



Techno-economic feasibility study on Fuel cell and Battery electric buses – Austria

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- **Austrian transport emissions and status**
- **Research objective and methodology**
- **System boundaries**
 - Topology of the buses
 - Electricity mixes
- **Results**
 - Global green house gas (GHG) emissions comparison
 - Total cost of ownership (TCO)
- **Conclusion**

Austrian transport emissions and status

Transport in Austria:

- 30.7 % of overall national Greenhouse Gas (GHG) emissions.

Austrian climate objectives:

- 36 % overall GHG emissions reduction by 2030 (compared to 2005 levels)
- 2050 - carbon free energy system

Current bus (diesel) fleet:

- Graz Holding – 162 buses \approx 10 mil km/yr
 - 18 m articulated buses (97)
 - 12 m solo buses (65)

move⁴zero

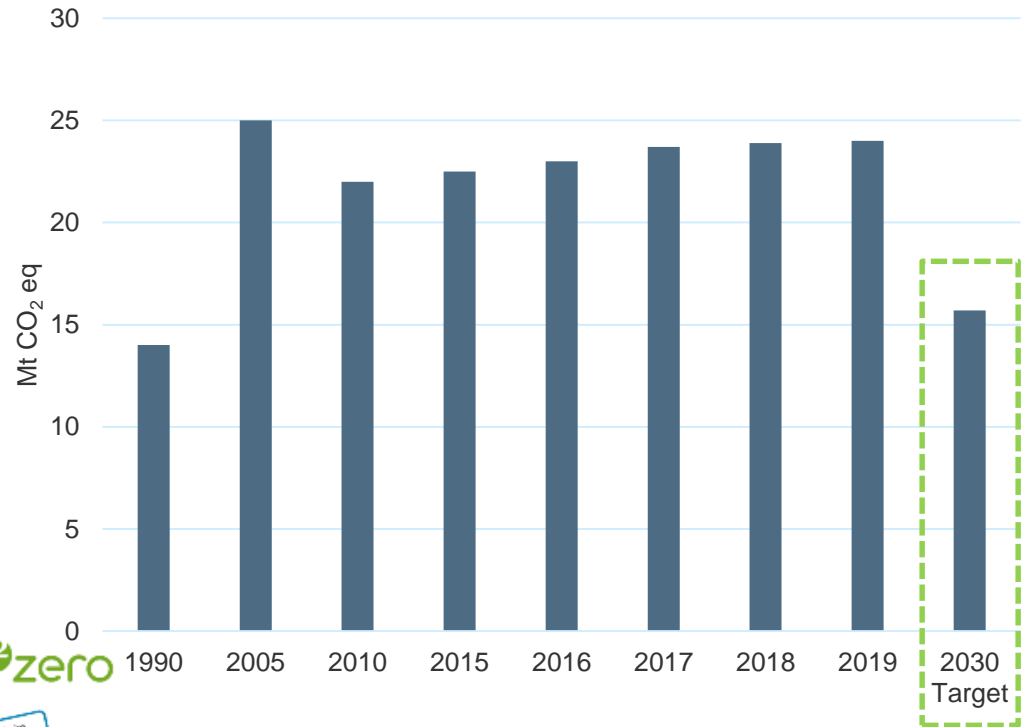
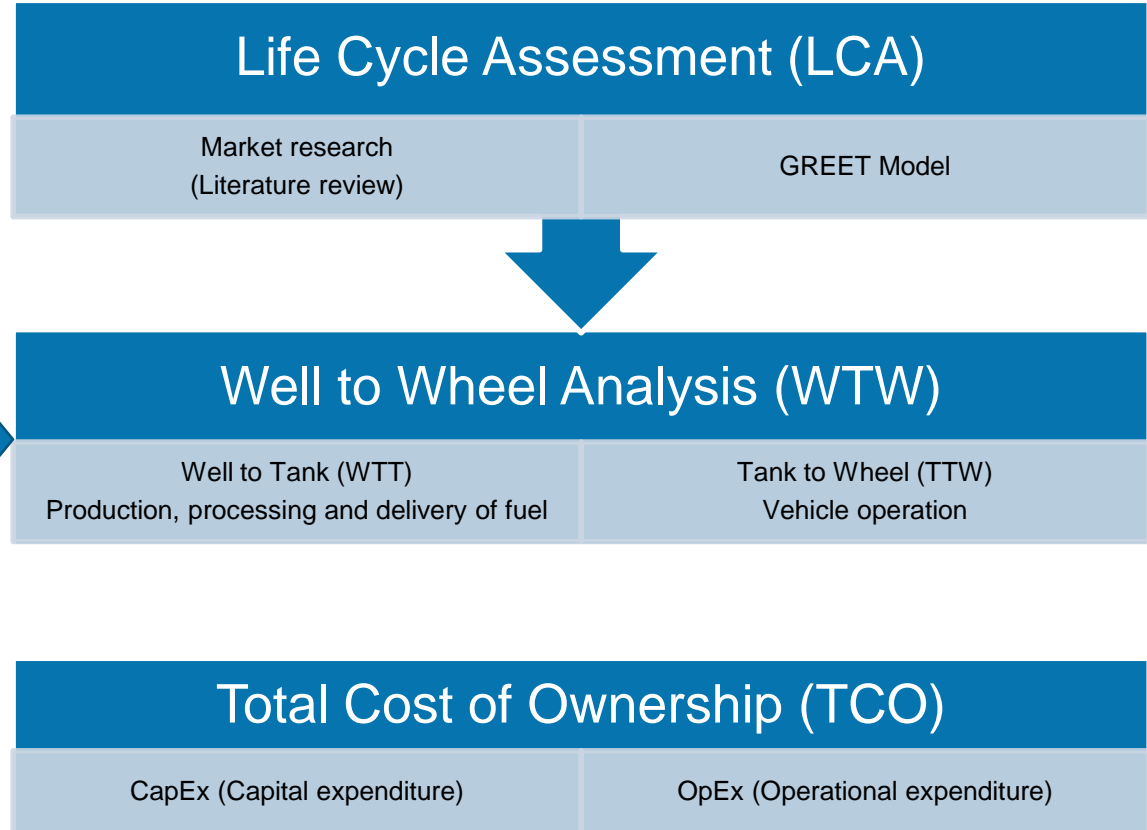



Figure 1: Transport GHG emissions in Austria (VCÖ, 2020)

Compare the **carbon footprint** (cradle to grave) of **battery dominant** (BEB) and **fuel cell dominant** buses (FCEB) to choose the best available option from both **environmental and economic** perspective.

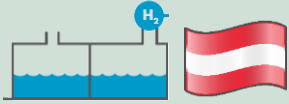
Manufacturing and recycling emissions





Topology of the buses


Solaris Urbino FC

	H ₂ Tank	Stack	Battery
12 m	37,5 kg	70 kW	30 kWh
18 m	40 kg	150 kW	60 kWh

Electrolysis 

Supply  Refuelling Station 

Refuelling: 12-15 min
Range: 350 km



H₂ Tank
Fuel cell
Battery
Powertrain


Manufacturing


Operation

Disposal/Recycle


Solaris Urbino BE

	Battery
12 m	395 kWh
18 m	550 kWh

Electricity grid mix 

Charging station 

Charging: 8-10 h
Range: approx. 200 km



Battery
Powertrain
Motor

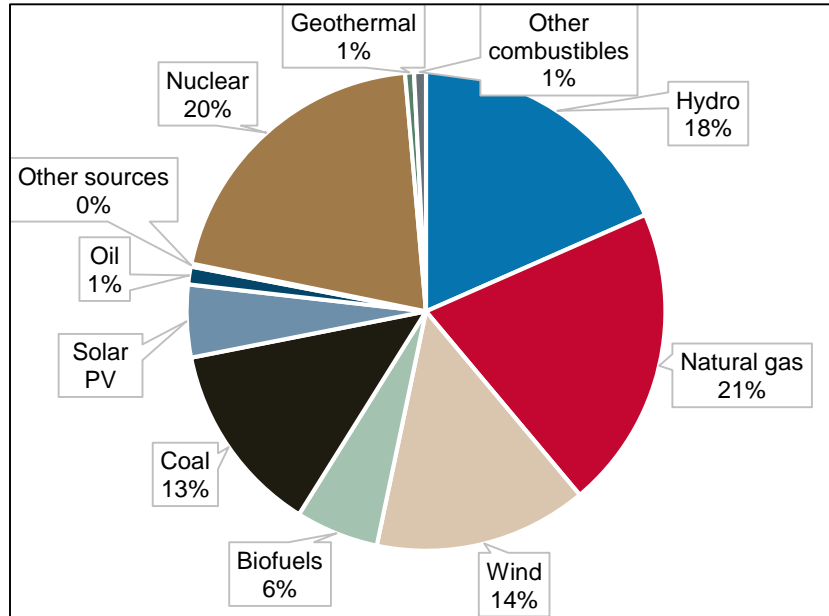


Figure 4: European Electricity mix (IEA, 2020)

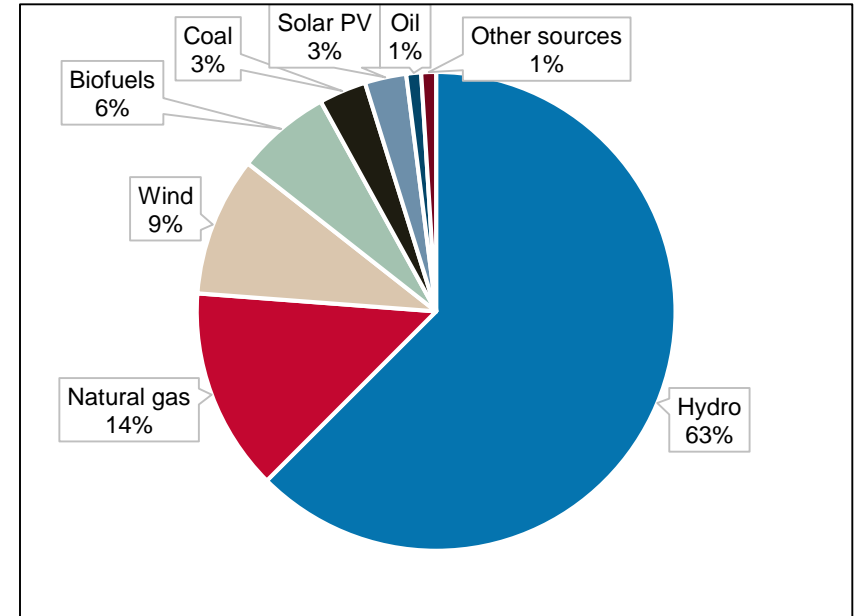


Figure 5: Austrian Electricity mix (IEA, 2020)

Bus Manufacturing – Europe
 370 g CO₂-eq/kWh - Avg EU electricity mix (IEA, 2020) ⚡

Operation (Well To Pump) – Austria
 130 g CO₂-eq/kWh – Avg. Austrian electricity mix ⚡
 19.87 g CO₂-eq/kWh – Avg. Austrian electricity mix (green) ⚡

GHG emissions comparison FCEB vs BEB

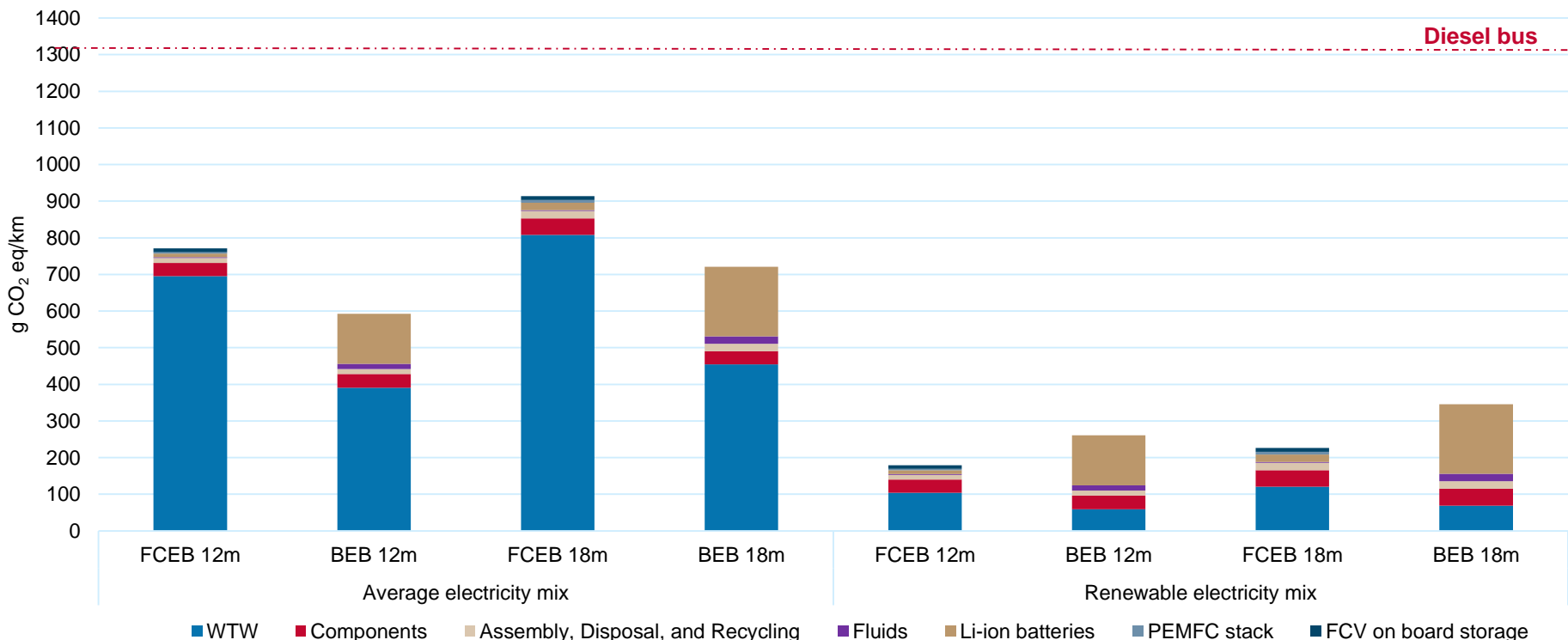


Figure 6: FCEB vs BEB GHG emissions in g CO₂ eq/km.

130 g CO₂-eq/kWh – Avg. Austrian electricity mix
 19.87 g/kWh – Avg. Austrian electricity mix (green)
 370 g/kWh – Avg. EU electricity mix (IEA, 2020)
 Diesel bus – 1300 g CO₂ eq / km (Carbonindependent, 2021)

FCEB vs BEB mileage at one full recharge

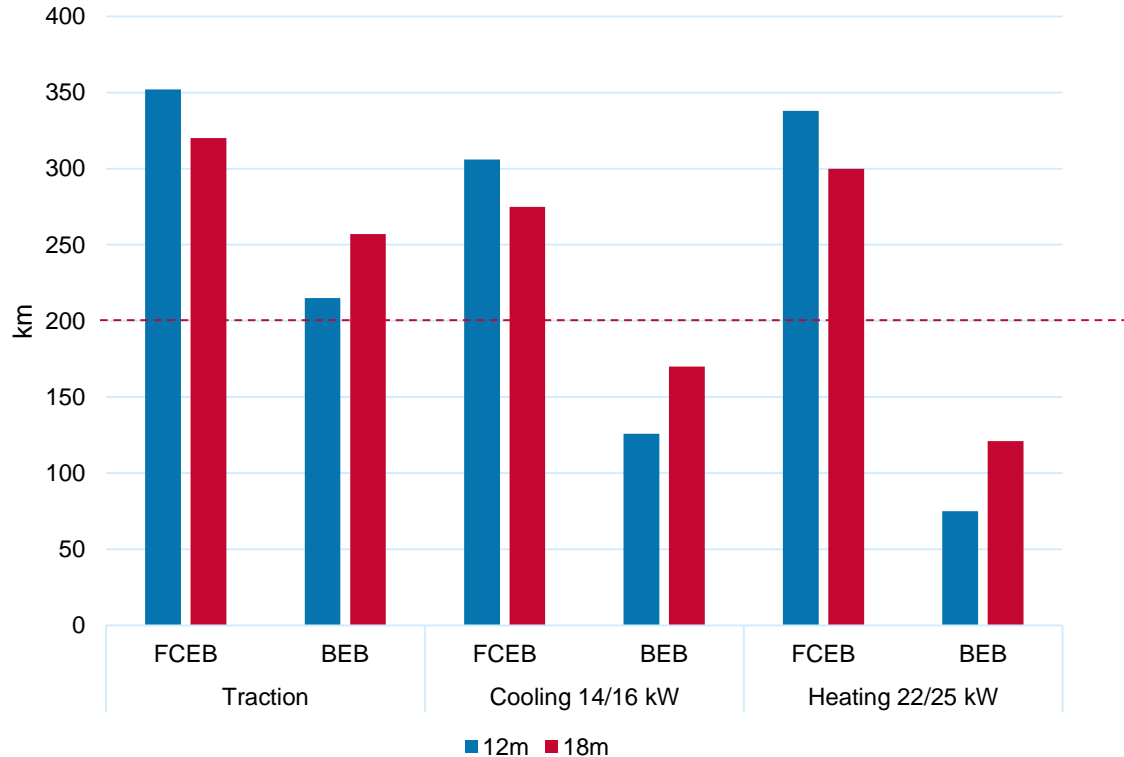


Figure 7: FCEB vs BEB mileage at one full recharge.

45% routes \geq 200 km
 Lifetime mileage 800,000 km
 Avg. 14 hr operation per day

Boundary conditions		
	FCEB 12 m	FCEB 18 m
Passenger capacity (avg weight = 80 kg)	50	80
PEMFC stack	70 kW	150 kW
Li-ion Battery pack	30 kWh	60 kWh
Fuel consumption (kg H ₂ /100 km)	8.0	9.5
	BEB 12 m	BEB 18 m
Passenger capacity (avg weight = 80 kg)	50	80
Li-ion Battery pack	395 kWh	550 kWh
Energy consumption (kWh/100 km)	220	256

FCEB vs BEB fleet: Lifetime GHG emissions

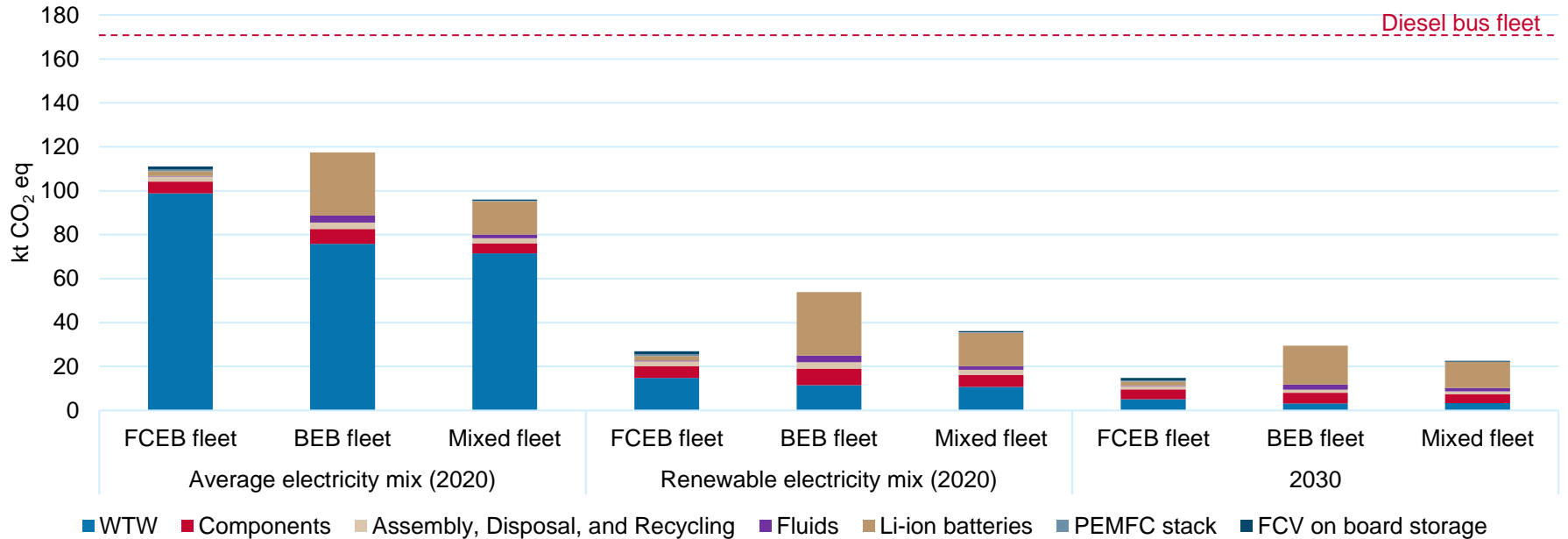


Figure 8: Comparison of lifetime GHG emissions for different case scenarios.

Lifetime mileage 800,000 km

- Homogenous FCEB fleet – 162 buses
- Homogenous BEB fleet – 227 buses
- Heterogenous/mixed fleet -
 - 97 BEBs (18 m)
 - 65 FCEBs (12 m)
- 2030 -
 - Renewable electricity mix
 - Lower fuel consumption
 - Lower material usage

Total cost of Ownership

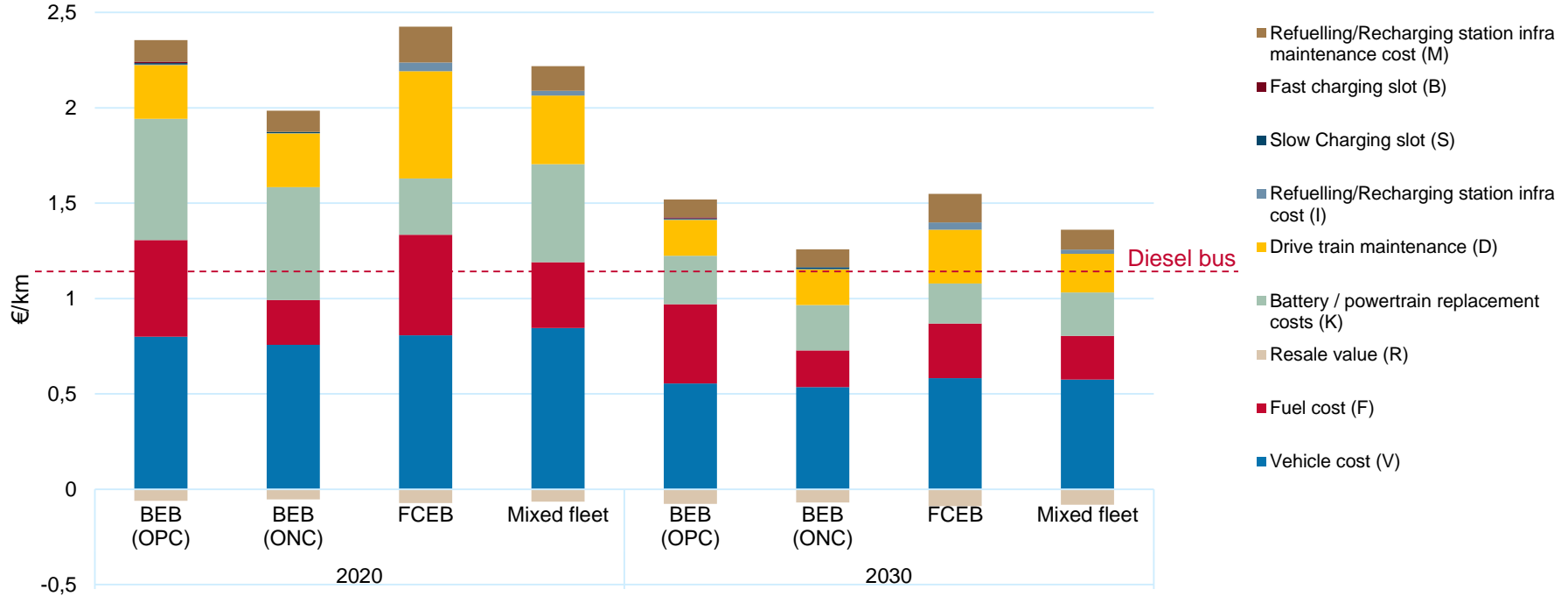























Figure 9: TCO comparison for different case scenarios.

- 800,000 km lifetime mileage \approx 15 years
- ONCs - 2:1 (0.1 € / kWh)
- OPCs - 20:1 (0.4 € / kWh)
- Homogenous FCEB fleet = 162 buses
- Homogenous BEB fleet = 227 buses
- Heterogenous/mixed fleet -
 - 97 BEBs (18 m) - ONCs
 - 65 FCEBs (12 m)
- ONC – overnight charging stations;
- OPC – opportunity charging stations

Conclusion

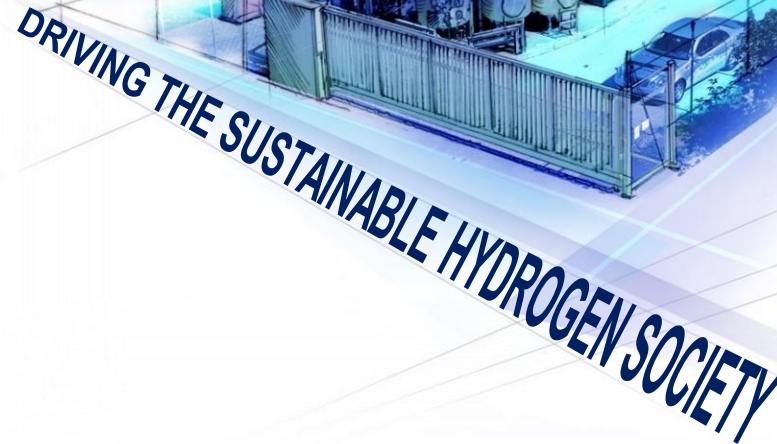
	BEB fleet	FCEB fleet	Mixed fleet (BEB 18m + FCEB 12m)
 Range	Seasonal changes <ul style="list-style-type: none"> Over night charging  Opportunity charging  	<ul style="list-style-type: none"> No range issues  	<ul style="list-style-type: none"> 12 m FCEBs 
 TCO	<ul style="list-style-type: none"> OPC: 2.3 €/km  ONC: 1.9 €/km  	<ul style="list-style-type: none"> 2.35 €/km  	<ul style="list-style-type: none"> 2.15 €/km 
 Components	Li-ion batteries  <ul style="list-style-type: none"> High Emissions Degree of recyclability 	<ul style="list-style-type: none"> Higher degree of recyclability  Energy storage options 	<ul style="list-style-type: none"> Energy storage options Grid balance 
 Emission Reduction	<ul style="list-style-type: none"> 50 kt CO₂ eq  110 kt CO₂ eq  	<ul style="list-style-type: none"> 56 kt CO₂ eq  136 kt CO₂ eq  	<ul style="list-style-type: none"> 68 kt CO₂ eq  130 kt CO₂ eq 

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Europe		
	GWh	% share
Nuclear	935670	22.47%
Coal	928032	22.29%
Natural gas	866763	20.82%
Hydro	615403	14.78%
Wind	384832	9.24%
Biofuels	166409	4.00%
Solar PV	120482	2.89%
Oil	64807	1.56%
Waste	50519	1.21%
Geothermal	18012	0.43%
Other sources	6298	0.15%
Solar thermal	5883	0.14%
Tide	526	0.01%

Austria		
	GWh	% share
Hydro	41213	60.74%
Natural gas	9914	14.61%
Wind	6030	8.89%
Biofuels	4570	6.74%
Coal	3620	5.34%
Solar PV	1438	2.12%
Oil	717	1.06%
Waste	336	0.50%
Other sources	13	0.02%

Table 1: Energy mix – China, Europe & Austria (IEA, 2020)

Total Cost of Ownership (Euro/km):

$$TCO = \frac{V+F+P+D+I+M+Q-R}{lifetime\ mileage} \dots\dots\dots (i)$$

- V - cost of one Bus,
- F - fuel cost over the lifetime of one bus,
- P - powertrain (battery/fuel cell stack) replacements cost,
- D - drive train maintenance cost per year per bus,
- I - refueling/recharging infrastructure costs per bus,
- M - infrastructure maintenance cost per year per bus,
- R - re-sale value of the bus,
- Q – Opportunity/Fast charging slot.

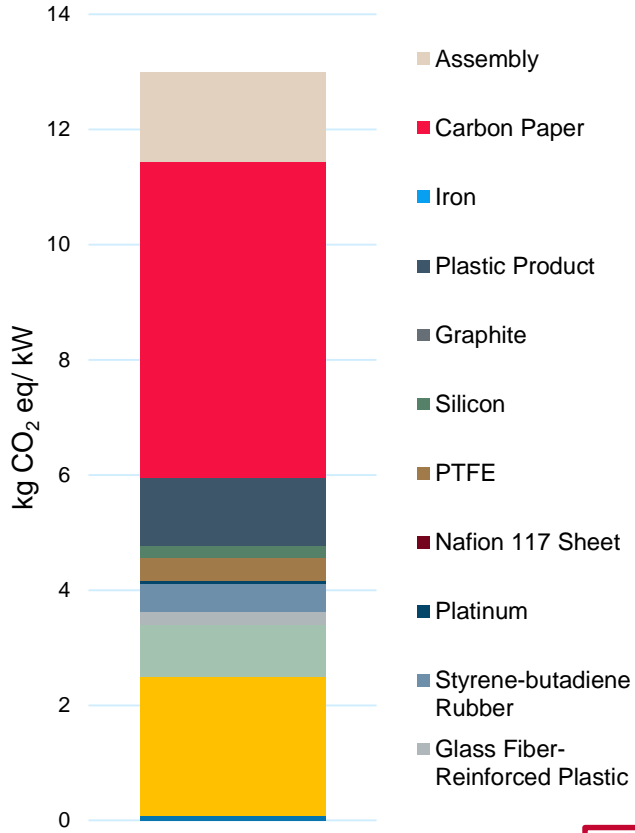
Appendix C

Parameters	BEB 12 m			FCEB 12 m			Source	Comments
	year	2020	2030 Target	year	2020	2030 Target		
Vehicle cost (V)	Sales cost (Euros)	520000	390000	Sales cost (Euros)	610000	430000	(Morrison, Stevens & Joseck, 2018); (New Bus ReFuelling for European Hydrogen Bus Depots)	Consumption - 2020 (220 kWh/100 km & 8 kg/100 km); 2030 (220 kWh/100 km & 6.5 kg/100km)
Fuel cost (F)	Euro/kWh	0.1	0.1	Euro/kg H2	6	4		
Resale value (R)	Euros	25000	30000	Euros	30000	40000		
Powertrain - replacement costs (K)	Battery pack >350 in Euros	87500	70000	100 kW FC stack price in Euros	62500	50000	(New Bus ReFuelling for European Hydrogen Bus Depots)	
Drive train maintenance	Euro/year/bus	15000	10000	Euro/year/bus	30000	15000		
Refuelling/Recharging station infra cost	Recharging station (Euros)	250000	200000	Refuelling station (Euros)	3000000	2500000		
Fast charging slot	Euros per slot	20000	15000				Jefferies and Göhlich 2020	
Refuelling/Recharging station infra maintenance cost	Euros	6000	5000		10000	8000		

Appendix D - Bus components weightage

Fuel Cell Bus – Solaris Urbino 12 m					Source	Battery Electric Bus – Solaris Urbino 12 m					Source
Components	Weight (kg)	Quantity	Replacements			Components	Weight (kg)	Quantity	Replacements		
Li ion NMC (30 kWh)	300	1	2	Shiau et al. 2009		Li ion NMC (395 kWh = 79kWh x 5)	790	5	2	Shiau et al. 2009	
PEMFC stack (70 kW)	140	1	2	Freudiger, Bigelow and Yurkovich, 2017; Stropnik et al., 2019; Ballard-FCveloCity-HD Spec Sheet, 2020							
Type 4 H ₂ tanks	80	5	-	Greene, Duleep, 2013 review							
Traction Motor	3000	1	-	default value - scaled		Traction Motor	3000	1	-	default value - scaled	
Vehicle assembly disposal recycling	13000	1	-	default value		Vehicle assembly disposal recycling	13000	1	-	default value	
Chassis	3500	1	-	default value - scaled		Chassis	3500	1	-	default value - scaled	
Vehicle body	4500	1	-	market research		Vehicle body	4500	1	-	market research	
Vehicle tire replacement	45.36	8	2	default value		Vehicle tire replacement	45.36	4	2	default value	
Electronic controller	60	1	-	default value		Electronic controller	60	1	-	default value	
Brake Fluid	0.45	1	12	default value		Brake Fluid	0.45	1	12	default value	
Engine/Powertrain Coolant	50	1	12	default value - scaled		Engine/Powertrain Coolant	50	10	12	default value - scaled	
Transmission Fluid	0.45	1	12	default value		Transmission Fluid	0.45	1	12	default value	
Windshield Fluid	25	1	12	default value - scaled		Windshield Fluid	25	1	12	default value - scaled	
Power Steering Fluid	0.45	1	12	default value		Power Steering Fluid	0.45	1	12	default value	

Fuel Cells and battery production: GHG emissions



	FCEB	BEB
	2 kg per kW	10 kg per kWh

370 g/kWh - EU electricity mix (IEA, 2020)
 270 g/kWh – SA electricity mix (IEA, 2020)

Figure 10: Fuel cell manufacturing emissions

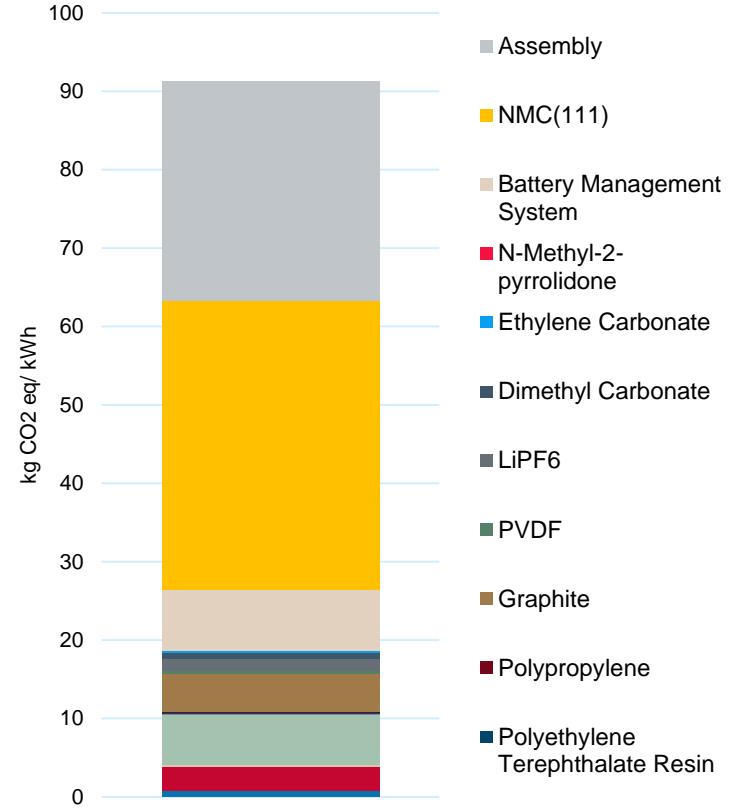
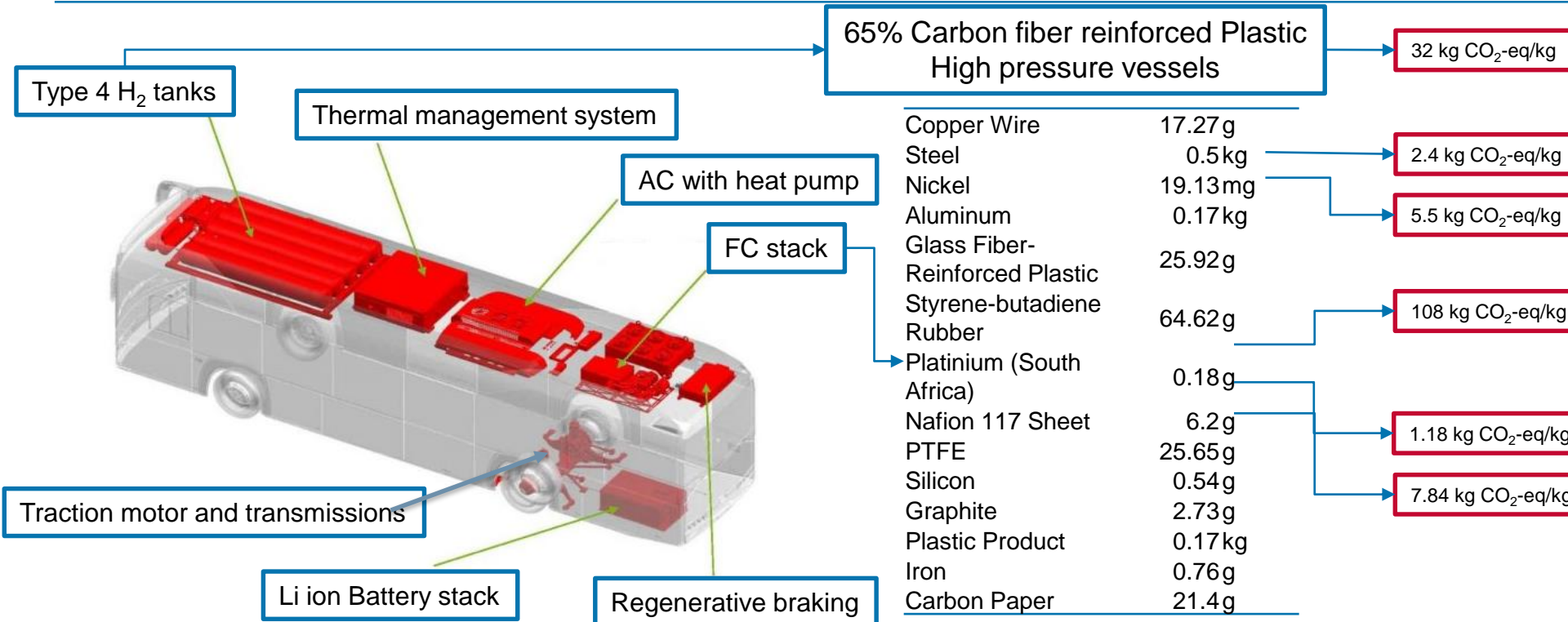


Figure 11: Li-ion battery cell manufacturing emissions

Manufacture - FCEB and components



EU electricity mix (IEA, 2020)
407 kg CO₂-eq/kWh (Alberto & Laura, 2018)

Manufacture - BEB and components



Body Components (1 kg)

Copper Wire	25 g
Steel	71 g
Aluminum	58 g
Glass	88 g
Styrene-butadiene Rubber	27 g
Plastic Product	0.21 kg
Magnesium	8 g
Other Vehicle Materials	43 g
Carbon Fiber-Reinforced Plastic	0.47 kg

Li ion Battery NMC 111 components (1 kg)

Engine/Powertrain Coolant	43.01 g
Copper Wire	0.12 kg
Steel	6.19 g
Aluminum	0.24 kg
Glass Fiber	4.85 g
High-Density Polyethylene	3.61 g
Polyethylene Terephthalate	2.06 g
Resin	2.06 g
Polypropylene	11.04 g
Graphite	0.16 kg
PVDF	21.53 g
LiPF6	16.13 g
Dimethyl Carbonate	45.02 g
Ethylene Carbonate	45.02 g
N-Methyl-2-pyrrolidone	1.76 g
Battery Management System	36.56 g
NMC(111)	0.25 kg

3.06 kg CO₂-eq/kg

8.92 kg CO₂-eq/kg

14.59 kg CO₂-eq/kg

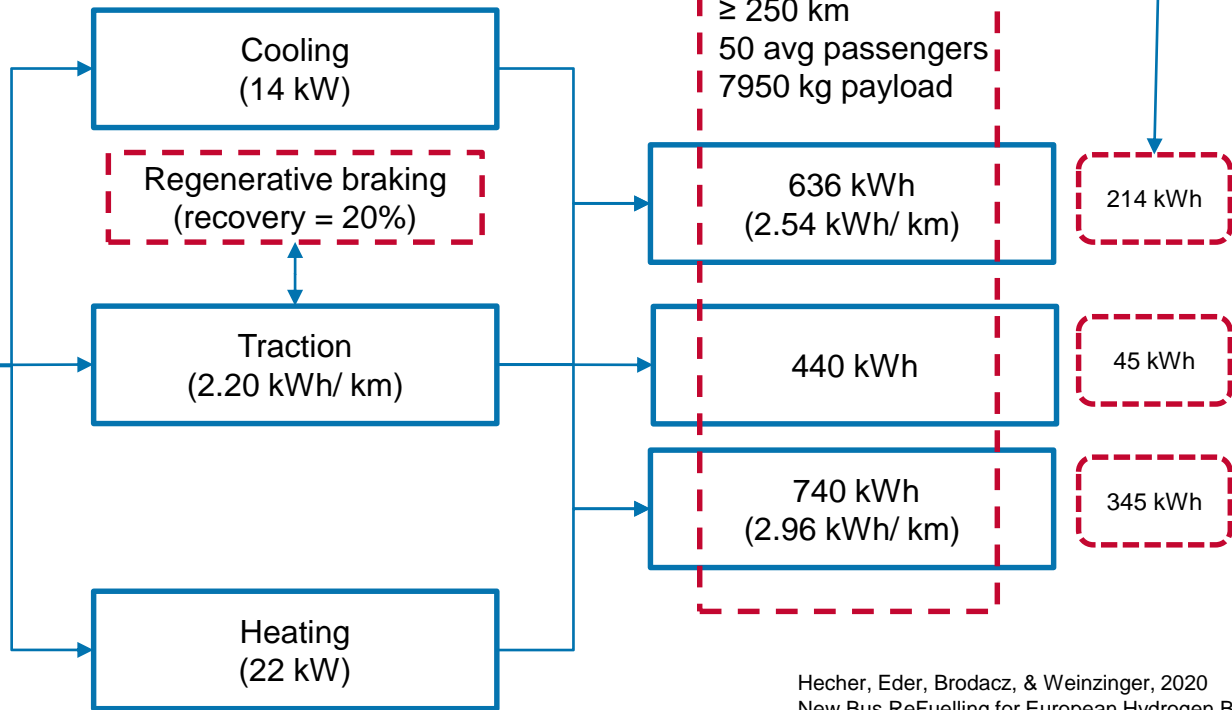
EU electricity mix (IEA, 2020)

407 kg CO₂-eq/kWh (Alberto & Laura, 2020)

TTW - BEB

BEB Manufacturer	Solaris Urbino 12
Overall length [m]	12
Passenger capacity [no.]	80
Motor rater power [kW]	2x125 kW
Battery type	Li-ion NMC
Battery capacity [kWh]	395 kWh (5x79 kWh)
Recharging time	apprx 5 hours
Range [km] (220 kWh/100 km)	200
Source	Solarisbus, 2019

45% routes ≥ 250
Lifetime mileage 800,000 km



Hecher, Eder, Brodacz, & Weininger, 2020
New Bus ReFuelling for European Hydrogen Bus Depots

Figure 14: TTW Austria BEB



$\eta_{RC} = 93\%$ 9.34 kg CO₂-eq/ 395 kWh

Auxiliary power Systems	Nominal power
Lightning	1-2 kW
Passenger information systems, ticket vending machine	1-3 kW
Charging of 24 V board batteries	0,5 - 2 kW
Air compressor	3-6 kW
Hydraulic pump	2-4 kW
Air condition	10-16 kW
Heating	5-25 kW

Source: Bartłomiejczyk & Kolačz, 2020

TTW - FCEB

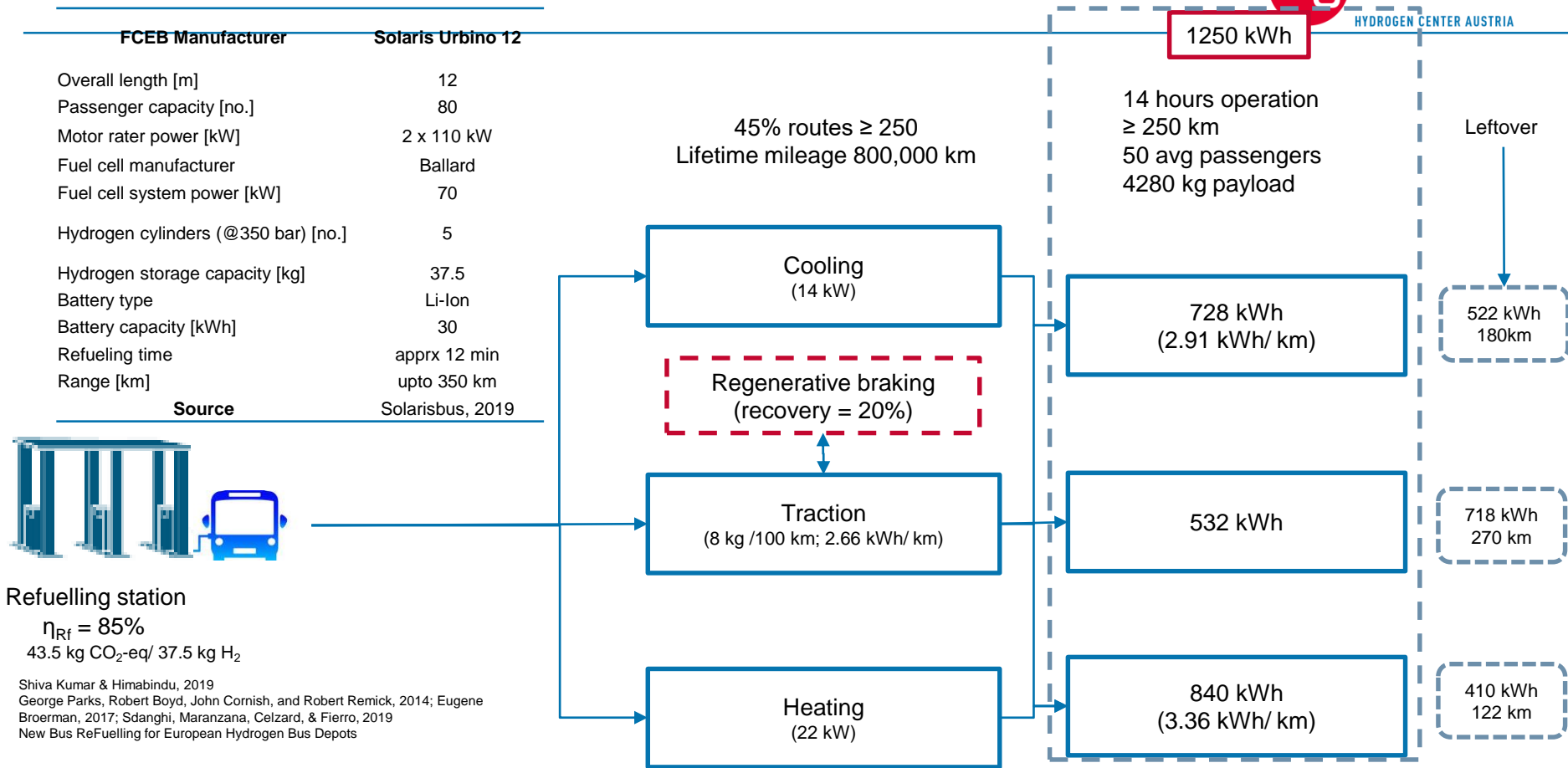


Figure 15: TTW Austria FCEB

WTT gaseous H₂ – FCEB (Austrian electricity mix)

HYDROGEN CENTER AUSTRIA

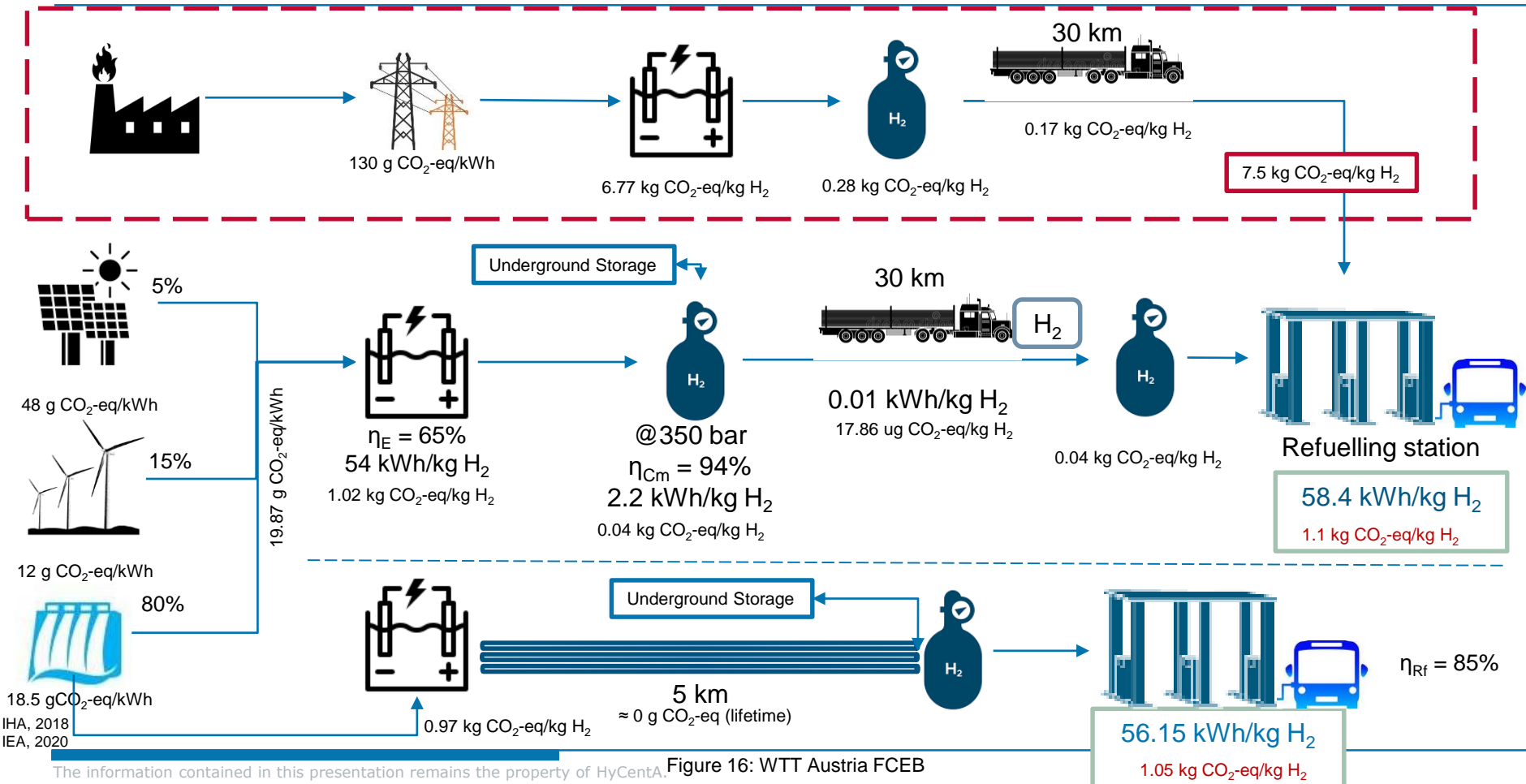


Figure 16: WTT Austria FCEB

WTT electricity – BEB (Austrian electricity mix)

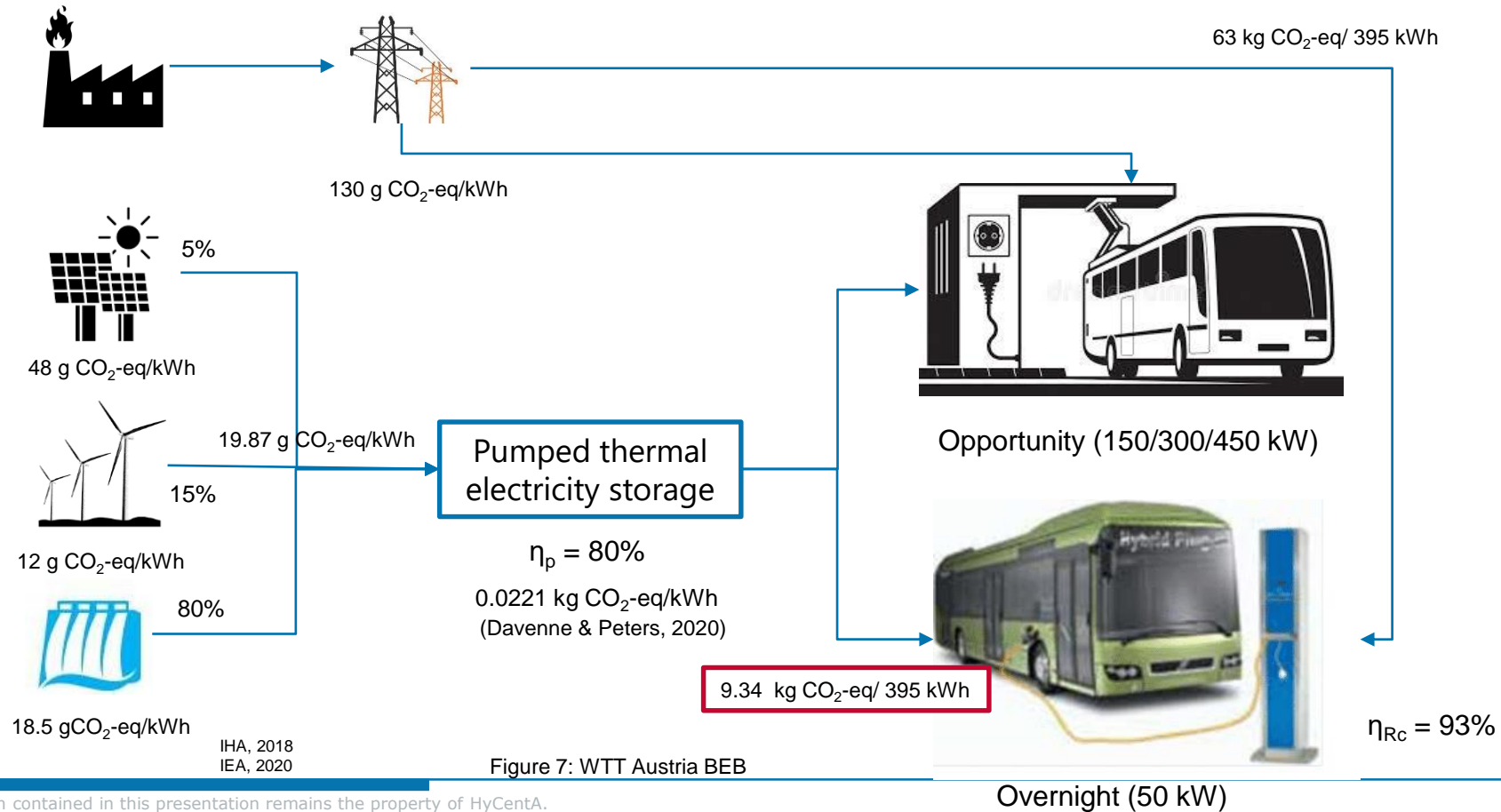


Figure 7: WTT Austria BEB