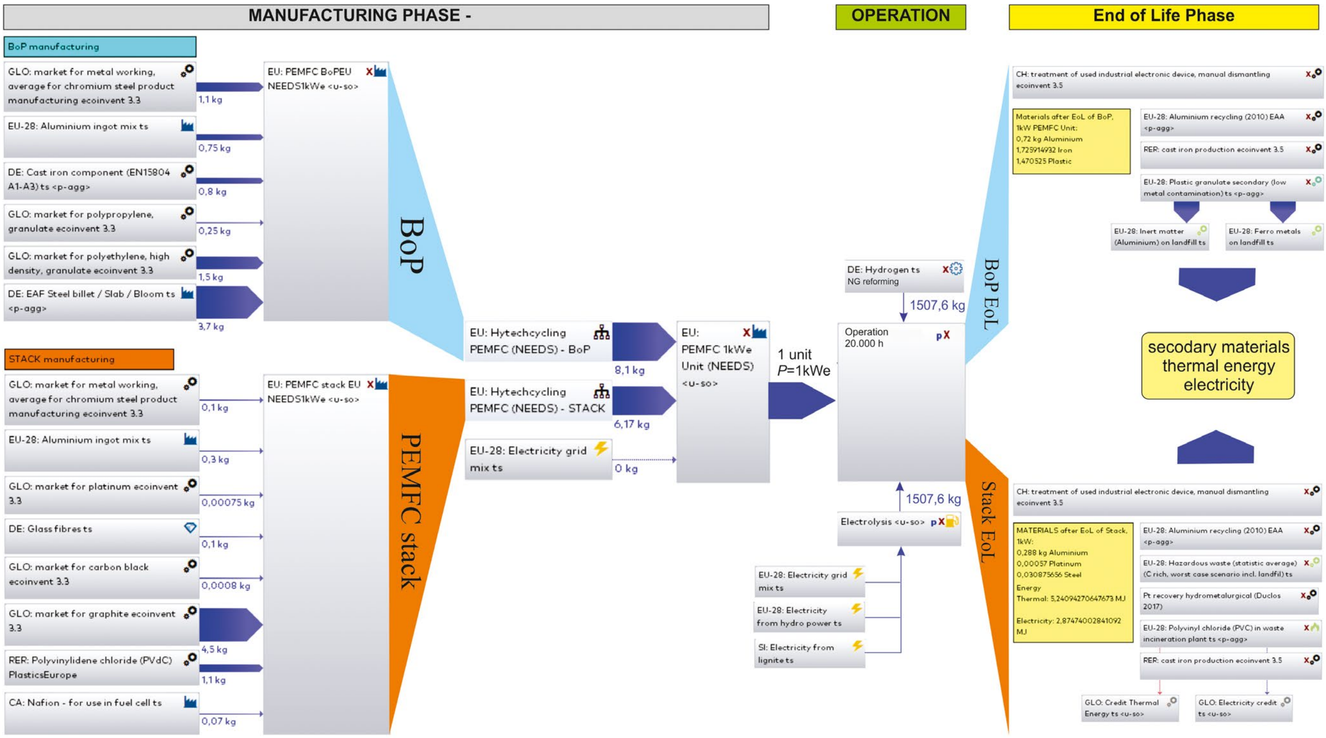

FIGURE 2 Life-cycle assessment model of manufacturing and operating of a 1-kWe PEMFC system

decade or even older. Examples of original sources are the NREL report from 1999,[65] and the NRDC reports from 2004[66] and 2008.[67] Nevertheless, all the original researches show very similar shares of worldwide hydrogen production technologies. Since NG-SR is the most economic and efficient method of producing hydrogen,[68] this is currently the predominant technology. In the USA, around 95% of all hydrogen is produced with NG-SR.[68] However, in order to increase the share of renewable hydrogen production, it is necessary to increase the share of electrolysis from RESs.

In this research, only two hydrogen production methods are presumed: a) water electrolysis and b) NG-SR. The electricity needed for electrolysis (189 MJ/kg of H_2) is generated from three different energy-grid mixes, which are EU Hydro power, SI Lignite, and the EU-28 mix, from the Gabi Professional Database.[49] Altogether, this makes four different scenarios in the operating phase. The EU28 electricity mix presents (scenario 1—EU mix) the basic approach of hydrogen production with electrolysis; the EU28 hydro mix (scenario 2—EU hydro) represents the best-possible or future RES-based hydrogen production with electrolysis; and SI lignite (scenario 3—SI lignite) as the worst electrolysis hydrogen production scenario. On the other hand, the majority of hydrogen today is produced with NG-SR; therefore, this scenario (scenario 4—NG reforming) is also evaluated in the operating phase.

For the operating lifetime of a stationary PEMFC system, 20 000 h was chosen, with no need to replace the stack in this timeframe.[53] The maximum hydrogen flow is 150 Nl/min where, according to the National Institute of Standards and Technology (NIST), normal conditions are taken to be at a pressure of 1 atm and a temperature of 20°C. In the whole operationg lifetime of 1kW PEMFC that coresponds to 1507.6 kg of hydrogen consumption, which is produced by electrolysis or NG-SR. If the hydrogen is produced with electrolysis, that corresponds to 284,855.6 MJ of electricity consumption.

4.2.3 | End-of-Life phase

In the EoL phase, different approaches were used for the PEMFC stack materials: recycling (REC), energy extraction (EE), and landfill (LF), as a worst-case scenario, where no other data were available for the EoL.[22] The first step in the EoL phase was manual dismantling of the system, where process treatment of the used industrial electronic device, manual dismantling from Ecoinvent 3.5, was used. In Table 4, the materials inputs for the EoL processes and the material-recovery ratio are presented for a 1-kW PEMFC system. For each material, the EoL approach, recycling ratio, and the used EoL process from the databases are shown. The EoL processes from the database were scaled according to the inventory data. The recycling ratio is defined according to the literature, industry data, or research papers.[30,69-71]

After the recycling process, secondary materials are available (Table 5) that can be used in the PEMFC system's manufacturing phase or in the manufacturing processes of other technologies. The reduced environmental impacts due to avoided (secondary) materials are subtracted from the environmental impacts in the manufacturing phase of the PEMFC unit.