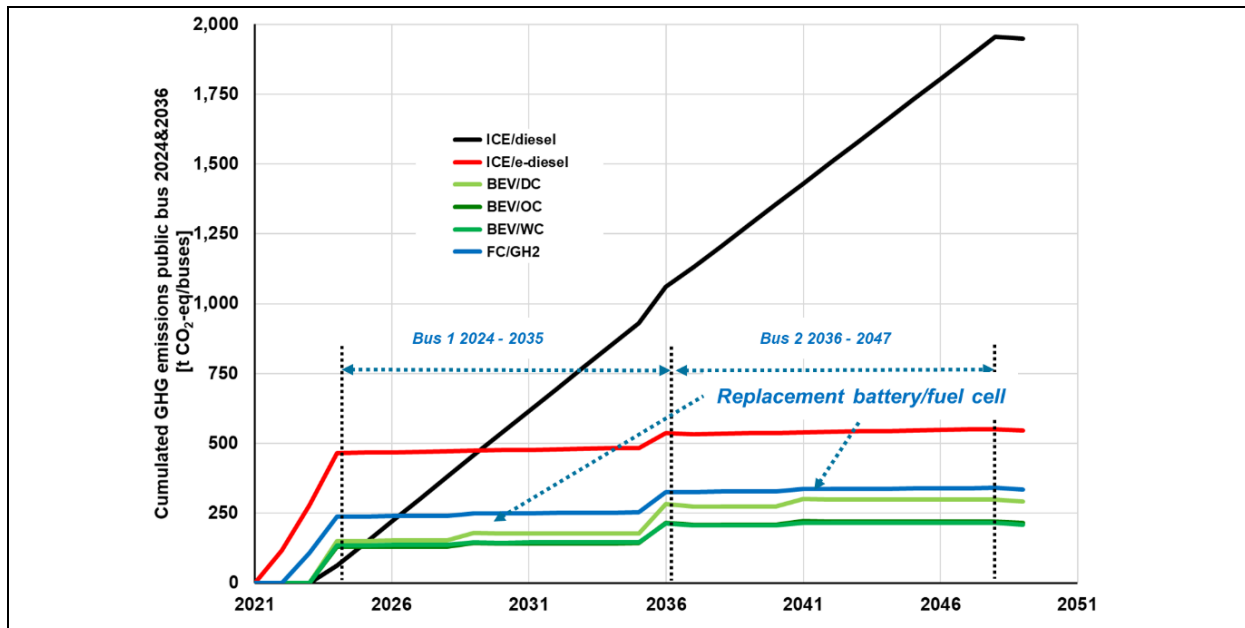


Figure 7: Global Warming Potential of the GHG emissions over time for the city buses

4.3 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 have the lowest radiative forcing at the end of its lifetime. The Climate Neutrality Potential in 2050 delivers additional assessment information as it reflects also the time in the lifecycle of the buses when the GHG emissions are released. For the buses using renewable energy the GHG emissions mainly occur in the construction phase, but over time these emissions are removed from the atmosphere, e.g. CO₂ sink in ocean, CH₄ and N₂O are degraded, so the radiative forcing is decreasing over time. For the diesel bus the radiative forcing is increasing over time as the GHG emission from the annual diesel combustion are in the operation phase.

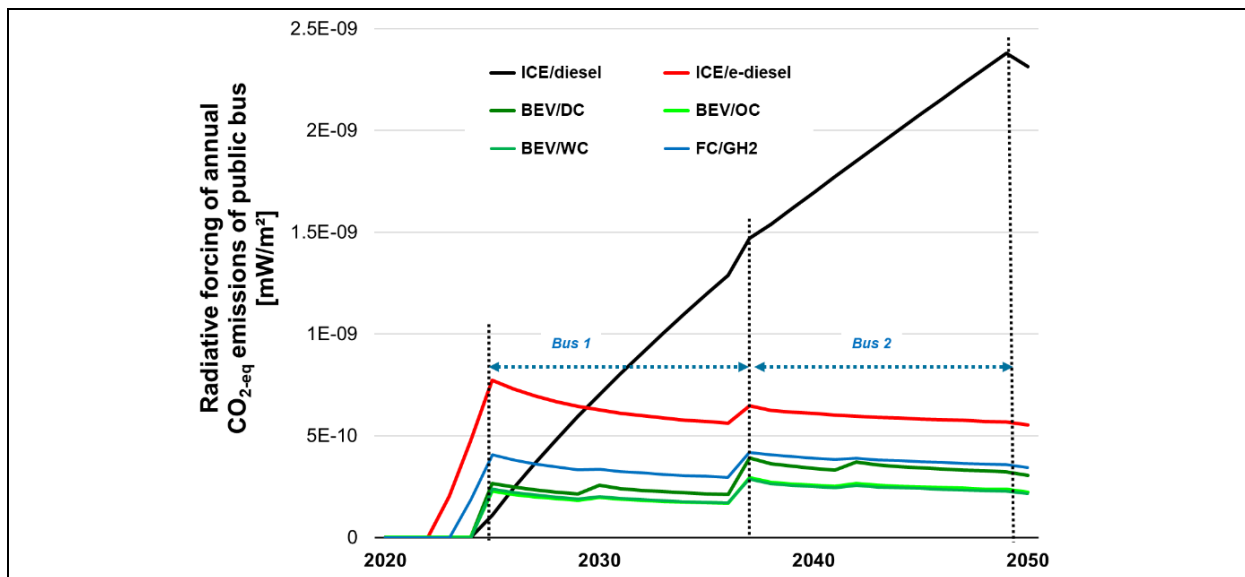


Figure 8: Climate Neutrality Potential of the radiative forcing over time for the city buses

4.4 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 H₂ 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 H₂ 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 H₂ 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 H₂ bus.

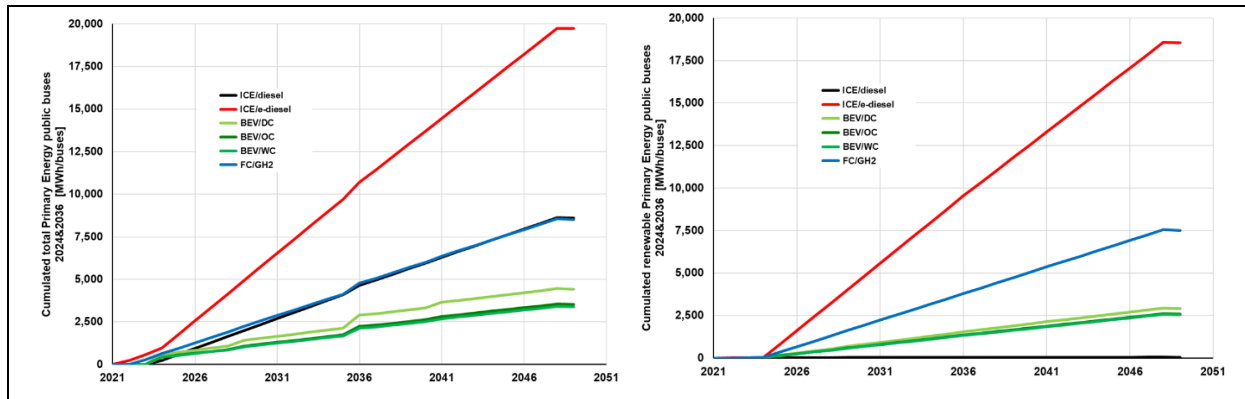


Figure 9: Total (left) and renewable (right) primary energy demand over time for the city buses without CCS

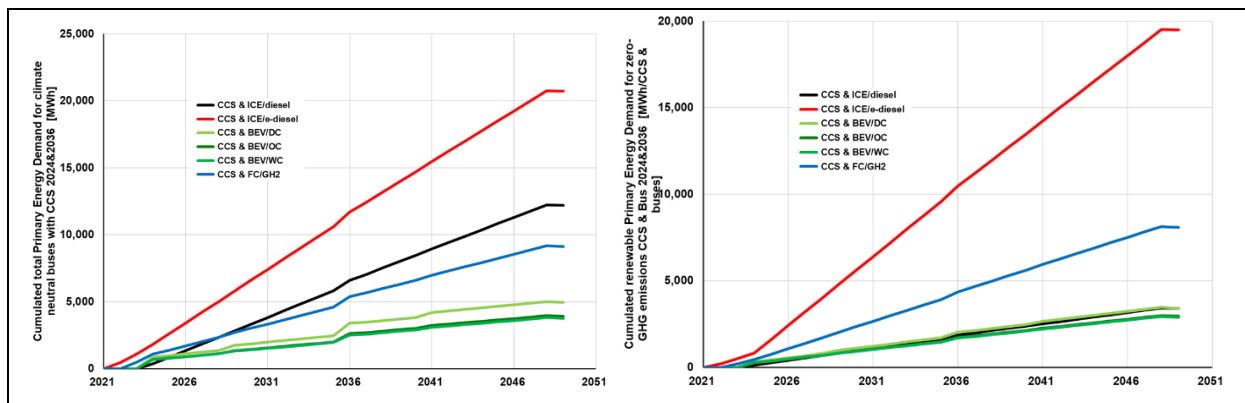


Figure 10: Total (left) and renewable (right) primary energy demand for “100% climate neutral” buses with CCS

4.5 Overall Results

Figure 11 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. As the renewable energy demand for buses with e-fuel, hydrogen and electricity is so much more than for the diesel bus (see Figure 9 and Figure 10), they extend the graph.

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 well-established 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.

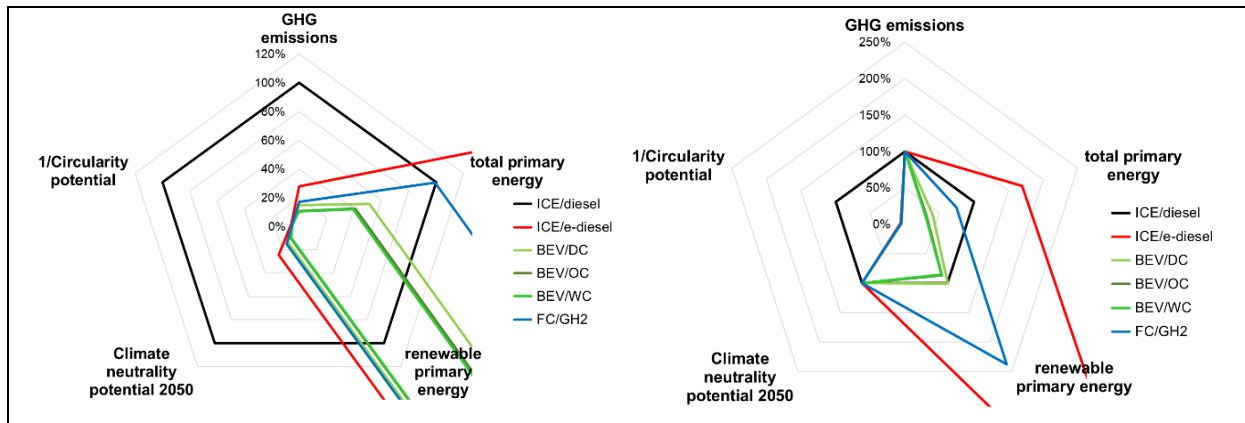


Figure 11: Overall comparison of the city buses without (right) / with CCS (left), diesel ICE = 100%

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/m^2 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.

The consideration of additional wind power in the construction phase is relevant in dynamic LCA to assess Circularity and Climate neutrality. Due to the significant higher electricity demand for e-fuel and hydrogen compared to the electric bus, the construction phase of the wind power plants might have to be started earlier for e-fuels and hydrogen than for electric bus.

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. The Circularity Potential of the electric, hydrogen and e-diesel bus a quite similar (31 – 36%), whereas for e-diesel (35%) and hydrogen (36%) it is a lower compared to electric buses (31 – 36%) due to the higher demand of renewable electricity. Due to the use of fossil diesel in the operation phase the circularity potential of the diesel bus is below 1.5%.

The battery electric buses have the lowest environmental effects in all considered 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 diesel bus has the highest environmental impacts, except the primary energy demand is lower than for e-diesel. The battery and fuel cell changes after 6 years have no significant influence on the results. The consideration over lifetime of two buses for 24 years gives a clear picture of the circularity index at the EoL.

The “100% Climate Neutrality” with CCS of all bus systems shows that more wind power is needed. Then the ICE/diesel with CCS needs about the same amount of electricity as for BEV systems. And it needs about 5 times less additional renewable electricity to use fossil diesel with CCS than using e-diesel with CCS. 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

The further development of the approach for “Climate Neutrality Potential” and “Circularity Potential” described here, seems to work well and gives benefits in addition to the existing impact categories in LCA. So the “Climate Neutrality Potential” and “Circularity Potential” might be to new or new impact categories. The team of IEA Task 46 will further develop this approach by reconsider methodology on recycling; the possible inclusions of the

criticality of materials in the circularity assessment, to consider fossil energy input also in the construction and end of life phase and to split the MCI in the production and EoL-phase.

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