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Cost projections for microwave plasma CO production using renewable energy

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ABSTRACT

Successful deployment of renewable fuel production requires substantial cost reduction along the entire value chain of the underlying manufacturing routes. To improve their performance, renewable fuel production technologies should follow a cost-reducing learning curve. In this article, we adopt recent evidence that learning-by-doing is directly influenced by the technology unit size and explore three scenarios for microwave plasma CO_2 conversion in which the learning rate varies between 10%, 15%, and 20%. Our projections reveal that the total investments required to deploy this CO_2 conversion technology at an exajoule scale decline from 83 down to 23 billion euros under a 10% increase in the value of the learning rate. The CO production costs in 2050 amount to 247–346 €(2019)/tCO, in which the range is determined by the value of the learning rate. Even under substantial learning until 2050 the levelized CO production cost is unlikely to become competitive with conventional natural gas-based CO production processes, except when a CO_2 tax is applied of up to 150 €(2019)/tCO_2. To optimally exploit effects of learning-by-doing, we recommend developing several CO production technologies simultaneously with multiple unit sizes, so as to improve the chance of ultimately selecting the process with the highest learning rate.

1. Introduction

To meet the goals of the Paris Agreement, most countries in the world likely have to progress to a carbon–neutral, and possibly even carbon-negative society within only three decades [1,2]. Harder-to-abate sectors like aviation, maritime shipping, and the chemical industry, currently heavily rely on oil because they use liquid hydrocarbons as fuel and feedstock source. Replacement of oil by renewable hydrocarbons seems an attractive strategy to decarbonize these sectors. To produce renewable liquid hydrocarbons, two approaches currently attract the most interest: biofuels and synthetic hydrocarbons (or a combination thereof). Biofuels are already covering a share of current demand in the transport sector and chemical industry. Sustainability and availability of these biomass feedstocks remain topics of serious debate [3]. In contrast to biofuels, renewable hydrocarbon fuels (also called e-fuels, synthetic fuels, or solar fuels), produced from CO_2 and renewable energy, seem to have a relatively low environmental impact in terms of greenhouse gas emissions, land area, and water usage [4,5]. Both options can currently not compete economically with fossil hydrocarbon fuel production routes [6]. We and others already provided some insight with regard to when and how some of the routes to produce renewable hydrocarbons might become competitive [5,7–10].

To enhance the competitiveness of renewable hydrocarbon production routes, several technologies should go down their learning curve to improve their costs and performance. The speed at which cost reductions occur is largely determined by the rate of technology diffusion and the steepness of the learning curve. Economies-of-scale, by increasing the technology unit size and entire plant design, are conventionally considered key to reducing costs. More recent insights, however, reveal that technologies with a smaller unit size may learn faster thanks to rapid advancements in innovation and automation [11–13]. A prime example is electricity production with photovoltaic (PV) panels, which experienced a substantial reduction in costs during the last decades. The reason-

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ing behind these rapid cost reductions is complex and depends on many variables. It seems likely that the small unit size of PV panels is the key factor enabling their mass production and application in many different markets (in e.g. space and the residential sector, as well as at utility scale). The PV panel size did not substantially change over time, which suggests that economies-of-scale play no role of significance for this technology in terms of the dimensions of individual products (scale effects do occur regarding e.g. the magnitude of production facilities and that of solar parks). The small modular size of the panels allows the use of automated processes, both during production, installation, and operation, while innovations are relatively easily implemented in the value chain. These characteristics have resulted in a high learning rate (LR) for PV technology and have saved many billion euros of investments during the phase of technology diffusion. Apart from faster learning phenomena, more-granular technologies are also associated with lower investment risk, more equitable access, and more opportunities to escape lock-in, all factors that help to realize a fast diffusion rate [13]. This combination of factors may yield the underlying mechanism for the successful deployment of solar PV, which otherwise would perhaps not have reached a cumulative capacity of nearly 600 GW in 2019 so quickly [14]. Technology learning and unit size thus seem important factors for successful technology diffusion.

To illustrate the influence of learning and unit size on the uptake of a novel technology, we here explore three development scenarios for a microwave plasma CO_2 reduction process that produces renewable carbon monoxide (CO), as has recently been described by van Rooij et al. [15]. Microwave technology is generally known from its residential application as an oven in kitchens around the world [16]. Also, industrial applications exist, originally as drying methods for food and feed [17], but more recently, also to pyrolyze various materials (e.g., tires, biomass, plastics) into hydrocarbon fractions [18]. Microwave generators possess a rapid on-off response time and can operate highly flexibly. This flexibility may have an advantage in coping with the increasing share of intermittent renewable electricity supply. In this context, microwave plasma technology could maybe play a meaningful role in the energy transition, especially if it can be applied to produce fuels from biomass, waste, or, the subject in this work, CO_2 [19]. We first determine the technology status in terms of development stage, performance, unit size, and costs. Next, we apply three different technology learning curve scenarios to project investments and CO production costs up to 2050. We finally discuss how microwave plasma technology might contribute to the energy transition and at what cost. We also provide some research and innovation guidelines that might help technology developers and decision makers to overcome the challenges that they are facing in bringing a new technology to scale in the energy sector.

2. Methodology and general assumptions

Plasma generation with microwave technology has received ample attention in academia during recent years, because the plasma approach is attractive for activation of stable molecules like CO_2 [19–22]. The concept benefits from a potential high energy efficiency in excess of 80%, flexible operation thanks to equilibration times on the order of milliseconds, absence of scarce materials, as well as a high-power density and thus small system footprint. Microwave plasma CO production systems are not yet commercially available and significant challenges remain, for instance, to improve the efficiency and robustness of the process [19]. We, therefore, base our imaginary CO_2 conversion facility on a previously reported analysis [15]. The plant at full load (8760 h/yr of operation) has a capacity of 20 ktCO, which equals 6.3 MW of CO output (MW_{CO}) per year, and generates oxygen (11 ktO_2/yr) as byproduct (Fig. 1).

The system consists of a set of parallel reactors, each including a microwave plasma generator and functioning at a conversion efficiency of 15% (mol/mol) and 50% energy efficiency. We assume that all CO_2 feedstock is either converted into CO or captured and recycled to the reactors, which translates into a CO_2 requirement of 31 $ktCO_2$ per year. Van Rooij et al. indicated that 603 $/tCO of electricity is consumed by the plant at a cost of 1.47 $ct/MJ electricity [15]. This suggests that 41 MJ of energy is consumed to produce 1 kg (or 10 MJ) CO and results in an overall process efficiency of 24% (energy out/energy in). If we consider that the microwave plasma process is 50% energy efficient, it means that approximately half of the energy is consumed by other process steps, such as cooling, compression, CO_2 absorption and regeneration, drying, and purification.

The total investment costs (CAPEX) are based on the equipment costs for a 20 kt (0.20 PJ) of CO per year plant [15] and expressed in €(2019) (Table 1). The microwave plasma generators dominate the equipment costs with 21 M€(2019). Other equipment costs, such as for compressors, reactors, pumps, coolers, and purification steps, add up to 7 M€(2019). The (although expensive) microwave plasma generators constitute only a single component of the total reactor equipment and hardly influence the costs associated with plant design, engineering, installation, contingency, permits, among others. Following this reasoning we only apply a typical installation factor of 4 [23] to "other equipment costs" and determine our total CAPEX at 48 M€(2019), or approximately 7600 €(2019)/kW_{CO}. The operating and maintenance (O&M) costs (excl. electricity and CO_2 input) are set at 5% of the total CAPEX, based on a comparable estimate of 7.6% of the equipment costs by van Rooij et al. [15].

The levelized CO production costs (C_{CO}) are calculated with formula (1) in which the total annual costs are divided by the amount of fuel produced annually (P_{CO}) [24]. The total annual costs consist of the discounted annualized CAPEX (with α being the capital recovery factor), the annual O&M costs, and the annual feedstock costs for electricity and CO_2. The capital recovery factor (α) is determined by formula (2) and is a function of the discount rate (r) and the plant lifetime (n).

$$C_{CO} = \frac{\alpha \times \text{CAPEX} + \text{O\&M} + F}{P_{CO}}, \tag{1}$$

$$\alpha = \frac{r}{1-(1+r)^{-n}}. \tag{2}$$

We here use a typical discount rate (the interest rate to determine the present value of future cash flows) of 10% and a plant lifetime of 25 years. The amount of full load hours (FLH) of the plant directly influences the amount of CO produced (P_{CO}) per unit of capacity. We assume that the operational capacity gradually increases from 2500 FLH per year in 2020 to 7000 FLH in 2050 thanks to a growing share of renewable electricity supply. Besides the availability of renewable electricity supply, the operational capacity also factors in the downtime of the plant due to maintenance and failure.

The use of synthetic fuels may grow to 3 EJ/yr in 2050 according to the IEA [25]. Methanol is one of the key base chemicals and currently nearly 2 EJ/yr (100 $MtCH_3OH$/yr) is produced [26]. The size of the future methanol market is yet uncertain but methanol's versatility, for instance as feedstock to produce fuels, plastics, or fine chemicals, makes it plausible that production volumes will easily have doubled to 4 EJ/yr by 2050 [27]. Efficient conversion of CO_2 into CO may lead to an attractive route to produce carbon-based products such as synthetic fuels and methanol. We here suppose that 25% of total synthetic fuels and methanol production in

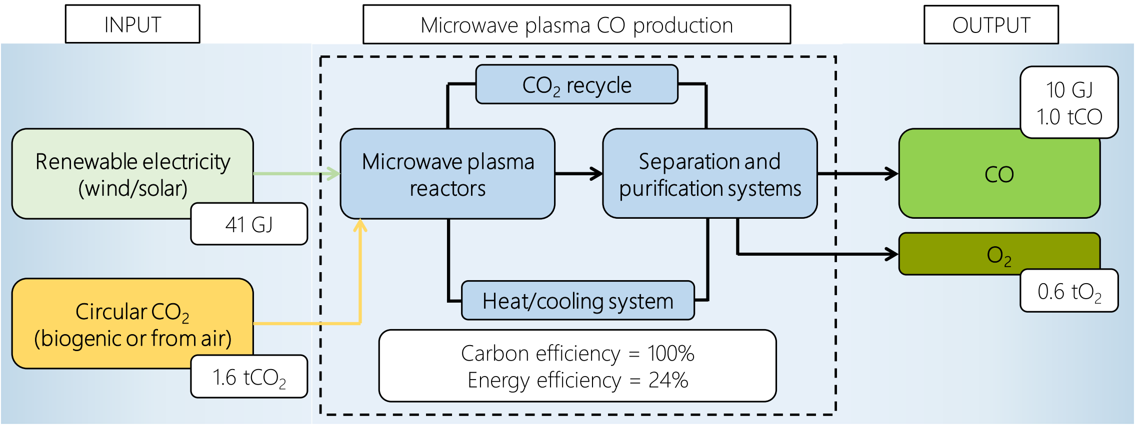

Fig. 1. Schematic representation of a microwave plasma CO production facility with in- and outputs.

Table 1
Main assumptions for the microwave plasma CO production plant.

Parameters	2019	unit
Plant size	20	ktCO/yr
	6.3	MW_{CO}
Plant lifetime	25	years
Microwave generator costs	21	M€(2019)
Other equipment costs (e.g. compressors,	7	M€(2019)
reactors, pumps, coolers, and purification)	20	M€(2019)
Installation costs (design, engineering,	48	M€(2019)
contingency, installation, permits, etc.)		
Total CAPEX		
Discount rate	10	%
O&M	5	%

2050 would use CO from microwave plasma CO_2 conversion as carbon feedstock. Such a production scale would in 2050 demand almost 0.9 EJ or nearly 90 million ton of CO (MtCO), if we assume that the average energy efficiency is around 75% (efficiency losses included) of which 37% of the energy in the synthesis gas (syngas, H_2/CO 2:1 (mol/mol)) comes from CO. To produce nearly 0.9 EJ of CO per year, 35 GW of installed microwave plasma CO production capacity runs for 7000 FLH in 2050 (Table 2).

In this paper we focus on how learning-by-doing may affect the deployment of a novel technology such as microwave plasma CO production. The level of learning-by-doing is often expressed in terms of relative cost reductions as function of cumulative deployment or use of a technology [28,29]. The learning curve indicates that with each doubling of cumulative capacity (X_t), starting from the initial cumulative capacity (X_0), the cost (P_t) of a technology typically decreases by a fixed percentage, called the learning rate (LR), in comparison to the initial price (P_0). A higher learning rate indicates that cost reductions are realized faster, and *vice versa*. The LR can be derived from equations (3) and (4), in which b is a constant known as the learning parameter [30]. Multiplying the annual installed capacity with the specific investment costs in that year provides the annual total investments. To calculate the cumulative investment costs in a specific year, we sum up the annual total investments until that year.

$$P_t = P_0\left(\frac{X_t}{X_0}\right)^{-b}, \tag{3}$$

$$\mathrm{LR} = 1 - 2^{-b}. \tag{4}$$

Our three scenarios only differ by the LR of the microwave plasma CO production process. Other parameters, such as capacity growth, process efficiency, and operational capacity, are kept identical across scenarios. The initial cumulative capacity in 2019 of 6 MW_{CO} (Table 2) corresponds to the first installation of our plant design. The difference in LR can be caused by several factors, but we here correlate it to technology unit size. We apply a low LR (10%) for a scenario in which large microwave plasma reactors (>100 MW unit size) are developed and scaled analogues to conventional large-scale industrial plants. For our base case scenario, we adopt an LR of 15%, which is ascribed to average technology unit sizes between 10 kW and 100 MW [12]. Industrial microwave generators fall within this range [15]. Microwave plasma reactors might also be designed and developed in a highly modular fashion in which every single unit functions at a capacity below 10 kW. Such a small unit size is similar to those of residential microwave ovens. For this reason, we employ for our small unit size scenario an LR of 20%, as has been reported for the microwave oven [16].

Table 2
Scenario assumptions for microwave plasma CO production projections.

Scenario parameters		Unit	2019	2030	2050
Cumulative installed capacity		GW	0.006	0.09	35
Total CAPEX	Small unit size			3150 (LR = 20%)	460 (LR = 20%)
	Average unit size	€(2019)/kW_{CO}	7600	4000 (LR = 15%)	990 (LR = 15%)
	Large unit size			5020 (LR = 10%)	2030 (LR = 10%)
Overall energy efficiency		%	24	29	50
Electricity in		GJ/tCO	41	34	20
Electricity costs		€(2019)/kWh	0.050	0.040	0.025
Operational capacity		FLH	2500	3500	7000
CO_2 in		tCO_2/tCO	1.6	1.6	1.6
CO_2 costs		€(2019)/tCO_2	50	50	50

3. Results

Starting from the initial CAPEX in 2019 of 7600 €(2019)/kW_{CO}, investment costs of microwave plasma CO production are projected from 2020 to 2050 (Fig. 2 and Fig. A1 in the Appendix). Under the same assumptions except for changing the LR from 10 to 15 to 20%, the CAPEX differs in 2050 from 2030 €(2019)/kW_{CO} for large unit size technology to approximately 990 €(2019)/kW_{CO} for average unit size and around 460 €(2019)/kW_{CO} for our small unit size scenario. In the latter scenario, microwave generators have approached the costs of microwave oven tubes that are used in the residential sector, while also the other equipment costs have substantially dropped. Cumulative investments in microwave plasma CO production technology from 2020 to 2050 range from 83 billion €(2019) for large unit size technology to almost 45 billion €(2019) for average unit size and approximately 23 billion €(2019) for our small unit size scenario (Fig. 2, right). In 30 years, a variance of 10% in LR thus leads to more than a factor three difference in necessary cumulative investments to deploy the technology up to the EJ production scale. The first 15 years of development represent only 3%–5% (1.3–2.3 billion €(2019)) of the total cumulative investments required until 2050.

We use formula (1) to calculate the levelized cost of microwave plasma CO production and show the breakdown of the costs for our average unit size scenario (Fig. 3). The production costs decline from around 1900 €(2019)/tCO in 2020 to 247–346 €(2019)/tCO in 2050 (depending on the value of the LR). We assume that electricity costs decline linearly from 0.050 €(2019)/kWh in 2020 to 0.025 €(2019)/kWh in 2050 as a result of an increasing share of relatively cheap renewable electricity supply (green area). Thanks to innovation, for instance by applying more efficient catalysts [31], the energy efficiency of the process improves from initially 24% to 50% in 2050, which further reduces the electricity cost component. The CO_2 feedstock costs remain constant over time as we assume that CO_2 can be supplied for 50 €(2019)/tCO_2 (or 79 €(2019)/tCO). We assume that CO_2 for such a price is acquired from a concentrated biogenic point source, e.g., from bioethanol production [32]. If CO_2 is provided by direct air capture, the production costs likely further increase [33–35], although projections show that under optimistic conditions the 50 €(2019)/tCO_2 target might be reached [36]. Both the electricity and CO_2 cost component remain the same between our scenarios.

The CAPEX component (light blue area) dominates the CO production costs in 2020 but, thanks to learning-by-doing and a higher amount of FLH, it declines significantly towards 2050. That trend is followed by the O&M costs (dark blue area) because those are fixed at 5% of the CAPEX. CAPEX and O&M together represent around 22% of the levelized cost of CO in 2050, which is a three-fold decrease of their relative share in 2020. The dashed lines depict the total levelized cost of CO production for the other two scenarios. In our large unit size scenario (LR = 10%, blue dashed line), the levelized cost of CO production in 2050 is 66 and 100 €(2019)/tCO higher than in, respectively, the average (LR = 15%) and small (LR = 20%, green dashed line) unit size scenarios. Such a difference, induced by a change in learning rate, has a significant impact on the business case for this route to produce CO.

In 2050, electricity has become the major cost component in our average unit size scenario, followed by the CO_2 feedstock costs. These two components together determine 78% of the total production costs. The steepness of the learning curve of the technologies that are involved to supply these two feedstocks (electricity and CO_2) have a profound effect on the levelized cost of CO production by microwave plasma technology. This illustrates that the future competitiveness of CO production routes based on CO_2 conversion powered by electricity highly depends on the consumption (efficiency) and costs of their two main feedstocks. But to realize such a dependence, microwave plasma technology first has to go down its learning curve because until 2032, in our average unit size scenario, CAPEX and O&M together still dominate the levelized cost of CO production. A sensitivity analysis to indicate the influence of the different parameters on the CO production costs in 2050 is presented in the Appendix (Fig. A2). This sensitivity analysis confirms that thanks to learning effects the CAPEX and FLH components have become less influential and the levelized production costs do increasingly rely on the costs of the two feedstocks (electricity and CO_2).

The competitiveness of a new CO production route depends on the future costs of conventional and alternative approaches. Today, methanol is mostly synthesized from syngas obtained through natural gas reforming. We estimate conventional CO production costs somewhere between the market prices of natural gas and methanol after correction for the energy content of CO in the syngas [15]. In 2019, natural gas prices ranged roughly between 2 and 5 €(2019)/GJ [14], while methanol prices varied between 12 and 19 €(2019)/GJ [26]. Based on these data, we determine the conventional CO production costs at around 7–12 €(2019)/GJ or 70–120 €(2019)/tCO. Note that additional purification costs to separate CO from the syngas are not considered. Our projected CO production costs via microwave plasma conversion of 247–346 €(2019)/tCO in 2050 are at least twice as high in comparison to

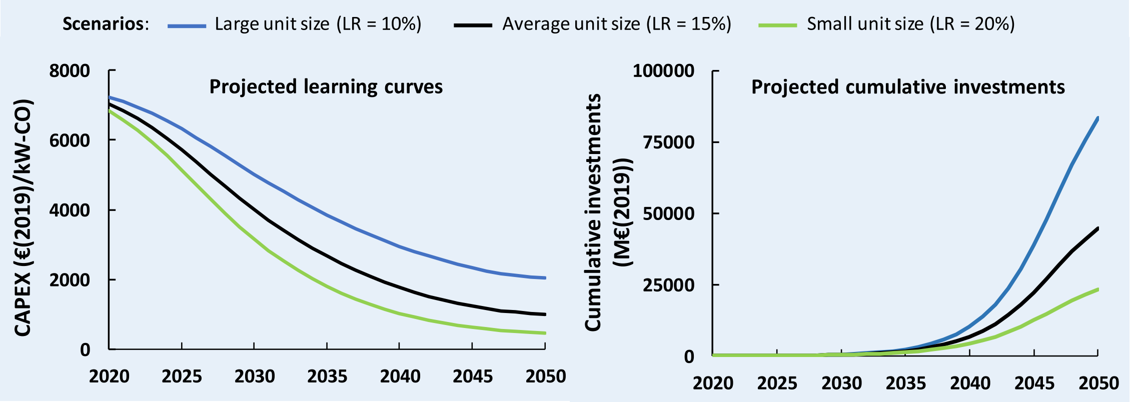

Fig. 2. Three scenarios for microwave plasma CO production technology: learning curves (left) and cumulative investments (right).

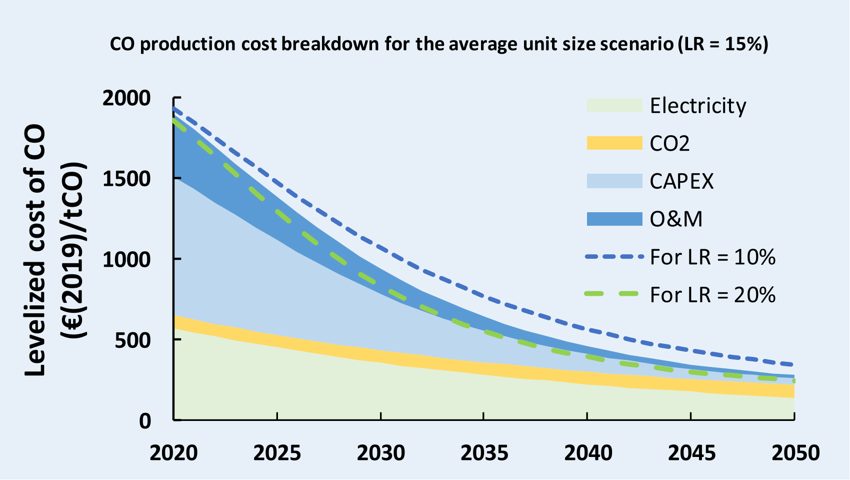

Fig. 3. Projected levelized cost of CO production with microwave plasma technology up to 2050. The breakdown of the costs is illustrated by the colored areas for the average unit size scenario (LR = 15%). The dashed lines (blue for LR = 10%, green for LR = 20%) indicate the CO production costs for the other two scenarios.

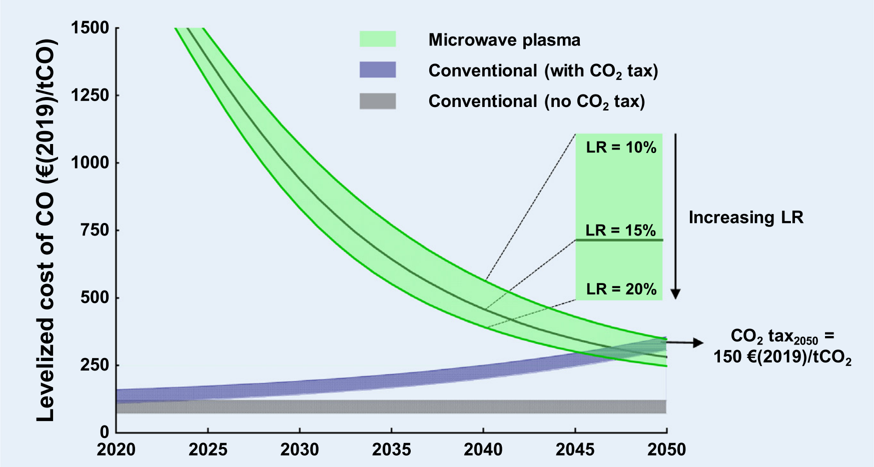

Fig. 4. Learning curve effect on the competitivity of microwave plasma CO production (in green) in comparison to the conventional natural gas-based process (with and without CO_2 taxation, in respectively blue and grey).

the conventional syngas production process (Fig. 4). When fossil fuel prices increase or particular sustainability measures are taken (e.g., CO_2 taxation), the novel route may become competitive.

In our most optimistic scenario, microwave plasma CO production becomes competitive with the conventional natural gas-based process if we apply a CO_2 tax of 110 €(2019)/tCO_2 in 2045 increasing to up to 150 €(2019)/tCO_2 in 2050. This means that CO production costs more than double between now and mid-century. Only if electricity and CO_2 feedstock costs decline more than anticipated in our scenarios, the levelized cost of CO production by microwave plasma technology tends to approach the current production costs via conventional natural gas-based routes. For instance, if electricity costs are 0.01 €(2019)/kWh, CO_2 is supplied for 25 €(2019)/tCO_2, and the LR for microwave plasma CO_2 conversion technology equals 20%, the costs of renewable CO production become close to parity with the high-end of the range of our current reference costs (without CO_2 taxation). The willingness-to-pay for renewable CO might be higher when sustainability incentives allow so, and/or for applications for which the purity (i.e., no mixture with H_2) is important. More extensive analysis would be required to fairly compare microwave plasma CO_2 conversion with alternative routes to produce renewable CO.

4. Discussion and conclusions

A difference in learning rate, e.g., as a consequence of different technology unit sizes, can have a dramatic impact on the total required investments for a technology during scale-up to the exajoule production level. During 30 years of learning-by-doing, the CAPEX of microwave plasma CO production technology may decline from currently around 7600 €(2019)/kW$_{CO}$ down to 460–2030 €(2019)/kW$_{CO}$, depending on the applied learning rate. Cumulative investments in microwave plasma technology until 2050 may vary by a factor three, from 23 billion €(2019) for rapid learning in our small unit size scenario, up to around 83 billion €(2019) for more gradual learning in our large unit size scenario. The early development phase is highly important for the commercialization of new technologies and their deployment scale-up in the years thereafter. Spending a few additional billion euros in the early development phase to finance the parallel exploration of several technologies with different unit sizes may save billions of euros in later stages of deployment if these extra efforts up-front help in selecting the option with the highest learning rate. We thus recommend programmatically developing technologies at different unit sizes to explore how the choice regarding granularity may affect the technology learning rate and thereby future fuel production costs. We project that renewable CO can be produced by microwave plasma technology for 247–346 €(2019)/tCO in 2050. The indicated cost range reflects the effect of the LR on the future improvement of CO production technology. Electricity and CO_2 will likely become the major cost components and we propose that an efficient use of these feedstocks in the conversion process would be one of the main development targets. Also, flexible and robust operation of the microwave plasma generator at similar cost levels as those of residential microwave ovens should be key endeavors. If such a development will be successful, the projected levelized CO production costs become competitive with conventional natural gas-based processes if an additional CO_2 tax is applied of up to 150 €(2019)/tCO_2 in 2050. Such a CO_2 tax may well be reached as projections with integrated assessment models report carbon prices of 200 €/tCO_2 and higher to keep the global temperature rise within limits [37].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

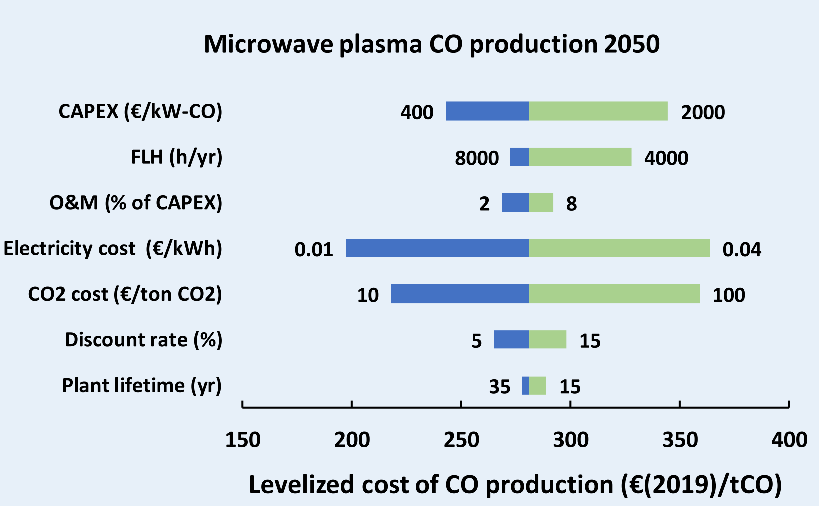

Fig. A2. Sensitivity analysis to indicate the influence of the different parameters on the levelized cost of CO production for 2050.

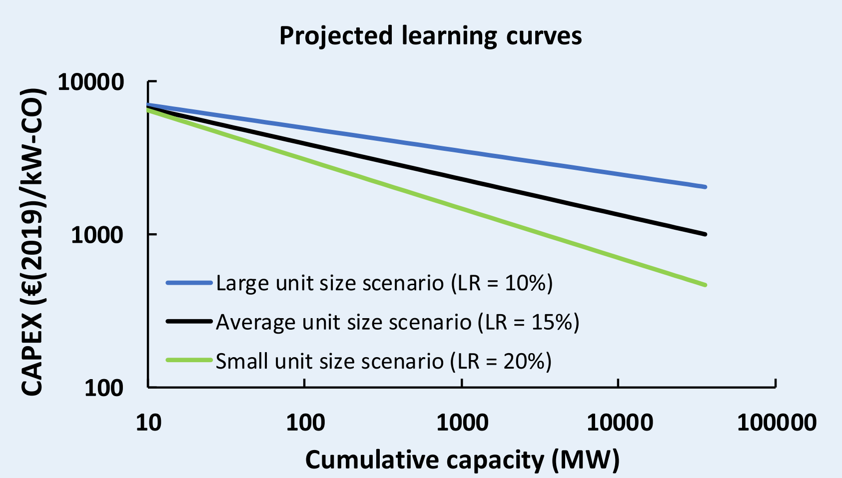

Fig. A1. Three projected learning curve scenarios for microwave plasma investment costs in which CAPEX has been plotted against the cumulative installed capacity on a double logarithmic scale.

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