CO_2 dissociation using a lab-scale microwave plasma torch: an investigation of industrially relevant parameters

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Under laboratory conditions, microwave plasma torches are known to be an energetically very efficient CO_2 conversion technology, for pressures ranging from 100 mbar up to atmospheric pressure. However, issues relevant for industrial application such as the wall-plug energy efficiency, including the electricity consumption of peripheral equipment, the performance for impure CO_2 streams (such as directly from carbon capture facilities), the stability at long-term operation and the suitability for intermittent operation are usually not addressed. This contribution aims to shed light on these industrially relevant parameters.

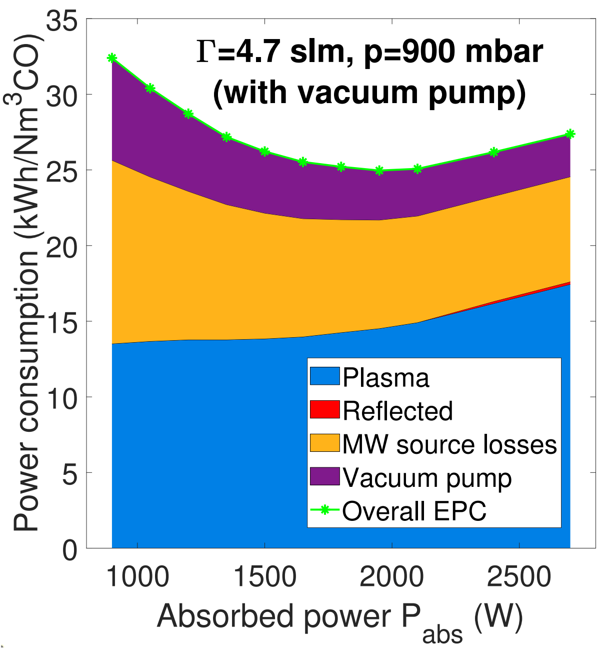

Fig. 1: Power distribution within the entire system [1].

Figure 1 illustrates the power requirements by the individual power consumption channels for the production of a certain amount of carbon monoxide. Energy efficiencies typically reported in literature consider only the plasma sub-system and are defined as follows:

$$\eta_p := \chi \cdot \frac{\Delta H \cdot \tilde{\Gamma}_{CO2,in}}{P_{abs}}. \quad (1)$$

In this equation, χ denotes the conversion, $\tilde{\Gamma}_{CO2,in}$ the particle inflow rate of CO_2 and P_{abs} the power that is absorbed by the plasma. As it is obvious from figure 1, this definition for the energy efficiency neglects several energy loss channels. However, to assess economic viability of CO_2 dissociation via microwave plasmas, it is crucial to consider the wall-plug energy efficiency η_{tot} taking into account all power requirements throughout the entire system:

$$\eta_{tot} := \chi \cdot \frac{\Delta H \cdot \tilde{\Gamma}_{CO2,in}}{P_{active,tot}} = \eta_p \cdot \eta_{MW\ coupling} \cdot \eta_{MW\ source} \cdot \eta_{equipment}. \quad (2)$$

Besides the plasma energy efficiency η_p, this includes also the efficiency of the coupling of the microwaves to the plasma $\eta_{MW\ coupling}$, the efficiency for the generation of microwaves $\eta_{MW\ source}$ and an

energy efficiency representing the power consumption by peripheral equipment $\eta_{\text{equipment}}$.
Conversions and the different energy efficiencies of a representative power scan experiment are shown in figure 2. It is interesting to note the opposite trend behaviour of plasma energy efficiency and wall-plug energy efficiency: when the power is increased from 0.9 kW to 2.73 kW, plasma energy efficiency drops from $(27\pm4)\%$ down to $(25.1\pm1.2)\%$ while the wall-plug energy efficiency even increases from 11.1% to 15.9%. Throughout all experiments, the highest wall-plug energy efficiency that could be obtained was $\eta_{\text{tot}} = 17.9\%$, corresponding to an electrical power consumption of 19.6 kWh per produced Nm^3 of carbon monoxide.
In a durability test over 29 h, long-term stability and reproducibility of the performance of the microwave plasma torch was investigated. As it is the basic idea of Power-to-Gas technologies to utilize temporary surpluses of electrical energy from intermittent renewable sources to produce valuable gases, the plasma was not operated continuously, but switched off and on several times. Even after 29 h, no degradation in the performance was observed. In particular the short switch-on and switch-off times are a unique selling point of plasma conversion technology compared to other CO_2 conversion technologies.
In order to assess the impact of impurities on the CO_2 conversion, experiments were performed in which controlled amounts of impurities (Ar, N_2, O_2, real air and synthetic air) were admixed to the CO_2 feed gas stream. Nitrogen, oxygen and argon concentrations of up to around 2% are tolerable for the plasma-based conversion. Humidity in the inflow, however, might have a very harmful effect on the conversion of CO_2. For industrial-scale application, this results in the requirement to use the microwave plasma torches only with dry CO_2 (water impurity $\leq$ 100 ppm).

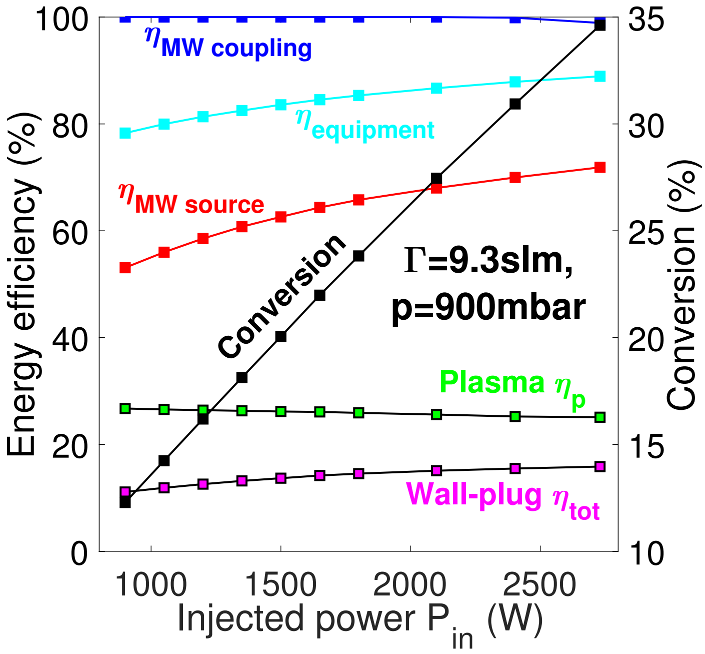

Fig. 2: Overview over conversion and the different energy efficiencies.

Together with studies on the removal of oxygen [2], these investigations assess the industrial applicability of plasma-based CO_2 dissociation by considering the interfaces of the process. Wall-plug energy efficiencies allow direct determination of operational expenditure, a durability test demonstrated suitability to be used with intermittent electricity and experiments with gas admixture demonstrated high robustness against most relevant impurities, except for water.

[1] C. K. Kiefer et al.: Chemical Engineering Journal **481**, 148326, 2024.
[2] R. Antunes et al.: ACS Sustainable Chemistry & Engineering **11**, 15984-15993, 2023.