# The COPPE-MSB model

MESSAGE[[1]](#footnote-1) is a mixed integer, perfect foresight optimisation model, designed to evaluate different strategies of energy supply development to meet a given demand, which can be exogenous or endogenous. It is included in the category of integrated assessment models (IAMs) that combine techno-economic and environmental variables to generate cost-optimal solutions, which minimise the total cost of expanding the energy system to meet the useful energy demand projected, subject to constraints such as availability of resources, infrastructure, import possibilities, environmental restrictions and regulations, investment limits, availability and price of fuels, and market penetration rates for new technologies, among others, that represent real-world restrictions to the full range of the variable in question.

COPPE-MSB is an expansion of the MESSAGE-Brazil model developed by the Cenergia lab at COPPE/UFRJ (Borba et al., 2012; de Lucena et al., 2009; Herreras-Martínez et al., 2015; Lucena et al., 2015; Nogueira et al., 2014). The most relevant new features introduced include the endogenisation of demand, higher resolution of temporal representation, and the geographical expansion to five distinct regions in Brazil (Rochedo et al., 2015). The COPPE-MSB model generates endogenous demand projections based on GDP and population drivers through elasticities, which are able to respond to energy price signals. The expanded spatial and temporal resolutions of COPPE-MSB also improve the response of the energy supply system to variations of demand given by regional load curves for various energy services demands. COPPE-MSB divides the country into five geographical regions: North, Northeast, South, Southeast and Mid-West. The model divides the year into twelve months, each represented by a typical day with 24 hours, leading to a total of 288 time slices.

Techno-economic parameters that form the input deck of COPPE-MSB are derived from various sources, including available literature, surveys, theses and dissertations conduced at the Energy Planning Program (PPE/COPPE) of the Universidade Federal do Rio de Janeiro. Resource prices, such as oil, gas, and coal are derived from a combination of literature and models developed in-house. Oil prices are the result of recent runs of a multi-Hubbert model based on Brazilian estimates of the Ultimately Recoverable Resources (URR) (Szklo et al., 2007).

# Techno-economic characterisation of evaluated energy systems

**Table 2.1. Characterisation of energy systems modelled in MESSAGE-Brazil.**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Investment cost (US$/kW)** | | **Variable O&M cost (US$/MWh)** | | **Fixed O&M cost (US$/kW/year)** | | **Conversion efficiency** | | **Availability** |
| **Power plant options** | | **2010** | **2050** | **2010** | **2050** | **2010** | **2050** | **2010** | **2050** | **2010 - 2050** |
| Coala | |  |  |  |  |  |  |  |  |  |
|  | Domestic coal-FBC | 3690 | 2500 | 4.6 | 3.1 | 39 | 26 | 0.38 | 0.42 | 0.85 |
|  | FBC with CCS | 4190 | 3000 | 8.1 | 6.2 | 91 | 78 | 0.22 | 0.34 | 0.85 |
|  | Pulverized imported coal -PC | 2000 | 2000 | 5.6 | 5.6 | 38 | 38 | 0.40 | 0.45 | 0.85 |
|  | PC with CCS | 2500 | 2500 | 9.1 | 9.1 | 90 | 90 | 0.23 | 0.36 | 0.85 |
|  | IGCC (imported coal) | 2400 | 2400 | 3.5 | 3.5 | 28 | 28 | 0.40 | 0.48 | 0.85 |
|  | IGCC with CCS | 2600 | 2600 | 7.1 | 7.1 | 54 | 54 | 0.35 | 0.42 | 0.85 |
|  | Co-firing of domestic coal and biomass | 3690 | 2500 | 4.6 | 3.1 | 39 | 26 | 0.35 | 0.40 | 0.85 |
| Natural gas (NG)b | |  |  |  |  |  |  |  |  |  |
|  | Open cycle -NGOC | 800 | 600 | 3.5 | 3.5 | 20 | 15 | 0.35 | 0.38 | 0.90 |
|  | Combined cycle -NGCC | 1190 | 1000 | 3.5 | 3.5 | 13 | 11 | 0.50 | 0.55 | 0.85 |
|  | NGCC with CCS | 3090 | 3090 | 3.5 | 3.5 | 23 | 23 | 0.43 | 0.43 | 0.85 |
|  | Flexible NGCC | 1300 | 1300 | 3.5 | 3.5 | 13 | 13 | 0.55 | 0.58 | 0.85 |
| Hydroelectric c | |  |  |  |  |  |  |  |  |  |
|  | Small hydroelectric (<30MW) | 2936 | 2936 | 0 | 0 | 65 | 65 | n.a. | n.a. | 0.571 in S1; 0.603 in S2 |
|  | Medium hydroelectric (>30MW; <300MW) | 2513 | 2513 | 0 | 0 | 58 | 58 | n.a. | n.a. | 0.571 in S1; 0.603 in S2 |
|  | Large hydroelectric (>300MW) | 2091 | 2091 | 0 | 0 | 52 | 52 | n.a. | n.a. | 0.522 in S1; 0.538 in S2 |
| Nucleard | | 4000 | 4000 | 0.8 | 0.8 | 136 | 136 | n.a. | n.a. | 0.85 |
| Biomassf | |  |  |  |  |  |  |  |  |  |
|  | Bagasse with backpressure turbines (22 bar) | 800 | 800 | 5.6 | 5.6 | 0 | 0 | 0.25 | 0.25 | 0.90 |
|  | Bagasse with CEST – existing | 959 | 959 | 4.8 | 4.8 | 0 | 0 | 0.25 | 0.25 | 0.90 |
|  | Bagasse with CEST - new | 2712 | 2392 | 4.6 | 4.6 | 0 | 0 | 0.30 | 0.30 | 0.90 |
|  | Bagasse with BIG/GT | 1009 | 1009 | 4.8 | 4.8 | 0 | 0 | 0.40 | 0.40 | 0.80 |
|  | Biomass -steam turbine | 3600 | 2500 | 6.3 | 6.3 | 50 | 50 | 0.28 | 0.28 | 0.60 |
|  | Municipal solid waste -MSW | 7050 | 6210 | 0 | 0 | 211 | 186 | 0.28 | 0.28 | 0.74 |
|  | Diesel | 1000 | 1000 | 14.3 | 14.3 | 0 | 0 | 0.35 | 0.35 | 0.35 |
|  | Heavy fuel oil | 1070 | 1070 | 14.3 | 14.3 | 0 | 0 | 0.30 | 0.33 | 0.55 |
| Non-conventional renewable energy | |  |  |  |  |  |  |  |  |  |
|  | Solar PV-utility scale | 4300 | 1300 | 0 | 0 | 51 | 15 | n.a. | n.a. | 0.17 |
|  | Solar PV-distributed generationg | 5300 | 2000 | 0 | 0 | 22 | 8 | n.a. | n.a. | 0.17 |
|  | Wind onshoref | 1810 | 1547 | 0 | 0 | 42 | 36 | n.a. | n.a. | 0.35 |
|  | Wind offshoref | 5000 | 3000 | 0 | 0 | 60 | 36 | n.a. | n.a. | 0.40 |
|  | Wavef | 6000 | 4500 | 0 | 0 | 20 | 20 | n.a. | n.a. | 0.15 |
|  | CSP-4hTES- back-up fossil boiler h | 5208 | 3315 | 0 | 0 | 85 | 54 | n.a. | n.a. | 0.32 |
|  | CSP-8hTES- back-up fossil boiler h | 6312 | 3912 | 0 | 0 | 103 | 64 | n.a. | n.a. | 0.37 |
|  | CSP-12hTES-back-up fossil boiler h | 7254 | 4422 | 0 | 0 | 118 | 72 | n.a. | n.a. | 0.42 |
|  | CSP-BIO i | 5856 | 3641 | 5.0 | 5.0 | 65 | 65 | 0.57 | 0.57 | 0.51 |
| Notes: Variable O&M cost does not include fuel cost. BIG/GT: biomass integrated gasification/gas turbines. CEST: condensing-extraction steam turbine. FBC: fluidized bed combustion. IGCC: integrated gasification combined cycle. n.a.: not applicable | | | | | | | | | |  |
|  | Sources: |  |  |  |  |  |  |  |  |  |
|  | a (Borba et al., 2012; Hoffmann et al., 2012) | |  |  |  |  |  |  |  |  |
|  | b (IEA, 2013a, 2013b) | | | |  |  |  |  |  |  |
|  | c (Lucena, 2010; Lucena et al., 2010) |  |  |  |  |  |  |  |  |  |
|  | d (Cabrera-Palmer and Rothwell, 2008; Varro and Ha, 2015) | | |  |  |  |  |  |  |  |
|  | e (Borba et al., 2012; IEA, 2012; Irena, 2012; Renewable and Agency, 2015) | |  |  |  |  |  |  |  |  |
|  | f Borba et al. (2012) |  |  |  |  |  |  |  |  |  |
|  | g (IEA, 2014) |  |  |  |  |  |  |  |  |  |
|  | h (Trieb et al., 2014). A back-up fossil boiler is considered within the investment cost. Nevertheless, for this project. this boiler cannot be used for electricity production. | | | | | | |  |  |  |
|  | i (Soria et al., 2015) |  |  |  |  |  |  |  |  |  |

# Installed capacity of power generation scenarios

**Table 3.1. Power generation installed capacity of baseline and low-carbon scenarios (GW).**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Nuclear** | **Coal** | **Coal CCS** | **NG** | **HFO** | **Diesel** | **Bagasse** | **Hydro** | **Wind** | **PV-solar** | **Total** |
| **2010** | **Baseline** | 2.0 | 6.1 | 0.0 | 15.4 | 4.0 | 4.4 | 6.5 | 81.6 | 4.0 | 0.0 | 124.0 |
| **2020** | **Baseline** | 2.0 | 6.6 | 0.0 | 21.0 | 5.1 | 2.0 | 12.3 | 93.3 | 17.4 | 9.7 | 169.4 |
| **LC0** | 2.0 | 6.1 | 0.0 | 21.5 | 6.0 | 2.0 | 9.0 | 83.8 | 29.0 | 9.2 | 168.6 |
| **LC100** | 2.0 | 6.1 | 0.0 | 21.5 | 6.0 | 2.0 | 9.0 | 83.8 | 29.0 | 9.7 | 169.1 |
| **2030** | **Baseline** | 3.5 | 6.6 | 0.0 | 17.2 | 4.9 | 1.5 | 13.7 | 93.3 | 17.4 | 10.1 | 168.1 |
| **LC0** | 3.5 | 6.1 | 0.0 | 17.4 | 5.9 | 1.5 | 9.9 | 83.8 | 29.0 | 9.9 | 167.0 |
| **LC100** | 3.5 | 6.1 | 0.3 | 17.4 | 5.9 | 1.5 | 11.7 | 83.8 | 29.0 | 9.9 | 169.1 |
| **2040** | **Baseline** | 3.5 | 16.0 | 0.0 | 14.1 | 1.7 | 0.6 | 16.6 | 107.4 | 25.3 | 10.7 | 196.0 |
| **LC0** | 3.5 | 12.3 | 0.0 | 11.2 | 1.3 | 0.6 | 13.3 | 88.7 | 42.1 | 10.2 | 183.2 |
| **LC100** | 3.5 | 5.7 | 3.0 | 11.2 | 1.3 | 0.6 | 14.9 | 88.8 | 42.1 | 10.2 | 181.1 |
| **2050** | **Baseline** | 3.5 | 29.5 | 0.0 | 7.7 | 0.4 | 0.5 | 10.5 | 118.3 | 17.4 | 16.0 | 203.8 |
| **LC0** | 3.5 | 19.7 | 0.0 | 6.3 | 0.2 | 0.5 | 20.9 | 88.8 | 42.1 | 11.6 | 193.4 |
| **LC100** | 3.5 | 4.2 | 5.2 | 6.3 | 0.2 | 0.5 | 24.7 | 89.7 | 42.1 | 11.6 | 188.0 |

# Emission factors of GHG and airborne pollutants

**Table 4.1. GHG emission factors of power generation technologies in 2050 (g/kWh).**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technologies** | | **CO2** | **CH4** | **N2O** |
| **NPP** | **PWR** | 0.00 | 0.00 | 0.00 |
| **Fossil fuel-based technologies** | **Coal\_pp\_BR** | 1134.43 | 0.01 | 0.01 |
| **Coal\_pp\_BR\_CCS** | 200.19 | 0.01 | 0.01 |
| **Coal\_pp\_Imp** | 883.80 | 0.01 | 0.00 |
| **Coal\_pp\_Imp\_CCS** | 101.01 | 0.01 | 0.01 |
| **Coal\_pp\_Cof** | 618.66 | 0.09 | 0.01 |
| **NG\_OC** | 577.11 | 0.04 | 0.01 |
| **NG\_CC** | 461.69 | 0.01 | 0.02 |
| **NG\_CC\_CCS** | 69.79 | 0.01 | 0.03 |
| **NG\_H2** | 0.00 | 0.00 | 0.00 |
| **HFO** | 843.43 | 0.01 | 0.00 |
| **Diesel** | 889.80 | 0.01 | 0.00 |
| **Renewable-based technologies** | **Forestry residues** | 0.00 | 0.39 | 0.05 |
| **Forestry residues\_CCS** | -1625.27 | 0.49 | 0.07 |
| **Bagasse** | 0.00 | 0.39 | 0.05 |
| **Bagasse\_CCS** | -1285.48 | 0.49 | 0.07 |
| **Biomass\_H2\_CCGT** | 0.00 | 0.00 | 0.00 |
| **Hydro** | 0.00 | 0.00 | 0.00 |
| **Wind** | 0.00 | 0.00 | 0.00 |
| **Solar** | 0.00 | 0.00 | 0.00 |
| **Solar\_CSP** | 0.00 | 0.00 | 0.00 |
| **Solar\_CSP\_hybrid\_Biomass\_8h** | 0.00 | 0.13 | 0.02 |
| **Solar\_CSP\_hybrid\_NG\_8h** | 153.90 | 0.00 | 0.01 |
| **EtOH stationary engine** | 0.00 | 0.02 | 0.00 |

Source: Elaborated by the authors.

**Table 4.2. Particulate matter formation and terrestrial acidification pollutant emission factors of power generation technologies in 2050 (g/kWh).**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technologies** | | **SO2** | **NOx** | **PM10** |
| **NPP** | **PWR** | 0.00 | 0.00 | 0.00 |
| **Fossil fuel-based technologies** | **Coal\_pp\_BR** | 3.81 | 2.51 | 0.09 |
| **Coal\_pp\_BR\_CCS** | 1.01 | 4.16 | 0.15 |
| **Coal\_pp\_Imp** | 2.85 | 2.22 | 0.07 |
| **Coal\_pp\_Imp\_CCS** | 0.49 | 2.39 | 0.08 |
| **Coal\_pp\_Cof** | 2.01 | 1.87 | 0.47 |
| **NG\_OC** | 0.00 | 0.80 | 0.01 |
| **NG\_CC** | 0.00 | 0.64 | 0.01 |
| **NG\_CC\_CCS** | 0.00 | 0.75 | 0.01 |
| **NG\_H2** | 0.00 | 0.00 | 0.00 |
| **HFO** | 1.73 | 1.55 | 0.27 |
| **Diesel** | 1.90 | 1.70 | 0.30 |
| **Renewable-based technologies** | **Forestry residues** | 0.06 | 1.04 | 1.99 |
| **Forestry residues\_CCS** | 0.01 | 1.25 | 2.38 |
| **Bagasse** | 0.62 | 1.04 | 1.99 |
| **Bagasse\_CCS** | 0.12 | 1.25 | 2.38 |
| **Biomass\_H2\_CCGT** | 0.04 | 0.68 | 0.00 |
| **Hydro** | 0.00 | 0.00 | 0.00 |
| **Wind** | 0.00 | 0.00 | 0.00 |
| **Solar** | 0.00 | 0.00 | 0.00 |
| **Solar\_CSP** | 0.00 | 0.00 | 0.00 |
| **Solar\_CSP\_hybrid\_Biomass\_8h** | 0.02 | 0.35 | 0.66 |
| **Solar\_CSP\_hybrid\_NG\_8h** | 0.00 | 0.21 | 0.00 |
| **EtOH stationary engine** | 0.00 | 0.66 | 0.00 |

Source: Elaborated by the authors.

**Table 4.3. Human toxicity airborne pollutant emissions factors of power generation technologies in 2050 (g.kWh).**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technologies** | | **Pb** | **Cd** | **Hg** | **As** | **Cr** | **Cu** | **Ni** | **Se** | **Zn** | **PCB** | **PCDD/F** | **Benzo(a)**  **pyrene** | **Benzo(b)**  **fluoranthene** | **Benzo(k)**  **fluoranthene** | **HCB** |
| **NPP** | **PWR** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **Fossil fuel-based technologies** | **Coal\_pp\_BR** | 8.8E-05 | 1.1E-05 | 1.7E-05 | 8.5E-05 | 5.4E-05 | 9.4E-05 | 5.9E-05 | 2.8E-04 | 2.3E-04 | 4.0E-11 | 1.2E-10 | 8.4E-09 | 4.4E-07 | 3.5E-07 | 8.0E-08 |
| **Coal\_pp\_BR\_CCS** | 1.5E-04 | 1.9E-05 | 3.0E-05 | 1.5E-04 | 9.5E-05 | 1.7E-04 | 1.0E-04 | 4.9E-04 | 4.0E-04 | 7.0E-11 | 2.1E-10 | 1.5E-08 | 7.8E-07 | 6.1E-07 | 1.4E-07 |
| **Coal\_pp\_Imp** | 1.4E-04 | 1.6E-05 | 2.6E-05 | 1.3E-04 | 8.2E-05 | 9.0E-06 | 8.7E-05 | 4.1E-04 | 7.9E-05 | 3.0E-11 | 9.0E-11 | 1.2E-08 | 3.3E-07 | 2.6E-07 | 6.0E-08 |
| **Coal\_pp\_Imp\_CCS** | 1.5E-04 | 1.9E-05 | 3.0E-05 | 1.5E-04 | 9.4E-05 | 1.0E-05 | 1.0E-04 | 4.6E-04 | 9.1E-05 | 3.4E-11 | 1.0E-10 | 1.3E-08 | 3.8E-07 | 3.0E-07 | 6.9E-08 |
| **Coal\_pp\_Cof** | 1.5E-04 | 1.6E-05 | 2.2E-05 | 1.2E-04 | 8.2E-05 | 6.3E-05 | 9.9E-05 | 2.9E-04 | 5.4E-04 | 9.5E-09 | 2.0E-10 | 3.0E-06 | 3.5E-07 | 2.2E-07 | 5.6E-08 |
| **NG\_OC** | 1.4E-08 | 2.3E-09 | 9.0E-07 | 1.1E-06 | 6.8E-09 | 6.8E-10 | 4.6E-09 | 1.0E-07 | 1.4E-08 | 0.0E+00 | 0.0E+00 | 5.0E-09 | 1.4E-08 | 1.0E-08 | 0.0E+00 |
| **NG\_CC** | 1.1E-08 | 1.8E-09 | 7.2E-07 | 8.6E-07 | 5.5E-09 | 5.5E-10 | 3.7E-09 | 8.1E-08 | 1.1E-08 | 0.0E+00 | 0.0E+00 | 4.0E-09 | 1.1E-08 | 8.0E-09 | 0.0E+00 |
| **NG\_CC\_CCS** | 1.3E-08 | 2.1E-09 | 8.4E-07 | 1.0E-06 | 6.4E-09 | 6.4E-10 | 4.3E-09 | 9.4E-08 | 1.3E-08 | 0.0E+00 | 0.0E+00 | 4.7E-09 | 1.3E-08 | 9.3E-09 | 0.0E+00 |
| **NG\_H2** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **HFO** | 4.4E-05 | 1.5E-05 | 1.5E-05 | 2.0E-05 | 1.5E-05 | 3.0E-05 | 1.5E-05 | 7.4E-05 | 2.0E-05 | 1.4E-12 | 1.1E-11 | 1.3E-06 | 5.5E-06 | 1.1E-06 | 2.4E-09 |
| **Diesel** | 4.9E-05 | 1.6E-05 | 1.6E-05 | 2.2E-05 | 1.6E-05 | 3.3E-05 | 1.6E-05 | 8.1E-05 | 2.2E-05 | 1.6E-12 | 1.2E-11 | 1.4E-06 | 6.0E-06 | 1.2E-06 | 2.6E-09 |
| **Renewable-based technologies** | **Forestry residues** | 2.6E-04 | 2.3E-05 | 1.9E-05 | 1.2E-04 | 1.2E-04 | 2.7E-04 | 1.8E-04 | 1.5E-05 | 2.3E-03 | 4.5E-08 | 6.4E-10 | 1.4E-05 | 5.5E-07 | 2.0E-07 | 6.4E-08 |
| **Forestry residues\_CCS** | 3.4E-04 | 2.9E-05 | 2.5E-05 | 1.5E-04 | 1.5E-04 | 3.5E-04 | 2.3E-04 | 2.0E-05 | 3.0E-03 | 5.7E-08 | 8.2E-10 | 1.8E-05 | 7.0E-07 | 2.5E-07 | 8.2E-08 |
| **Bagasse** | 2.6E-04 | 2.3E-05 | 1.9E-05 | 1.2E-04 | 1.2E-04 | 2.7E-04 | 1.8E-04 | 1.5E-05 | 2.3E-03 | 4.5E-08 | 6.4E-10 | 1.4E-05 | 5.5E-07 | 2.0E-07 | 6.4E-08 |
| **Bagasse\_CCS** | 3.4E-04 | 2.9E-05 | 2.5E-05 | 1.5E-04 | 1.5E-04 | 3.5E-04 | 2.3E-04 | 2.0E-05 | 3.0E-03 | 5.7E-08 | 8.2E-10 | 1.8E-05 | 7.0E-07 | 2.5E-07 | 8.2E-08 |
| **Biomass\_H2\_CCGT** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **Hydro** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **Wind** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **Solar** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **Solar\_CSP** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **Solar\_CSP\_hybrid\_Biomass\_8h** | 8.8E-05 | 7.5E-06 | 6.5E-06 | 4.1E-05 | 3.9E-05 | 9.0E-05 | 6.1E-05 | 5.1E-06 | 7.8E-04 | 1.5E-08 | 2.1E-10 | 4.8E-06 | 1.8E-07 | 6.6E-08 | 2.1E-08 |
| **Solar\_CSP\_hybrid\_NG\_8h** | 3.6E-09 | 6.0E-10 | 2.4E-07 | 2.9E-07 | 1.8E-09 | 1.8E-10 | 1.2E-09 | 2.7E-08 | 3.6E-09 | 0.0E+00 | 0.0E+00 | 1.3E-09 | 3.8E-09 | 2.7E-09 | 0.0E+00 |
| **EtOH stationary engine** | 2.9E-05 | 9.8E-06 | 9.8E-06 | 1.3E-05 | 9.8E-06 | 2.0E-05 | 9.8E-06 | 4.9E-05 | 1.3E-05 | 9.4E-13 | 7.1E-12 | 8.4E-07 | 3.6E-06 | 7.1E-07 | 1.6E-09 |

Source: Elaborated by the authors.

# Characterisation factors of mid-point impacts

**Table 5.1. Characterisation factors of CC. PMF. TAP and HT mid-point impacts**

|  |  |  |
| --- | --- | --- |
| **Impact category** | **Pollutant** | **Characterisation factors** |
| **Climate change (CC)** | CO2 | 1 |
| CH4 | 34 |
| N2O | 298 |
| **Particulate matter formation (PMF)** | SO2 | 0.20 |
| NOx (as NO2) | 0.22 |
| PM (as PM10) | 1 |
| **Terrestrial acidification potential (TAP)** | SO2 | 1 |
| NOx | 0.71 |
| **Human toxicity (HT)** | Pb | 202.28 |
| Cd | 348.68 |
| Hg | 38996.64 |
| As | 148.10 |
| Cr | 0.01 |
| Cu | 0.09 |
| Ni | 17.51 |
| Se | 382.73 |
| Zn | 1.20 |
| PCB | 37.94 |
| PCDD/F | 8.65 |
| Benzo(a)pyrene | 112.80 |
| Benzo(b)fluoranthene | 112.80 |
| Benzo(k)fluoranthene | 112.80 |
| HCB | 818.23 |

Source: Elaborated by the authors based on EcoInvent (2016); Myhre et al. (2013).

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