# Supplementary Information

**Ecological Assessment of Fuel Cell Electric Vehicles with Special Focus on Type IV Carbon Fiber Hydrogen Tank**

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**S1 Technical specification of commercial brands of FCEV**

**Table S 1: State of the art FCEV**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Description** | **Unit** | **Toyota Mirai** | **Hyundai Nexo** | **Hyundai ix35 FC** | **Honda FCX-ZC2** | **Honda Clarity** | **Mercedes Benz GLC F-CELL** |
| Fuel cell | kW | 114 | 95 | 100 | 86 | 130 | 147 |
| Electric motor | kW | 113 | 120 | 100 | 80 | 130 | 147 |
| Electric storage technology | kWh | 1.6 | 1.6 | - | - | - | 1.4 |
| Tank capacity | kg of H2 | 5.7 | 6.3 | 5.64 | 3.75 | 5.0 | 4.4 |
| Operation pressure | bar | 700 | 700 | 700 | 355 | 700 | 700 |
| Driving mileage | km | 550 | 666 | 594 | 430 | 650 | 437 |
| Fuel consumption | kg H2/ 100 km | 0.76 | 0.84 | 0.99 | 0.87 | 0.77 | 0.97 |
| Source |  | (PLC 2014) | (NEXO 2018) | (HYUNDAI 2018) | (Co 2018) | (Stefan Voswinkel 2018) | (Daimler 2018) |

**S2 Carbon fiber manufacturing**

**Table S 2: Carbon fiber properties Toray T700 G and T700 S** (Torayca, 2018)

|  |  |  |
| --- | --- | --- |
|  | **T700 G** | **T700 S** |
| Tensile Strength, MPa | 4,900 | 4,900 |
| Tensile Module, GPa | 240 | 230 |
| Strain, % | 2.0 | 2.1 |
| Density, g/cm3 | 1.80 | 1.80 |
| Filament diameter, µm | 7.0 | 7.0 |
| Yield 12 k, g/1000 m | 800 | 800 |
| Yield 24 k, g/1000 m | 1,650 | 1,650 |
| Sizing type and amount, % | 31 E, 0.5 | 60 E, 0.3 |

**Table S 3: Components for acrylonitrile polymerization \***

|  |  |  |
| --- | --- | --- |
| **Components** | **Wt, %** | **Amount, kg** |
| Acrylonitrile (AN) | 95 | 1.12 |
| Methyl acrylate | 4 | 0.05 |
| Itaconic acid | 1 | 0.01 |
| Demineralized water | 65 | 0.76 |

\*According to MegaCarbon project, data provided by Institut für Textiltechnik of RWTH Aachen University

**Table S 4: Polymerization energy requirement** (DOE, 2017)

|  |  |  |
| --- | --- | --- |
| Energy demand - polymerization | 39.43 kWh/kg of CF | 16.30 kWh/kg of PAN |
| 15.3 % Electricity | 6.03 kWh/kg of CF | 2.49 kWh/kg of PAN |
| 84.7 % heat | 33.39 kWh/kg of CF | 13.81 kWh/kg of PAN |

CF: carbon fiber, PAN: polyacrylonitrile (carbon fiber precursor)

**Table S 5: Assumption model of carbon fiber**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Original raw material** | **Source** | **Process** | **Assumption** | **In Ecoinvent** |
| Potassium persulfate (PPS) | (Kap-Seung et al., 2014) | A: PAN Polymerization | Sodium persulfate | Sodium persulfate |
| Itaconic acid | Mega Carbon | B: Spinning dope | Acrylic acid | Acrylic acid |

**S3 Exhaust gas treatment calculation**

The exhaust gases coming from stabilization (process M) are low in concentration but high in volume, they are treated in process L1 by a regenerative thermal oxidizer unit, (Eisenmann, 2016). While, gases coming from the carbonization (process N and O) are highly concentrated but small in volume, and they are treated in process L2 in a high turbulence combustion chamber (CC) and a selective catalyst recover (SCR) is used to retain nitrogen oxides (NOx).

Equation S. 1 and Equation S. 2 describe the reaction that takes place in L1 and L2, respectively. We assume processes L1 and L2 are stereometric reactions with oxygen, to minimize the complex nature of the processes. Table S 6 and Table S 7 mention the composition of the exhaust gases coming from the stabilization and carbonization processes, respectively. In the framework of MegaCarbon project, ITA's[[1]](#footnote-1) experts proposed the mass balance for the exhaust gas treatments.

Equation S. 1 Reactions process L1

Equation S. 2 Reactions process L2

**Table S 6 Products formed from 100 g Courtelle (Morgan, 2005)**

|  |  |
| --- | --- |
| **Product** | **Weight, g** |
| Hydrogen cyanide, HCN | 2.16 |
| Water vapour, H2O | 19.6 |
| Carbon dioxide, CO2 | 7.5 |
| Carbon monoxide, CO | 1.0 |
| Ammonia, NH3 | 0.19 |

**Table S 7 Emissions from carbonization of PAN fiber. (Arnold et al., 2018)**

|  |  |  |
| --- | --- | --- |
| **Ecoinvent database** | **Exhaust air** | **Mass [g/100g stabilized PAN]** |
| Hydrogen | H2 | 0.013 |
| Nitrogen | N2 | 13.8 |
| Carbon monoxide | CO | 2.06 |
| Methane | CH4 | 2.36 |
| Carbon dioxide | CO2 | 3.24 |
| Ammonia | NH3 | 1.317 |
| Water vapor | H2O | 5.29 |
| Hydrogen cyanide | HCN | 14.3 |
| Ethene | C2H4 | 0.412 |
| Ethane | C2H6 | 0.442 |

**S4 Hydrogen storage tank. Consideration for the life cycle inventory**

**Table S 8 Datasheet HDPE Pulverizer (Wanrooe, 2014)**

|  |  |
| --- | --- |
| Machine | HDPE Plastic Pulverizer |
| Capacity | 200 kg/h |
| Net power | 40.5 kW |
| Energy demand | 0.23 kWh/kg |

Table S 9: German electricity mix 2050 (Pregger, Naegler et al. 2019)

|  |  |
| --- | --- |
| Process | 2050 |
|  | % |
| Hard coal | 1.4 |
| Oil | 0.2 |
| Natural gas | 20.3 |
| Hydropower | 4.4 |
| Wind onshore | 24.6 |
| Wind offshore | 21.5 |
| Biomass | 12.6 |
| Photovoltaics | 11.6 |
| Geothermal | 3.3 |

**S5 LCI Carbon fiber manufacturing**

The carbon fiber manufacturing follows the approach of Institut für Textiltechnik, RTWH Aachen University. Each process contains the assumptions of the model. The suspension polymerization of acrylonitrile is adopted, taking sodium persulfate as initiator. The result is 1 kg of Polyacrylonitrile (PAN). The calculation of each compound is based on a conversion rate of 85 %, the values are adapted to produce 1kg of PAN (Mützel, 2012). The share of the constituents is taken from (Moore and Feast, 1981). The conversion rate from precursor to carbon fiber is 42 % and from precursor to carbon fiber 35 %. The energy intensity obtained is given by (DOE, 2017): 39.4 kWh/kg of finished carbon fiber, state of the art value (meaning that it is the best value reachable at the moment), 15.3 % for electricity and 84.7 % for heat.

Table S 10 Carbon fiber manufacturing Stage I: processes A to J. Current scenario

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | |  | |  | **Environmental Impacts (ReCipe)** | | | | |  |
|  |  | |  | | **GWP** | **HTP-inf** | **POFP** | **PMFP** | **TAP100** |  |
| **Flow** | **Amount** | | **Unit** | | **kg CO2-Eq** | **kg 1,4-DCB-Eq** | **kg NMVOC** | **kg PM10-Eq** | **kg SO2-Eq** | **Ecoinvent V3.3, process** |
| **Process A, Polyacrylonitrile (PAN)** | **2.832E+00** | | **kg** | | **2.594E+01** | **7.052E+00** | **5.003E-02** | **2.924E-02** | **1.010E-01** | A: Suspension Polimerization - DE |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Heat, in chemical industry | 3.911E+01 | | kWh | | 1.150E+01 | 1.496E+00 | 2.102E-02 | 1.171E-02 | 3.729E-02 | market for heat, in chemical industry, U - RER |
| Acrylonitrile | 3.172E+00 | | kg | | 9.385E+00 | 1.616E+00 | 2.292E-02 | 1.449E-02 | 5.510E-02 | market for acrylonitrile, U - GLO |
| Electricity | 7.080E+00 | | kWh | | 4.593E+00 | 3.752E+00 | 4.940E-03 | 2.510E-03 | 7.230E-03 | market for electricity, low voltage, U - RER |
| Methyl acrylate | 1.416E+02 | | g | | 3.972E-01 | 1.782E-01 | 1.000E-03 | 4.600E-04 | 1.200E-03 | market for methyl acrylate, U - GLO |
| Acrylic acid | 2.832E+01 | | g | | 6.597E-02 | 8.640E-03 | 1.400E-04 | 6.545E-05 | 1.400E-04 | acrylic acid production, U - RoW |
| Water, deionized | 2.166E+03 | | g | | 2.070E-03 | 1.460E-03 | 5.922E-06 | 4.524E-06 | 9.744E-06 | market for water, deionised, U - Europe without Switzerland |
| **Process B, Precursor** | **1.076E+01** | | **kg** | | **2.583E+01** | **5.246E+00** | **3.854E-02** | **1.972E-02** | **7.848E-02** | B:Spinning dope\_Cu |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Compressed air | 1.732E-02 | | Nm3 | | 5.350E-03 | 1.547E-02 | 1.770E-05 | 1.705E-05 | 4.273E-05 | compressed air production, U - RER |
| DMSO recuperated | 8.071E+00 | | kg | | -1.584E+00 | -2.318E+00 | -1.372E-02 | -1.069E-02 | -2.590E-02 | C:DMSO-Water recovey |
| Electricity | 5.319E-01 | | kWh | | 3.458E-01 | 2.825E-01 | 3.700E-04 | 1.900E-04 | 5.400E-04 | market for electricity, low voltage, S - DE |
| Ethylene glycol | 1.806E-03 | | kg | | 3.550E-03 | 1.240E-03 | 1.161E-05 | 7.121E-06 | 1.323E-05 | market for ethylene glycol, U - GLO |
| Methyl acrylate | 1.133E-01 | | kg | | 3.178E-01 | 1.426E-01 | 8.000E-04 | 3.700E-04 | 9.600E-04 | market for methyl acrylate, U - GLO |
| Nitrogen | 4.454E-02 | | kg | | 3.085E-02 | 2.234E-02 | 3.933E-05 | 2.103E-05 | 5.579E-05 | Nitrogen\_Air separation |
| Polyacrilonitrile (PAN) | 2.832E+00 | | kg | | 2.594E+01 | 7.052E+00 | 5.003E-02 | 2.925E-02 | 1.010E-01 | A: Suspension Polimerization - DE |
| Steam, in chemical industry | 3.234E+00 | | kg | | 7.729E-01 | 4.894E-02 | 9.900E-04 | 5.500E-04 | 1.800E-03 | steam, in chemical industry, U - RER |
| **Process C, DMSO recuperated** | **8.071E+00** | | **kg** | | **-1.584E+00** | **-2.096E+00** | **-1.339E-02** | **-1.050E-02** | **-2.541E-02** | DMSO\_Recuperated |
| *dimethyl sulfoxide* | *4.438E+00* | | kg | |  |  |  |  |  | avoided product |
| *dimethyl sulfoxide production - RER* | *4.438E+00* | | kg | |  |  |  |  |  |  |
| *DMSO Waste* | *2.502E-01* | | kg | |  |  |  |  |  | Waste flow |
| Industrial water | 5.804E+01 | | kg | |  |  |  |  |  | Industrial Water \_ Carbon Fiber (avoided product) |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Coagulated solution | 0.000E+00 | | kg | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Waste flow |
| Compressed air | 2.082E-02 | | Nm3 | | 4.490E-03 | 1.161E-02 | 1.511E-05 | 1.680E-05 | 3.488E-05 | compressed air production, U - RER |
| Dimethyl sulfoxide | 2.546E-01 | | kg | | -5.047E+00 | -2.821E+00 | -1.814E-02 | -1.313E-02 | -3.372E-02 | market for dimethyl sulfoxide, U - GLO |
| Electricity | 9.107E-01 | | kWh | | 5.919E-01 | 4.836E-01 | 6.400E-04 | 3.200E-04 | 9.300E-04 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 1.955E-02 | | kg | | 3.524E-02 | 1.314E-02 | 1.100E-04 | 5.943E-05 | 1.200E-04 | ethylene glycol production, U - RER |
| Nitrogen | 4.335E-02 | | kg | | 3.002E-02 | 2.174E-02 | 3.828E-05 | 2.046E-05 | 5.430E-05 | Nitrogen\_Air separation |
| Steam, in chemical industry | 1.287E+01 | | kg | | 3.077E+00 | 1.948E-01 | 3.950E-03 | 2.210E-03 | 7.170E-03 | steam production, in chemical industry, U - RER |
| Water + DMSO | 0.000E+00 | | kg | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Waste flow |
| **Process D, coagulated fiber** | **6.557E+00** | | **kg** | | **2.640E+01** | **5.417E+00** | **3.883E-02** | **1.987E-02** | **7.884E-02** | D:Spinning process |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Electricity | 1.422E-01 | | kWh | | 9.242E-02 | 7.550E-02 | 9.939E-05 | 5.052E-05 | 1.500E-04 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 8.149E-01 | | g | | 1.600E-03 | 5.600E-04 | 5.239E-06 | 3.213E-06 | 5.970E-06 | market for ethylene glycol, U - GLO |
| Spinning dope - PRECURSOR | 1.076E+01 | | kg | | 2.616E+01 | 5.310E+00 | 3.866E-02 | 1.978E-02 | 7.862E-02 | B:Spinning dope - PAN Precursor production |
| **Process E, coagulated fiber** | **4.379E+00** | | **kg** | | **2.851E+01** | **6.622E+00** | **4.128E-02** | **2.119E-02** | **8.277E-02** | E:Stretching and washing process |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Coagulated fiber | 6.557E+00 | | kg | | 2.640E+01 | 5.417E+00 | 3.883E-02 | 1.987E-02 | 7.884E-02 | D:Spinning process |
| Compressed air | 3.158E-02 | | m3 | | 6.810E-03 | 1.762E-02 | 2.292E-05 | 2.549E-05 | 5.292E-05 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 1.837E+00 | | kWh | | 1.194E+00 | 9.756E-01 | 1.280E-03 | 6.500E-04 | 1.880E-03 | market for electricity, low voltage, U - DE |
| Industrial water | 4.379E+01 | | kg | | 2.078E-01 | 1.678E-01 | 2.600E-04 | 1.400E-04 | 3.800E-04 | Industrial Water \_ Carbon Fiber |
| Steam, in chemical industry | 2.910E+00 | | kg | | 6.956E-01 | 4.405E-02 | 8.900E-04 | 5.000E-04 | 1.620E-03 | steam production, in chemical industry, U - RER |
| Water, deionized | 1.757E-03 | | kg | | 1.679E-06 | 1.181E-06 | 4.804E-09 | 3.669E-09 | 7.904E-09 | water production, deionised, U - Europe without Switzerland |
| **Process F, precursor** | **4.491E+00** | | **kg** | | **2.877E+01** | **6.813E+00** | **4.186E-02** | **2.161E-02** | **8.370E-02** | F:Sizing I |
| *Water* | 3.154E+00 | | kg | |  |  |  |  |  | Elementary flows, emission to water, ground water |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Compressed air | 7.018E-04 | | Nm3 | | 1.500E-04 | 3.900E-04 | 5.094E-07 | 5.665E-07 | 1.176E-06 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 1.609E-01 | | kWh | | 1.046E-01 | 8.546E-02 | 1.100E-04 | 5.719E-05 | 1.600E-04 | market for electricity, low voltage, U - DE |
| Industrial water | 3.271E+00 | | kg | | 1.553E-02 | 1.253E-02 | 1.926E-05 | 1.061E-05 | 2.813E-05 | Industrial Water \_ Carbon Fiber |
| PAN Fiber | 4.379E+00 | | kg | | 2.851E+01 | 6.622E+00 | 4.129E-02 | 2.119E-02 | 8.277E-02 | E:Stretching and washing process |
| Potassium permanganate | 1.123E-01 | | kg | | 1.448E-01 | 9.286E-02 | 4.400E-04 | 3.500E-04 | 7.400E-04 | potassium permanganate, U - RER |
| Water, deionized | 6.557E-01 | | kg | | 6.300E-04 | 4.400E-04 | 1.793E-06 | 1.370E-06 | 2.950E-06 | water production, deionised, U - Europe without Switzerland |
| **Process G, precursor** | **2.767E+00** | | **kg** | | **2.938E+01** | **6.940E+00** | **4.261E-02** | **2.202E-02** | **8.503E-02** | G:Drying |
| *Water vapour* | 1.724E+00 | | kg | |  |  |  |  |  | Elementary flows, emission to air, unspecified |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Compressed air | 1.458E-03 | | Nm3 | | 4.500E-04 | 1.300E-03 | 1.489E-06 | 1.435E-06 | 3.597E-06 | compressed air, 1000 kPa gauge, U - RER |
| Electricity | 1.761E-01 | | kWh | | 1.145E-01 | 9.353E-02 | 1.200E-04 | 6.258E-05 | 1.800E-04 | market for electricity, low voltage, U - DE |
| PAN fiber after sizing I | 4.491E+00 | | kg | | 2.877E+01 | 6.814E+00 | 4.186E-02 | 2.161E-02 | 8.370E-02 | F:Sizing I |
| Steam, in chemical industry | 2.059E+00 | | kg | | 4.921E-01 | 3.116E-02 | 6.300E-04 | 3.500E-04 | 1.150E-03 | steam production, in chemical industry, U - RER |
| **Process H, precursor** | **2.764E+00** | | **kg** | | **2.996E+01** | **7.497E+00** | **4.360E-02** | **2.283E-02** | **8.698E-02** | H:Relaxation |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Compressed air | 6.403E-01 | | Nm3 | | 1.380E-01 | 3.572E-01 | 4.600E-04 | 5.200E-04 | 1.070E-03 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 3.511E-01 | | kWh | | 2.282E-01 | 1.864E-01 | 2.500E-04 | 1.200E-04 | 3.600E-04 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 7.723E-02 | | g | | 1.500E-04 | 5.319E-05 | 4.965E-07 | 3.045E-07 | 5.658E-07 | market for ethylene glycol, U - GLO |
| PAN fiber dried | 2.767E+00 | | kg | | 2.938E+01 | 6.940E+00 | 4.261E-02 | 2.203E-02 | 8.504E-02 | G:Drying |
| Steam, in chemical industry | 9.134E-01 | | kg | | 2.183E-01 | 1.382E-02 | 2.800E-04 | 1.600E-04 | 5.100E-04 | steam production, in chemical industry, U - RER |
| **Process I, precursor** | **2.781E+00** | | **kg** | | **3.005E+01** | **7.550E+00** | **4.380E-02** | **2.296E-02** | **8.726E-02** | I\_Sizing\_II\_cu |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Electricity | 7.178E-02 | | kWh | | 4.666E-02 | 3.812E-02 | 5.017E-05 | 2.551E-05 | 7.343E-05 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 6.179E-02 | | g | | 1.200E-04 | 4.256E-05 | 3.972E-07 | 2.436E-07 | 4.526E-07 | market for ethylene glycol, U - GLO |
| PAN fiber relaxed | 2.767E+00 | | kg | | 2.996E+01 | 7.497E+00 | 4.360E-02 | 2.283E-02 | 8.698E-02 | H:Relaxation |
| Silicone | 1.391E+01 | | g | | 4.356E-02 | 1.434E-02 | 1.500E-04 | 1.000E-04 | 2.100E-04 | market for silicone product, U - GLO |
| **Process J, precursor** | **2.781E+00** | | **kg** | | **3.039E+01** | **8.094E+00** | **4.445E-02** | **2.349E-02** | **8.863E-02** | J: PAN Fiber precursor |
| **Inputs** |  | |  | |  |  |  |  |  |  |
| Compressed air | 4.244E-01 | | Nm3 | | 1.312E-01 | 3.790E-01 | 4.300E-04 | 4.200E-04 | 1.050E-03 | compressed air, 1000 kPa gauge, U - RER |
| Electricity | 3.110E-01 | | kWh | | 2.021E-01 | 1.651E-01 | 2.200E-04 | 1.100E-04 | 3.200E-04 | market for electricity, low voltage, U - DE |
| PAN fiber after sizing II | 2.781E+00 | | kg | | 3.005E+01 | 7.550E+00 | 4.380E-02 | 2.296E-02 | 8.726E-02 | I\_Sizing\_II\_cu |

Table S 11 Carbon fiber manufacturing Stage II: Processes K to U. Current scenario

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | |  | |  | | **Environmental Impacts (ReCipe)** | | | | |  |
| **Flow** | **Amount** | | **Unit** | | **GWP** | | **HTP-inf** | **POFP** | **PMFP** | **TAP100** |  |
| **kg CO2-Eq** | | **kg 1,4-DCB-Eq** | **kg NMVOC** | **kg PM10-Eq** | **kg SO2-Eq** | **Ecoinvent V3.3, process** |
| **Process K, precursor** | **2.780E+00** | | **kg** | | **3.049E+01** | | **8.218E+00** | **4.462E-02** | **2.362E-02** | **8.892E-02** | **K: Pan Fiber Unwinded** |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Compressed air | 1.000E-01 | | Nm3 | | 2.067E-02 | | 5.350E-02 | 6.962E-05 | 7.742E-05 | 1.600E-04 | market for compressed air, U - GLO |
| Electricity | 1.300E-01 | | kWh | | 8.615E-02 | | 7.038E-02 | 9.265E-05 | 4.710E-05 | 1.400E-04 | market for electricity, low voltage, U - DE |
| PAN fiber winded | 2.780E+00 | | kg | | 3.039E+01 | | 8.094E+00 | 4.446E-02 | 2.349E-02 | 8.862E-02 | J: PAN Fiber precursor |
| Water, deionized | 2.847E+02 | | g | | 2.700E-04 | | 1.900E-04 | 7.785E-07 | 5.947E-07 | 1.281E-06 | market water, deionized, U - Europe without Switzerland |
| **Process L1, exhaust gases** | **-3.683E+01** | | **kg** | | **5.485E-01** | | **-1.356E+01** | **5.900E-04** | **-5.890E-02** | **-4.524E-01** | **L:1\_Exhaust\_gas\_treatment** |
| *Argon* | *4.640E-01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Carbon dioxide* | *6.002E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Nitrogen* | *2.736E+01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Water vapour* | *7.640E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Ammonia | 1.850E-01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | -5.920E-02 | -4.533E-01 | Elementary flows, emission to air, unspecified |
| Argon | 4.643E-01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Carbon dioxide | 1.821E+00 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Carbon monoxide | 4.860E-01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Cyanide | 2.098E+00 | | kg | | 0.000E+00 | | -1.401E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| electricity, low voltage | 8.438E-01 | | kWh | | 5.485E-01 | | 4.481E-01 | 5.900E-04 | 3.000E-04 | 8.600E-04 | market for electricity, low voltage, U - DE |
| Nitrogen | 2.702E+01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| **Process L2, exhaust gases** | **-1.078E+01** | | **kg** | | **1.003E+01** | | **-2.786E+00** | **1.192E-01** | **4.365E-02** | **1.145E-01** | **L\_2:\_Exhaust\_Gas\_treatment** |
| *Carbon dioxide* | *7.568E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Nitrogen* | *3.709E+01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Nitrogen oxides* | *1.077E-01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *1.077E-01* | *2.369E-02* | *6.031E-02* | *Elementary flows, emission to air, unspecified* |
| *Water vapour* | *5.110E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Air, used | 3.530E+01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Ammonia | 3.500E-02 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | -1.120E-02 | -8.575E-02 | Elementary flows, emission to air, unspecified |
| Carbon dioxide | 1.420E-01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Carbon monoxide | 7.300E-02 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Compressed air | 1.000E+00 | | Nm3 | | 1.470E-01 | | 4.595E-01 | 5.100E-04 | 5.000E-04 | 1.230E-03 | Compressed air production, U - RER |
| Cyanide | 9.450E-01 | | kg | | 0.000E+00 | | -6.309E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Electricity | 2.825E-01 | | kWh | | 1.836E-01 | | 1.500E-01 | 2.000E-04 | 1.000E-04 | 2.900E-04 | market for electricity, low voltage, U - DE |
| Ethane | 1.800E-02 | | kg | | 0.000E+00 | | 0.000E+00 | -3.740E-03 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Ethene | 7.000E-03 | | kg | | 0.000E+00 | | 0.000E+00 | -1.182E-02 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Hydrogen | 2.358E-06 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Methane | 1.400E-02 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Natural gas | 2.057E+00 | | kg | | 1.086E+00 | | 4.716E-01 | 5.630E-03 | 4.660E-03 | 1.683E-02 | market for natural gas, at service station, U - GLO |
| Nitrogen | 9.503E+00 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Nox retained | 1.067E+01 | | kg | | 8.614E+00 | | 2.442E+00 | 2.069E-02 | 2.590E-02 | 1.216E-01 | NOx retained, by selective catalytic reduction, U - GLO |
| Oxygen, in air | 1.638E+00 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, resource, unspecified |
| Water vapour | 3.900E-02 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| **Process M, stabilized precursor** | **2.503E+00** | | **kg** | | **4.346E+01** | | **1.888E+01** | **5.917E-02** | **3.129E-02** | **1.113E-01** | **M: Stabilization process** |
| *Ammonia* | *1.850E-01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *5.920E-02* | *4.533E-01* | *Elementary flows, emission to air, unspecified* |
| *Argon* | *4.640E-01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, resource, in air* |
| *Carbon dioxide* | *1.821E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Carbon monoxide* | *4.860E-01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Cyanide* | *2.098E+00* | | *kg* | | *0.000E+00* | | *1.401E+01* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Nitrogen* | *2.702E+01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, Resource, in air* |
| *Oxygen, in air* | *3.646E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, resource, in air* |
| *Water vapour* | *4.759E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Emission to air, high population density* |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Air, used | 3.655E+01 | | kg | | 0.000E+00 | | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | Elementary flows, emission to air, unspecified |
| Compressed air | 1.909E-01 | | Nm3 | | 5.901E-02 | | 1.704E-01 | 1.900E-04 | 1.900E-04 | 4.700E-04 | compressed air, 1000 kPa gauge, U - RER |
| Electricity | 1.882E+01 | | kWh | | 1.224E+01 | | 9.996E+00 | 1.316E-02 | 6.690E-03 | 1.926E-02 | market for electricity, low voltage, U - DE |
| Natural gas | 2.200E-01 | | kg | | 1.174E-01 | | 5.099E-02 | 6.100E-04 | 5.000E-04 | 1.820E-03 | natural gas, at service station, U - GLO |
| PAN fiber unwinded | 2.780E+00 | | kg | | 3.049E+01 | | 8.218E+00 | 4.462E-02 | 2.361E-02 | 8.892E-02 | K: Pan Fiber Unwinded |
| Exhausted air treated, L1 | 3.682E+01 | | kg | | 5.485E-01 | | -1.356E+01 | 5.900E-04 | -5.890E-02 | -4.524E-01 | L:1\_Exhaust\_gas\_treatment |
| **Process N, LT carbonized precursor** | **1.252E+00** | | **kg** | | **5.851E+01** | | **2.701E+01** | **1.668E-01** | **7.624E-02** | **2.710E-01** | **N: Carbonization (LT)** |
| *Air, used* | *2.575E+01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Ammonia* | *2.553E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *8.171E-03* | *6.256E-02* | *Elementary flows, emission to air, unspecified* |
| *Carbon dioxide* | *1.036E-01* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Carbon monoxide* | *5.326E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Cyanide* | *6.894E-01* | | *kg* | | *0.000E+00* | | *4.603E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Ethane* | *1.313E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *2.728E-03* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Ethene* | *5.107E-03* | | *kg* | | *0.000E+00* | | *0.000E+00* | *8.626E-03* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Hydrogen* | *1.720E-06* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Methane* | *1.021E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Nitrogen* | *6.933E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Water vapour* | *2.845E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Exhausted air treated,L2 | -7.865E+00 | | kg | | 7.320E+00 | | -2.033E+00 | 8.696E-02 | 3.185E-02 | 8.354E-02 | L\_2:\_Exhaust\_Gas\_treatment |
| Electricity | 4.166E+00 | | kWh | | 2.708E+00 | | 2.212E+00 | 2.910E-03 | 1.480E-03 | 4.260E-03 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 7.823E-04 | | kg | | 1.540E-03 | | 5.400E-04 | 5.029E-06 | 3.085E-06 | 5.731E-06 | market for ethylene glycol, U - GLO |
| Fiber (PANox) | 2.503E+00 | | kg | | 4.346E+01 | | 1.888E+01 | 5.917E-02 | 3.129E-02 | 1.113E-01 | M: Stabilization process |
| Nitrogen | 6.613E+00 | | kg | | 4.580E+00 | | 3.316E+00 | 5.840E-03 | 3.120E-03 | 8.280E-03 | Nitrogen\_Air separation |
| Steam, in chemical industry | 1.857E+00 | | kg | | 4.438E-01 | | 2.810E-02 | 5.700E-04 | 3.200E-04 | 1.030E-03 | steam, in chemical industry, U - RER |
| **Process O, HT carbonized precursor** | **9.840E-01** | | **kg** | | **6.810E+01** | | **3.342E+01** | **2.110E-01** | **9.506E-02** | **3.364E-01** | **O: Carbonization (HT)** |
| *Air, used* | *9.536E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Ammonia* | *9.455E-03* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *3.026E-03* | *2.317E-02* | *Elementary flows, emission to air, unspecified* |
| *Carbon dioxide* | *3.836E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Carbon monoxide* | *1.972E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Cyanide* | *2.553E-01* | | *kg* | | *0.000E+00* | | *1.704E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Ethane* | *4.863E-03* | | *kg* | | *0.000E+00* | | *0.000E+00* | *1.010E-03* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Ethene* | *1.891E-03* | | *kg* | | *0.000E+00* | | *0.000E+00* | *3.194E-03* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Hydrogen* | *6.370E-07* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Methane* | *3.782E-03* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Nitrogen* | *2.567E+00* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| *Water vapour* | *1.054E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Elementary flows, emission to air, unspecified* |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Exhausted air treated,L2 | -2.912E+00 | | kg | | 2.710E+00 | | -7.528E-01 | 3.220E-02 | 1.180E-02 | 3.093E-02 | L\_2:\_Exhaust\_Gas\_treatment |
| Electricity | 8.059E+00 | | kWh | | 5.239E+00 | | 4.280E+00 | 5.630E-03 | 2.860E-03 | 8.240E-03 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 7.503E-03 | | kg | | 1.477E-02 | | 5.170E-03 | 4.823E-05 | 2.958E-05 | 5.496E-05 | market for ethylene glycol, U - GLO |
| Fiber (PANvc) | 1.252E+00 | | kg | | 5.851E+01 | | 2.701E+01 | 1.668E-01 | 7.624E-02 | 2.710E-01 | N: Carbonization (LT) |
| Nitrogen | 2.348E+00 | | kg | | 1.626E+00 | | 1.178E+00 | 2.070E-03 | 1.110E-03 | 2.940E-03 | Nitrogen\_Air separation |
| **Process P, carbon fiber** | **1.005E+00** | | **kg** | | **6.826E+01** | | **3.355E+01** | **2.112E-01** | **9.517E-02** | **3.367E-01** | **P: Electrolysis** |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Ammonium bicarbonate | 2.012E-02 | | kg | | 2.214E-02 | | 1.192E-02 | 4.085E-05 | 2.975E-05 | 7.626E-05 | Ammonium bicarbonate, U - RER |
| Compressed air | 2.932E-03 | | Nm3 | | 9.100E-04 | | 2.620E-03 | 2.996E-06 | 2.887E-06 | 7.235E-06 | Compressed air, 1000 kPa gauge | cut-off, U - RER |
| Electricity | 2.117E-01 | | kWh | | 1.376E-01 | | 1.124E-01 | 1.500E-04 | 7.522E-05 | 2.200E-04 | market for electricity, low voltage, U - DE |
| Ethylene glycol | 1.793E-04 | | kg | | 3.200E-04 | | 1.200E-04 | 1.009E-06 | 5.450E-07 | 1.138E-06 | Ethylene glycol, U - RER |
| Industrial water | 1.763E-01 | | kg | | 8.400E-04 | | 6.800E-04 | 1.038E-06 | 5.722E-07 | 1.516E-06 | Industrial Water \_ Carbon Fiber |
| PAN fiber (n.HT) | 9.845E-01 | | kg | | 6.810E+01 | | 3.342E+01 | 2.110E-01 | 9.506E-02 | 3.364E-01 | O: Carbonization (HT) |
| Water, deionized | 8.860E-05 | | kg | | 8.469E-08 | | 5.959E-08 | 2.423E-10 | 1.851E-10 | 3.987E-10 | market water, deionised, U - Europe without Switzerland |
| **Process Q, carbon fiber** | **1.092E+00** | | **kg** | | **1.366E+02** | | **6.716E+01** | **4.224E-01** | **1.904E-01** | **6.734E-01** | **Q\_Washing process** |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Carbon Fiber (n.E) | 1.005E+00 | | kg | | 6.826E+01 | | 3.355E+01 | 2.112E-01 | 9.517E-02 | 3.367E-01 | P: Electrolysis |
| Compressed air gauge | 5.338E-03 | | Nm3 | | 1.150E-03 | | 2.980E-03 | 3.874E-06 | 4.309E-06 | 8.944E-06 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 4.770E-02 | | kWh | | 3.100E-02 | | 2.533E-02 | 3.334E-05 | 1.695E-05 | 4.880E-05 | market for electricity, low voltage, U - DE |
| Industrial water | 4.909E-01 | | kg | | 2.330E-03 | | 1.880E-03 | 2.890E-06 | 1.593E-06 | 4.222E-06 | Industrial Water \_ Carbon Fiber |
| **Process R, carbon fiber** | **1.015E+00** | | **kg** | | **6.841E+01** | | **3.366E+01** | **2.113E-01** | **9.526E-02** | **3.369E-01** | **R: Drying I carbon fiber** |
| *Water vapour* | *7.643E-02* | | *kg* | | *0.000E+00* | | *0.000E+00* | *0.000E+00* | *0.000E+00* | *0.000E+00* | *Emission to air, high population density* |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Carbon Fiber (n.W) | 1.090E+00 | | kg | | 6.829E+01 | | 3.358E+01 | 2.112E-01 | 9.519E-02 | 3.367E-01 | Q\_Washing process |
| Compressed air | 0.000E+00 | | Nm3 | | 2.500E-04 | | 7.100E-04 | 8.173E-07 | 7.877E-07 | 1.974E-06 | Compressed air, 1000 kPa gauge, U - RER |
| Electricity | 1.500E-01 | | kWh | | 9.750E-02 | | 7.965E-02 | 1.000E-04 | 5.330E-05 | 1.500E-04 | market for electricity, low voltage, U - DE |
| Steam | 9.000E-02 | | kg | | 2.182E-02 | | 1.380E-03 | 2.804E-05 | 1.565E-05 | 5.086E-05 | Steam, in chemical industry, U - RER |
| **Process S, carbon fiber** | **1.026E+00** | | **kg** | | **6.846E+01** | | **3.369E+01** | **2.116E-01** | **9.538E-02** | **3.372E-01** | **S: Sizing III** |
| **Inputs** |  | |  | |  | |  |  |  |  |  |
| Carbon fiber (n.D) | 1.015E+00 | | kg | | 6.841E+01 | | 3.366E+01 | 2.113E-01 | 9.526E-02 | 3.369E-01 | R: Drying I carbon fiber |
| Compressed air | 2.000E-03 | | Nm3 | | 4.300E-04 | | 1.120E-03 | 1.452E-06 | 1.614E-06 | 3.351E-06 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 2.226E-02 | | kWh | | 1.447E-02 | | 1.182E-02 | 1.556E-05 | 7.910E-06 | 2.277E-05 | market for electricity, low voltage, U - DE |
| Epoxy resin | 1.015E-02 | | kg | | 3.556E-02 | | 8.550E-03 | 2.100E-04 | 1.100E-04 | 2.200E-04 | Epoxy resin insulator, U - RER |
| Dionized water | 2.505E-04 | | kg | | 2.394E-07 | | 1.685E-07 | 6.851E-10 | 5.233E-10 | 1.127E-09 | market water, deionised, U - Europe without Switzerland |
| **Process T, carbon fiber** | **1.000E+00** | | **kg** | | **6.877E+01** | | **3.393E+01** | **2.119E-01** | **9.555E-02** | **3.377E-01** | **T: Drying II** |
| **Input** |  | |  | |  | |  |  |  |  |  |
| Carbon Fiber (n.S) | 1.026E+00 | | kg | | 6.846E+01 | | 3.369E+01 | 2.116E-01 | 9.538E-02 | 3.372E-01 | S: Sizing III |
| Compressed air | 7.800E-04 | | Nm3 | | 1.700E-04 | | 4.400E-04 | 5.662E-07 | 6.296E-07 | 1.307E-06 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 4.534E-01 | | kWh | | 2.947E-01 | | 2.408E-01 | 3.200E-04 | 1.600E-04 | 4.600E-04 | market for electricity, low voltage , U - DE |
| Steam | 3.062E-02 | | kg | | 7.320E-03 | | 4.600E-04 | 9.406E-06 | 5.251E-06 | 1.706E-05 | steam, in chemical industry, U - RER |
| **Process U, carbon fiber** | **1.000E+00** | | **kg** | | **6.912E+01** | | **3.424E+01** | **2.123E-01** | **9.578E-02** | **3.383E-01** | **U: Final Winding** |
| **Input** |  | |  | |  | |  |  |  |  |  |
| Carbon fiber (n.DII) | 1.000E+00 | | kg | | 6.877E+01 | | 3.393E+01 | 2.119E-01 | 9.555E-02 | 3.377E-01 | T: Drying II |
| Compressed air gauge | 5.850E-02 | | Nm3 | | 1.261E-02 | | 3.263E-02 | 4.246E-05 | 4.722E-05 | 9.803E-05 | market for compressed air, 1000 kPa gauge, U - GLO |
| Electricity | 5.200E-01 | | kWh | | 3.380E-01 | | 2.761E-01 | 3.600E-04 | 1.800E-04 | 5.300E-04 | market for electricity, low voltage, U - DE |

**S6 Results life cycle assessment of FCEV**

Table S 12 LCA results per FCEV for 150,000 km

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **GWP** | | **HTPinf** | | **IRP** | | **FDP** | | **TETPinf** | |
|  | kg CO**2-Eq** | | kg 1,4-DCB-Eq | | kg U235-Eq | | kg Oil-Eq | | kg 1,4-DCB-Eq | |
| **FCEV components** | **Current** | **Future** | **Current** | **Future** | **Current** | **Future** | **Current** | **Future** | **Current** | **Future** |
| Battery | 233.06 | 110.01 | 225.65 | 115.84 | 41.98 | 5.02 | 61.45 | 30.11 | 0.02 | 0.01 |
| Electric motor | 538.79 | 525.60 | 1,764.44 | 1,753.14 | 27.41 | 24.18 | 140.92 | 137.90 | 0.25 | 0.25 |
| Electricity demand | 454.99 | 92.02 | 371.71 | 44.53 | 86.45 | 2.80 | 120.31 | 34.09 | 0.03 | 0.02 |
| Fuel cell | 2,893.96 | 666.85 | 7,394.72 | 3,705.62 | 171.09 | 45.59 | 537.04 | 188.64 | 1.02 | 0.28 |
| Glider | 4,869.71 | 4,066.79 | 7,220.48 | 6,532.02 | 394.60 | 198.16 | 1,383.25 | 1,199.12 | 0.87 | 0.87 |
| Hydrogen tank | 5,610.00 | 3,037.06 | 2,755.31 | 698.94 | 646.30 | 117.28 | 2,041.15 | 1,362.50 | 0.48 | 0.35 |
| Hydrogen demand | 5,754.97 | 3,203.95 | 1,721.35 | 1,483.61 | 346.67 | 221.40 | 1,438.87 | 1,280.80 | 2.05 | 1.66 |
| Maintenance | 1,103.91 | 1,103.91 | 666.54 | 666.54 | 202.26 | 202.26 | 483.00 | 483.00 | 0.06 | 0.06 |
| Transport | 5.38 | 5.38 | 1.41 | 1.41 | 0.43 | 0.43 | 1.99 | 1.99 | 0.00 | 0.00 |
| Disposal | 540.03 | 540.03 | 562.23 | 562.23 | 7.36 | 7.36 | 16.88 | 16.88 | 0.40 | 0.40 |
| **Total** | **22,004.79** | **13,351.60** | **22,683.85** | **15,563.89** | **1,924.55** | **824.49** | **6,224.86** | **4,735.03** | **5.19** | **3.91** |

GWP: global warming potential; HTPinf: human toxicity; IRP: ionizing radiation; FDP: fossil depletion; TETPinf: terrestrial ecotoxicity

Table S 13 Life cycle inventory for the Fuel cell electric vehicle assembly process. Current scenario

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Component** | **Input flow** | **Default provider** | | | **Amount** | | **Units** | | |
| Hydrogen Tank | HY TANK Production phase | Hydrogen Tank Type IV (102 kg) | | | 1.000 | | Item(s) | | |
| Fuel cell stack | aFC Miotty | FC Miotty | | | 1.250 | | Item(s) | | |
| Glider | Glider, passenger car | Market for glider, passenger car | cut-off, U - GLO | | | 800.000 | | kg | | |
| [Battery](file:///C:\Users\BenitezBritos\Documents\2018\Article_draft\Tables_article_AB_00.xlsx#RANGE!A1) | Li-Ion Battery Pack, LFP-TiO (Bauer) | Li-Ion Battery Pack production, LFP-TiO, modular (Bauer) | | | 16.888 | | kg | | |
| [Electric motor](file:///C:\Users\BenitezBritos\Documents\2018\Article_draft\Tables_article_AB_00.xlsx#RANGE!A1) | Electric motor, electric passenger car | Market for electricity, low voltage, U - DE | | | 53.000 | | kg | | |
| Transport | transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Transport, freight, lorry 3.5-7.5 metric ton, EURO5 | cut-off, U - RER | | | 10.600 | | t\*km | | |
| Electricity | electricity, low voltage | Market for electricity, low voltage| cut-off, U - DE | | | 700.000 | | kWh | | |
|  | **Output flow** | | |  | |  | |  |
| Fuel cell electric vehicle | Assembly Fuel cell electric vehicle | | Assembly FCEVb | | 1.000 | | Item(s) | | |

aFC: fuel cell; bFCEV: fuel cell electric vehicle

Table S 14 Life cycle inventory for components of the Fuel cell electric vehicle. Current scenario

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Description** | **Flow** | **Default provider** | **Amount** | **Units** |
| **Hydrogen Tank** | **Inputs** |  |  |  |
| Carbon fiber | U: Final Winding Carbon Fiber | 75.933 | kg |
| Compressed air, 100 kPa gauge | Market for compressed air, 1000 kPa gauge, cut-off, U - GLO | 0.149 | m3 |
| Electricity, low voltage | Market for electricity, low voltage | cut-off, U - DE | 852.684 | MJ |
| Epoxy resin, liquid | Market for epoxy resin, liquid | cut-off, U - GLO | 26.067 | kg |
| Liner HPDE Production phase 149 Liters | Plastic Liner HDPE | 1.000 | Item(s) |
| **Outputs** |  |  |  |
| **HY TANK Production phase** | **Hydrogen Tank Type IV (102 kg)** | **1.000** | **Item(s)** |
| **Plastic Liner**  **HDPE** | **Inputs** |  |  |  |
| Electricity, low voltage | Market for electricity, low voltage | cut-off, U - DE | 1.725 | kWh |
| Injection moulding | Injection moulding| cut-off, U - RER | 7.545 | kg |
| Metal working | Metal working, average for metal product manufacturing| cut-off, U - RER | 0.900 | kg |
| Natural gas | Market for natural gas, from high pressure network (1-5 bar), at service station | cut-off, U - GLO | 0.750 | kg |
| Polyethylene, high density, granulate | Polyethylene production, high density, granulate |cut-off, U - RER | 8.333 | kg |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Transport, freight, lorry 3.5-7.5 metric ton, EURO5 | cut-off, U - RER | 1.667 | t\*km |
| **Outputs** |  |  |  |
| **Liner HPDE Production phase 149 Liters** | **Plastic Liner HDPE** | **1.000** | **Item(s)** |
| *Carbon dioxide* |  | 2.268 | kg |
| *Carbon monoxide* |  | 2.465E-03 | kg |
| *Mercury* |  | 6.164E-9 | kg |
| *Methane* |  | 6.985E-4 | kg |
| *Nitrogen oxides* |  | 8.218E-4 | kg |
| *NMVOC, non-methane volatile organic compounds, unspecified origin* |  | 3.287E-4 | kg |
| *Sulfur dioxide* |  | 2.260E-5 | kg |
| **Fuel cell stack** | **Inputs** |  |  |  |
| Air management | Air management | 1.250 | Item(s) |
| Control | Control | 1.250 | Item(s) |
| Disposal FC | Disposal FC | 1.250 | Item(s) |
| Fuel Cell Stack | Fuel Cell Stack | 1.250 | Item(s) |
| Fuel management | Fuel management | 1.250 | Item(s) |
| Heat management | Heat management | 1.250 | Item(s) |
| Other BoP | Other BoP | 1.250 | Item(s) |
| Water management | Water management |  |  |
| **Outputs** |  |  |  |
| **FC Miotty** | **FCa Miotty** | **1.250** | **Item(s)** |
| **Glider\*** | Glider, passenger car | glider production, passenger car | cut-off, U | 800.000 | kg |
|  | *\*Taken without changes from (Wernet et al., 2016)* | | | | |
| [**Battery**](file:///C:\Users\BenitezBritos\Documents\2018\Article_draft\Tables_article_AB_00.xlsx#RANGE!A1) | **Inputs** |  |  |  |
| BMS, for Li-Ion battery, at plant | Battery management system (BMS) production, for LIB (Bauer) | 0.047 | kg |
| Cooling system, for Li-Ion battery pack (Ellingsen) | Cooling system, for Li-Ion battery pack (Ellingsen) | 0.000 | kg |
| Electricity, medium voltage | market group for electricity, medium voltage |cut-off, S - Europe without Switzerland | 9.000 | kWh |
| Heat, central or small-scale, natural gas | market for heat, central or small-scale, natural gas |cut-off, U - Europe without Switzerland | 20.000 | MJ |
| LFP-TiO Battery Cell, Li-Ion battery (Bauer) | LFP-TiO Battery Cell, Li-Ion battery, modular (Bauer) | 0.767 | kg |
| Li-Ion battery pack housing, at plant | Pack housing production, Li-Ion battery pack, at plant (Zackrisson / Bauer) | 0.186 | kg |
| Transport, freight train | market for transport, freight train |cut-off, U - Europe without Switzerland | 0.075 | t\*km |
| Transport, freight, lorry 16-32 metric ton, EURO5 | market for transport, freight, lorry 16-32 metric ton, EURO5 | cut-off, U - GLO | 0.025 | t\*km |
| Wastewater, average | market for wastewater, average cut-off, S - Europe without Switzerland | -0.025 | m3 |
| Water, decarbonized, at user | water production and supply, decarbonized | water, decarbonized, at user | cut-off, U - RER | 25.300 | kg |
| **Outputs** |  |  |  |
| **Li-Ion Battery Pack, LFP-TiO (Bauer)** | **Li-Ion Battery Pack production, LFP-TiO, modular (Bauer)** | **1.000** | **kg** |
| [**Electric motor**](file:///C:\Users\BenitezBritos\Documents\2018\Article_draft\Tables_article_AB_00.xlsx#RANGE!A1)**\*** | Electric motor, electric passenger car | market for electricity, low voltage, U - DE | 53.000 | kg |
|  | *\*Taken without changes from (Wernet et al., 2016)* |  |  |  |
| **Transport\*** | Transport, freight, lorry 3.5-7.5 metric ton, EURO5 | transport, freight, lorry 3.5-7.5 metric ton, EURO5 | cut-off, U - RER | 10.600 | t\*km |
|  | *\*Taken without changes from (Wernet et al., 2016)* |  |  |  |
| **Electricity\*** | Electricity, low voltage | market for electricity, low voltage| cut-off, U - DE | 700.000 | kWh |
|  | *\*Taken without changes from (Wernet et al., 2016)* |  |  |  |

aFC: fuel cell; bFCEV: fuel cell electric vehicle

Table S 15 Life cycle inventory for the Fuel cell electric vehicle use phase for a lifetime of 150,000 km. Current scenario

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Description** | **Input flow** | **Default provider** | **Amount** | **Units** |
| Fuel cell electric vehicle | Assembly Fuel cell electric vehicle | Assembly bFCEV | 1.000 | Item(s) |
| Disposal | FCEV disposal phase | FCEV disposal phase | 1.000 | Item(s) |
| Maintenance | Passenger car maintenance | maintenance, passenger car | passenger car maintenance | cut-off, U - RER | 1.000 | Item(s) |
| Hydrogen | Tankstelle, GH2 Truck | Tankstelle, GH2 Truck | 1,140.000 | kg |
|  | **Output flow** |  |  |  |
| Use phase | Use phase FCEV | Use phase FCEV | 150,000.000 | km |

aFC: fuel cell; bFCEV: fuel cell electric vehicle

Table S 16: Disposal phase (Wernet et al., 2016)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Description** | **Input flow** | | **Default provider** | **Amount** | **Units** |
| Electronics | electronics scrap from control units | | treatment of electronics scrap from control units, cut-off, U - RER | -1.000 | kg |
| Dismantling | manual dismantling of used electric passenger car | | manual dismantling of used electric passenger car, cut-off, U - GLO | -1.000 | Item |
| Used glider | used glider, passenger car | | treatment of used glider, passenger car, shredding | used glider, passenger car | cut-off, U - GLO | -800.000 | kg |
| Used battery | used Li-ion battery | | treatment of used Li-ion battery, hydrometallurgical treatment | used Li-ion battery | cut-off, U - GLO | -10.000 | kg |
| Used powertrain | used powertrain from electric passenger car, manual dismantling | | treatment of used powertrain for electric passenger car, manual dismantling | used powertrain from electric passenger car, manual dismantling | cut-off, U – GLO | -74.000 | kg |
| Waste plastic | waste plastic, mixture | | market for waste plastic, mixture | waste plastic, mixture | cut-off, U - Europe without Switzerland | -109.500 | kg |
|  | **Output flow** | | | | |
| Disposal phase | FCEV disposal phase | FCEV disposal phase | | 1.000 | Item(s) |

Table S 17: Assumptions for future scenario

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Component** | **Criteria** | **Process** | **Input flow** | **Current (baseline)** | **Future** | **Units** |
| Carbon fiber manufacturing     (DOE, 2017) | -22 % energy demand | A: Polymerization | electricity, medium voltage 2050 | 2.495 | 2.220 | kWh/kgCF |
|  |  | heat, in chemical industry | 13.810 | 12.290 | kWh/kgCF |
| -36 % energy demand | B: Spinning dope production | electricity, medium voltage 2050 | 0.454 | 0.444 | kWh/kgCF |
| Whole spinning process | D: Spinning process | electricity, medium voltage 2050 | 0.121 | 0.116 | kWh/kgCF |
|  | E: Stretching and washing process | electricity, medium voltage 2050 | 1.569 | 1.498 | kWh/kgCF |
|  | F: Sizing I | electricity, medium voltage 2050 | 0.137 | 0.131 | kWh/kgCF |
|  | G: Drying | electricity, medium voltage 2050 | 0.150 | 0.147 | kWh/kgCF |
|  | H: Relaxation | electricity, medium voltage 2050 | 0.300 | 0.293 | kWh/kgCF |
|  | I: Sizing II | electricity, medium voltage 2050 | 0.061 | 0.059 | kWh/kgCF |
|  | J: Winding up | electricity, medium voltage 2050 | 0.266 | 0.254 | kWh/kgCF |
| -31 % energy demand | M: Stabilization | electricity, medium voltage 2050 | 18.824 | 15.907 | kWh/kgCF |
| Stabilization and carbonization | N: Carbonization LT | electricity, medium voltage 2050 | 4.166 | 3.843 | kWh/kgCF |
|  | O: Carbonization HT | electricity, medium voltage 2050 | 8.059 | 7.435 | kWh/kgCF |
| Tank | Carbon composite amount | HY\_TANK\_Production\_phase | Carbon fiber | 75.933 | 68.489 | kg/item |
| (Roh et al., 2013) | reduction at 92 kg |  | epoxy resin, liquid | 26.067 | 23.511 | kg/item |
|  |  |  | ***Carbon composite*** | ***102.000*** | ***92.000*** | ***kg/item*** |
| Fuel cell  (Miotti et al., 2015) | Platinum load: 0.001 kg/m2 | Catalyst FC | platinum | 0.002 | 0.001 | kg/m2 |
| Battery  (Peters et al., 2017) | Improvement energy density LFP to  140 Wh/kg | Li-Ion\_Common Base | Li-Ion Battery Pack, LFP-TiO (Bauer) | 16.888 | 10.145 | kg/item |
| FCEV  (Bhaskar, 2009) | -20% energy demand assembly | Assembly\_FCEV | electricity, medium voltage 2050 | 700.000 | 560.000 | kWh/vehicle |

This table contains the changes considered for the future scenario,

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1. Institut für Textiltechnik, RTWH Aachen University [↑](#footnote-ref-1)