

INTEGRATING CONCENTRATED SOLAR POWER AND MOLTEN CARBONATE ELECTROLYSIS

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ABSTRACT

Molten Carbonate Electrolysis (MCE) is an innovative technology that allows to produce renewable syngas from steam and carbon dioxide. A new system design is presented, integrating the electrolyzer technology with solar energy. Two separate solar technologies are considered: photovoltaic and concentrated solar power. Due to the peculiarities of MCE technology, both electrical power and heat are used as energy inputs for electrochemical and chemical endothermic reactions. Electricity produced by solar photovoltaic (PV) supplies power to the electrolyzer, while concentrated solar power (CSP) provides high-temperature heat to keep the electrolyzer in operation for an increased number of hours per day, without depending on the power grid supply. The synergy between CSP and MCE is strengthened thanks to molten carbonates, serving as a heat transfer fluid for CSP and electrolytes in the MCE. Preliminary results show how solar-to-syngas efficiency increases up to 22.5% compared to a reference scenario of 18% where the MCE runs solely on PV electricity. Moreover, thanks to the thermal storage function of CSP+molten carbonate, the MCE improves its daily duty cycle up to c.a. 10% in low-solar radiation periods.

1. INTRODUCTION

In this face of escalating environmental challenges and urgent need for sustainable solutions, technologies that address net-zero emissions (NZE) and clean energy play a pivotal role in shaping a greener future. Electrolysis and carbon capture have emerged as promising technologies to reduce climate change, offering innovative pathways to mitigate the impact of greenhouse gas emissions (IEA, 2021). The two technologies are integrated into a carbon closed-loop vision, in which solar energy is used to produce so-called e-fuels. Considering energy applications, there are many sectors where electrical motors and batteries can hardly substitute carbon-based fuels. Typical e-fuel applications are heavy-duty transport and hard-to-abate sectors. E-fuels are non-fossil hydrocarbons that are produced from water, carbon dioxide and renewable energy sources. E-fuel synthesis processes usually consist of i) a reduction phase, where renewable energy is used to pretreat water and carbon dioxide into a platform chemical, and ii) a synthesis phase, where the intermediate platform chemicals are transformed into gaseous or liquid carbon fuels. The overall process allows not only to have renewable fuel but also to store energy from renewable sources, such as solar and wind, that suffer instability and unpredictability. The main e-fuel production process is the so-called Fisher-Tropsch, where water and carbon dioxide are previously reduced, thanks to external renewable energy, into a mixture of hydrogen and carbon monoxide, that is called syngas (Lamprecht, et al. 2010). Historically, the Fisher-Tropsch process was

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based on syngas from coal gasification, with a high carbon footprint. With the development of renewables and relative storage issues, Fisher-Tropsch has become one of the main available technologies to produce e-fuels from renewable syngas (green syngas or e-syngas) (Cinti, et al. 2016). In the literature, syngas production is mainly presented as the separate process of hydrogen production and carbon dioxide reduction, or, in the case of high-temperature electrolyzers, via the CO-electrolysis process (Graves, et al. 2011). In the latter, both H₂ and CO originate from electrochemical reactions. This is possible using high-temperature electrolyzers such as Solid Oxide Electrolyzer (SOE) or Molten Carbonate Electrolyzer (MCE). High-temperature electrolyzers are not only tolerant to carbonaceous compounds, such as CO and CO₂, but due to the presence of catalysts and adequate temperatures, enhance the chemical/electrochemical reduction of CO₂ (see sub-section 2.2). MCE is a key technology, since it is an efficient power-to-gas technology, with the ability to store surplus renewable electricity and deliver tailor-made syngas for further gas-to-liquid synthesis processes. Moreover, like SOEs, MCEs take advantage of the recent development of the fuel cell technologies based on the same electrolyte - namely Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC). Nevertheless, MCE benefits from the bigger size of MCFC (above the MW size) compared with SOFC (facing the 100-kW power challenge) (Wang. 2015).

1.2 Scope of the paper

This paper aims to conduct a preliminary analysis of an innovative concept integrating solar power and MCE, through the utilization of a zero-dimensional energy model. Due to the peculiarities of the two technologies, higher efficiency can be achieved with an accurate coupling. MCEs employ molten salts (carbonates) as high-temperature electrolytic fluid, while the same fluid is familiar to the concentrated solar power technology as one of the most promising options for heat transfer. The introduction of CSP allows to increase solar-to-syngas efficiency from 18% when only PV electricity is used, up to 22.5%. As a drawback, MCE power density is reduced to 100 W m_{MCE}^{-2} .

2. SYSTEM CONFIGURATIONS

The integration of solar energy with syngas production presents a promising approach to sustainable energy production with enhanced efficiency. In thermochemical processes, by using Concentrated Solar Power (CSP) as an external heat source for high-temperature reactions, some advantages may be achieved, such as higher-quality syngas, and reduced fuel gas usage for autothermal reactions, resulting in increased Lower Heating Value of the producer syngas. However, in system design proposed in this paper, syngas production is achieved with an electrochemical reactor calling for both thermal and electrical power supply. Therefore, a hybrid configuration with CSP and photovoltaic panel (PV) is considered to feed the MCE unit.

2.1 Photovoltaic Panels (PV)

PV has shown a great impact in the transition towards green energy solutions and electrification. Advances in technology have elevated the efficiency of modern solar cells, with top-tier PV systems achieving solar-to-power conversion rates exceeding 20% (*Solarreviews, 2024*). However, excluding rooftop applications, their main drawback compared to other power generation systems, is related to land-use. It is estimated that the PV technology land-use intensity (direct/indirect land footprint vs. Energy generated in one year) is on average 184 m²/kWe (*Lovering, et al. 2022*) and shows a strong dependence on the latitude (*Martin Chivelet, 2016*).

2.2 Concentrated solar power (CSP)

A CSP system normally consists of a few fundamental elements: solar collectors (mirrors, heliostats), heat receivers, a working fluid for heat transfer and heat exchangers to deliver heat to the energy users. CSP collectors are categorized according to the technology used to concentrate solar light: parabolic troughs (presently the most adopted), parabolic dish systems, flat-plate heliostats and Fresnel reflectors.

Then, the receiver plays a crucial role, serving as the point where concentrated solar energy is absorbed, leading to a significant increase in temperature. In parabolic trough systems, the receiver is located at the focal line of the parabolic-shaped mirrors and consists of a tube containing the heat transfer fluid. Typically, this system operates at 300°C to 550°C. In Solar Power Tower systems, the receiver is installed at the top of a tower, where the absorbed solar energy is transferred to the thermal fluid reaching even above 700°C. In parabolic dish systems, the receiver is placed into the dish focal point, usually containing a heat engine. These systems normally operate in the range 700-1500°C. CSP efficiency¹ (fraction of the solar energy transferred to the thermal fluid in the receiver) is in the range 60-70% for parabolic troughs (Ech & Steinmann, 2005), 70-90% for flat-plate collectors (Newheat). However, it rapidly decreases with the collector temperature increase and for decreasing direct normal irradiation (Yousef, et al 2023). From the point of view of land use, CSP shows an average intensity of 175 m² kWe⁻¹ (Lovering, et al. 2022), corresponding, considering the thermodynamic cycle efficiency of 28.5%, to 50 m² kWth⁻¹ net thermal power at the receiver (Marzouk 2022). The land use intensity index is calculated on the average power produced per year. In a CSP plant, a heat transfer (HT) fluid travels through the receiver, to absorb heat from concentrated solar radiation. The following features should be checked to identify a good HT fluid: low melting point, high boiling point and low vapour pressure at high temperature (to prevent early vapour phase formation and increased efficiency in heat transfer), thermal- and photo-stability, good thermal conductivity, low viscosity and compatibility with the other materials in the systems, low corrosion with metal alloys, as well as low environmental concerns and cheap price. Examples of common working fluids are thermal oil (0-400°C), molten salts (50-600°C K-Na-Li nitrates and nitrites), solar salts (200-800°C for Na-K-Zn) carbonates (400-800°C for Li-Na-K carbonates and fluorides/carbonates), and liquid metals (0-800°C for liquid Na-K, up to 1500°C for liquid Pb-Bi) (Vignarooban, et al.2015), but also air, water/steam and other gases (like N₂ and CO2) (Pacio & Wetzel. 2013). To the end of the current investigation, molten carbonate salts deserve special attention. The Li-Na-K carbonate is a ternary eutectic mixture (32.1% ti₂CO₃, 33.4% ti₂C Na₂CO₃, and 34.5%_{wt} K₂CO₃) proposed to replace nitrate salts for improved thermal stability (Wu, et al. 2011), viscosity like standard solar salts, and excellent performances regarding the corrosion risk (Wang, et al 2023). Under various atmospheres, the Li-Na-K carbonate shows little variation of its melting point (400-405°C). However, while decomposition temperatures usually fall in the range 800-850°C, significant changes in decomposition temperature depend on the gas atmosphere, i.e. 1000, 700, 670°C with CO₂, Ar, and air respectively (*Olivares, et al. 2012*).

2.3 Molten Carbonate electrolysis

High-temperature electrolyzer cells present the most effective option for producing hydrogen and syngas in stationary settings. Due to the peculiarities of the reactions and of the materials composing the cells, syngas can be produced via electrochemical reactions from steam and carbon dioxide. High temperatures Molten Carbonate Electrolyzers (MCE) operate in the range 600-700°C. In MCEs, the negative electrode, called fuel electrode (FE), is made of porous Ni combined with Cr and/or Al, and the positive electrode, called oxygen electrode (OE), comprises porous lithiated-Ni. The electrolyte employed in MCEs is a eutectic mixture of Li, K, and/or Na carbonates, maintaining a liquid form throughout operation due to the elevated operating temperature (*Sheikh, et al. 2024*). Fig. 1 reports a scheme of an MCE, where in the FE the reduction of steam and carbon dioxide, reactions (1) and (2) respectively, takes place, and in the OE reaction (3) occurs.

The overall reactions depicting H_2O and CO_2 evolution into fuel species are shown in (4) and (5) respectively. CO_2 has two main roles in the reaction: CO_2 is one of the reactants that is reduced into CO, and it is the necessary molecule for the formation of the carbonates (CO_3^{2-}) at the FE and released at the OE (Fig. 1). When operating, the MCE produces carbon monoxide and hydrogen, thus in the FE, due to the operating temperature and the Ni catalyst, also the Water Gas Shift (WGS), reaction (6), as to be considered to determine the final composition of the syngas produced.

¹ Data are referred to standard conditions, namely 20°C and global solar irradiation 1000 W/m².

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$$H_2O + CO_2 + 2e^- \rightarrow CO_3^{2-} + H_2$$
 (1)

$$2\mathrm{CO}_2 + 2\mathrm{e}^- \to \mathrm{CO}_3^{2-} + \mathrm{CO} \tag{2}$$

$$CO_3^{2-} \to CO_2 + \frac{1}{2}O_2 + 2e^-$$
 (3)

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{4}$$

$$CO_2 \rightarrow CO^+ \frac{1}{2} O_2 \tag{5}$$

$$CO_2 + H_2 \leftrightarrow H_2O + CO$$
 (6)

Depending on the concentration of reactants WGS or reverse WGS can take place and, consequently, increase or reduce the conversion of the inlet reactants (CO_2 and H_2O) with an impact on the energy equilibrium of the electrolyzer (Murmura, et al. 2023) and the syngas composition. The energy balance of the MCE is described by Eq. (7), where ΔO is the heat exchanged with the external, P is the inlet electrical power, and hout and hin are the outlet and inlet enthalpy flows of the outlet and inlet gas streams respectively. Such enthalpy flows are related to the thermodynamic conditions (mainly pressure and temperature), and the composition of inlet and outlet fluids. The outlet gas composition depends on both the chemical and electrochemical equilibrium. Inlet electrical power is defined as in Eq. (8), where A is the MCE total active area, V is the operating voltage and J is the operating current density. Merging the two equations it is possible to calculate the operating voltage V, Eq. (9). The MCE efficiency is defined as the ratio between the chemical energy of syngas and the electrical power inlet and defined by Eq. (10). Similarly to chemical reactors, the heat flows strongly impact the values of efficiency. In the case of heat losses ($\Delta Q > 0$), energy efficiency is reduced. In the case of adiabatic operation ($\Delta Q = 0$), the system operates in the so-called thermoneutral condition. Generally, thermoneutral voltage depends on various parameters: it decreases by increasing the pressure and by decreasing the temperature, the reactant utilization, and the hydrogen-to-carbon ratio (Perez-Trujillo, et al. 2020). Molten carbonate electrolyzers, like all high-temperature electrolyzers, can operate considering inlet heat flow from the external ($\Delta Q < 0$), improving efficiency and reaching the highest performances (*O'Brien, et al. 2010*). The main drawback is related to the lower power densities and, as a result, a larger system size. The power density (p) is calculated as in Eq. (11).



Figure 1: Operating scheme of an MCE cell.

The impact of the heat contribution in the MCE equilibrium is depicted in Fig.2 where the voltage and power density of a cell operating at 650°C are derived from the literature (*Perez-Trujillo*, et al. 2018). The figure reports also two voltage values, thermoneutral voltages V_{xtn} , defined in Eq. (12), where F is Faraday constant, subscript x is the reacting species, CO₂ and H₂O, and Δh_n is the relative enthalpy balance of reduction reactions - see reactions at (1) and (3). Thermoneutral voltage is the value of voltage that realizes the condition ΔQ =0. The definition in Eq. (13) can be easily derived from Eq. (8) and Eq. (10) and from the relation between current density and syngas flow rate. The graph in Fig. 2 is

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separated into three parts. For cell voltage values higher than V_{tnCO2} , the MCE operates in exothermic conditions ($\Delta Q>0$) and heat must be removed from the cell. For voltage lower than the smaller V_{tnH2O} , the cell operates in endothermic conditions ($\Delta Q<0$). Fig. 2 reports also a transition phase between the two thermoneutral voltages that is strongly related to the equilibrium of the WGS. In conclusion, the cell can operate at higher efficiencies ($\Delta Q<0$) at power density values in the range 0-2000 W m_{MCE}⁻².

$$\Delta Q + P + h_{out} - h_{in} = 0 \tag{7}$$

$$P = A \cdot V \cdot J \tag{8}$$

$$V = \frac{\Delta Q + h_{out} - h_{in}}{A \cdot I} \tag{9}$$

$$\eta = \frac{n_{syn} \cdot LHV_{syn}}{P} = \frac{n_{syn} \cdot LHV_{syn}}{\Delta Q + h_{out} - h_{in}}$$
(10)

$$p = V \cdot J = \frac{\Delta Q + h_{out} - h_{in}}{A} \tag{11}$$

$$V_{xtn} = \frac{\Delta h_x}{2 \cdot F} \tag{12}$$

$$n_{syn} = \frac{A \cdot J}{2 \cdot F} \tag{13}$$



Figure 2: Power density and voltage of MCE vs. current density (Perez-Trujillo, et al. 2018).

2.3 CSP coupling with synthesis reactors: towards the New Concept

The literature reports on different configurations for the coupling of CSP and thermochemical reactors, as widely reported concerning gasification and pyrolysis processes. The main integration approaches involve the installation of the reactor at the solar receiver place (*Abanades, et al. 2021*). However, this may encounter limitations when scaling up the concept above lab and pilot-scale facilities. Moreover, to have a constant renewable heat supply notwithstanding the intermittency of solar power, thermal energy storage is required. For instance, viable solution may involve thermal storage with molten salts

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(*Bellouard, et al. 2020*) or thermal storage through fluidization sand (*Yakan & Patel, 2023*) in fluidized and circulating reaction beds. A few works report about the integration of CSP and MCE, using the MCE as a rechargeable battery which store electricity and delivers syngas (*Xue, et al, 2022*). Given the features presented for the two technologies, it appears very promising to use the molten carbonates both as electrolytic fluid for the MCE and for HT/storage medium to drive solar thermal power from the CSP receiver to the user (the MCE itself). Therefore, the innovative system design for the syngas production is reported in Fig. 3. The design proposes the integration of the MCE with solar energy. In detail, two different solar technologies are considered: (i) photovoltaic for renewable electricity production and (ii) concentrated solar power to supply heat to the system.



Figure 3: Conceptual scheme of the innovative plant proposed.

The overall concept can be classified as a solar-to-syngas system, where steam and CO_2 are the reactant feedstocks. Heat is supplied to the MCE using carbonates as heat transfer fluids. The innovation proposed is the use of the same carbonates as heat transfer fluid and electrolyte of MCE. This solution improves the integration of the two technologies obtaining an optimal heat supply to the MCE (directly inside the electrochemical reactor). Moreover, the use of a heat transfer fluid allows to consider also heat storage solutions improving the integration of the system with the non-predictable and non-continuous energy source. Nonetheless, the new system poses also important challenges, namely the fact that carbonates, the electrolyte, are supplied at high temperatures to the MCE and subtracted at lower temperatures. This results in an open layout configuration for the electrolyte in the electrolyzer. Such a solution is not available today, but literature reports of laboratory experiences where carbonate salts are regularly added to the cell during operation (in that case to refill carbonates eutectic) (*Perez-Trujillo, et al. 2018*), (*Hu, et al., 2016*). The operando electrolyte refill in MCE is currently a topic under investigation and can be pursued with various approaches (*Kim, et al., 2023*). The green syngas production is a combination of four subsystems and their integration:

- PV converts solar energy into electrical power, used as power input for the MCE. Performances are well known, while power production is constrained by daylight hours and weather conditions, presenting a challenge for the integration in the system (unless electric energy storage is implemented);
- CSP usually operates with a different kind of fluids and needs to be adapted to this specific configuration and the operating temperatures (600-700°C); it provides thermal power to the MCE to fill the electrolysis requirements when thermoneutral conditions are not reached.
- Heat transfer is the core technology and innovative application for the system. The selected fluid acts also as heat storage and supports the integration with the solar source;
- MCE is the technology where syngas production takes place. Operating conditions such as temperature, current density and gas flows strongly impact the performance.

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Based on the final use, the syngas may require additional treatment. The main products, H_2 and CO, are mixed with carbon dioxide and steam. Steam and CO₂ can be separated with upgrading technologies (e.g. condensation and pressure swing absorption) and recirculated into the system. Due to the electrochemical reactions of MCE, CO₂ is also produced at the OE and, depending on the selected strategy (*Barelli, et al., 2021*) can be separated and recirculated.

3 NOVEL CONCEPT ENERGY EVALUATION

3.1 Simulation framework

The system is preliminarily studied with an energy balance analysis implemented in a commercial calculation sheet. For the study, some technical parameters are a-priori assumed as reported in Table 1. The thermoneutral voltage is defined as the average between the two values V_{tnCO2} and V_{tnH2O} . This is an approximation since a specific thermodynamic model is not implemented. Current density (j) varies between two values, 100 and 1000 A m_{MCE}^{-2} . The j-V correlation (polarization curve) is derived from literature as for Fig. 2. Regarding energy efficiencies, 18%, and 90% were considered for the PV and HT respectively, while for CSP three values of efficiency were considered: 70%, 75% and 80% *(Marzouk 2023), (Newheat)*.

 Table 1. Model specifications

Parameter	Unit	Value	
Thermoneutral voltage – V _{tn_syn}	V	1.37	
Current density – J	A m_{MCE}^{-2}	100 - 1000	
PV efficiency (solar-to-electrical power)		0.18	
CSP thermal efficiency (solar-to-gross thermal power)		0.7 - 0.75 - 0.8	
Heat transfer efficiency		0.9	

3.2 Results: MCE performance

The initial findings of the system analysis are reported in Fig. 4: on the left side, the plot shows the *heat ratio* versus the MCE power density. The *heat ratio* (HR) is defined as in Eq. (14).

$$HR = \frac{\Delta Q}{h_{out} - h_{in}} \tag{14}$$

HR decreases when power density increases. For lower values of power density, the system reaches up to 27%. This means that 27% of the produced chemical energy can be supplied in the form of heat from the CSP unit. The leftover is supplied as electrical power by the PV unit. When HR is zero (p=1370 W m_{MCE}^2), the MCE operates at thermoneutral conditions, and all the inlet energy comes from the PV in the form of electrical power supply. The ratio between heat duty and electrical power strongly impacts the system efficiency. Since the CSP overall solar-to-net heat efficiency is much more efficient, compared to the solar-to-power efficiency, the higher the HR is, the higher is the system efficiency is reported for the three values of CSP efficiencies studied. As expected overall efficiency is obtained at higher values of CSP efficiency and lower power densities. Vice versa, at thermoneutral condition, the system efficiency reaches the minimum value of 18%, equivalent to the sole performance of PV. Likewise all electrolyzer technologies, the main drawback of reaching higher efficiencies is the reduction of power density.

To reach higher efficiency lower power densities are required and, consequently the extensive installed power of the system increases, and relative capital costs. Deeper evaluations and detailed models are necessary to consider the impact of balance of plant components both on efficiencies and costs. To have a complete outlook at system level, a preliminary evaluation was performed on the size in terms of power and surface of the PV and CSP units.

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Figure 4: Results: (left) Heat ratio and (right) Efficiency vs. MCE power density.

3.2 Results: outlook on green syngas synthesis

Based on the performance curves shown in Fig.4, an outlook on power profiles is here presented, considering the solar radiation of Rhodes (Greece, latitude 36°N). Geo-referenced solar radiation data are retrieved from the PV GIS tool (*PVGIS, JRC*). Rhodes is an example of a mid-latitude spot, exhibiting an average yearly PV potential of around 1700 kWh/kWp. The climate shows moderate seasonality, with 180 kWh/kWp (summer) in July and 98 kWh/kWp in December (winter).

The outlook here presented considers a 1 MW-nameplate power MCE, composed of two 500 kW modules. The MCE runs exclusively on renewable power, from the PV and the CSP. Neither electrical storage, nor grid supply are considered in the following profiles because this analysis aims at highlighting the independence degree of the proposed system.

Therefore, considering a PV plant of 1,4 MW peak power and the HR-power density curves from Fig.4, three typical operative days are modelled, regarding Spring/Fall (modelled on the March solar profile), Summer (modelled on the July solar profile) and Winter (modelled on the December solar profile). Table 2 reports the daily producibility of the PV (E_{PV}), the share of PV energy fed to the MCE on a daily basis (E_{elMCE}), and the heat duty requirement (ΔQ) to assure operation at full load within the constraints discussed in the previous section. The thermal solar plant appears as an auxiliary system, having a greater impact on syngas productivity when the solar radiation is lower. As Table 2 shows, the gain in winter months approaches 10%. The energy balance values in Table 2 are completed by daily profiles shown in Fig.5, where the normalized power of PV, MCE and CSP are plotted against a period of 24 hours (normalization basis: MCE nameplate power).

winter at Knodes latitudes.				
		Spring/Autumn	Summer	Winter
E _{PV}	MWh _e /day	7548	10262	5225
E _{elMCE}	MWhe/day	6668	78606	4079
ΔQ	MWh _{th} /day	332	140	421
Gain	%	4.7%	1.7%	9.4%

 Table 2. MCE energy balance: full load hours in three typical days in Spring/Fall, Summer and

 Winter at Rhodes latitudes

Considering the winter season as a design parameter to determine the size of the CSP system (since it reveals the maximum heat duty to counterbalance electricity supply), a solar collector field with a 0,08-ha surface would be required in addition to a 2-ha PV plant.

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Figure 5: Daily operation simulation according to solar radiation profiles registered in Rhodes (Greece) in Spring/Fall, Summer, and Winter.

This study has not considered intra-day weather variability yet, which may further highlight the impact of thermal storage to pursue the MCE operation strategy presented in Fig.4. Therefore, the use of an auxiliary CSP system with thermal storage achieved through the MCE molten salts shows a promising outlook for future detailed investigation.

4 CONCLUSIONS

This paper presents a new concept to produce green syngas, based on the integration of solar renewable power and molten carbonate electrolyzer. The solar power is collected via two separate systems, namely photovoltaic panels, and concentrated solar power for heat generation. Heat is supplied to the MCE taking advantage of the electrolyte material (a eutectic mixture of carbonate salts) that can be also used as heat transfer fluid. As a result, the heat allows to improve MCE efficiency reducing the power density. With the new system, green syngas production increases from an overall efficiency solar to syngas of 18% and power density of 1370 W m_{MCE}^2 to a value of 22.5% for a power density of 100 W m_{MCE}^2 . Moreover, considering possible implementation strategies, it appears that a small CSP system can improve green syngas productivity especially in months of low solar radiation when the PV alone has a lower electricity output. From simulation profiles, it can be concluded that a syngas production gains up to 9.4% in the face of just 4% increase in land use intensity. This result is obtained under prudent assumption, which does not consider the positive effect of thermal storage in case of weather variability and moderate integration of electricity supply from the power grid. Deeper studies are

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necessary to evaluate a complete analysis of the design strategies and the impact of the new concept on the cost of the system using the levelized cost of syngas methodology.

NOMENCLATURE

А	Active Area	(m_{MCE}^2)
CSP	Concentrated Solar Power	
E	Energy	
F	Faraday constant	$(C \text{ mol}^{-1})$
FE	Fuel Electrode	
HR	Heat Ratio	(%)
HT	Heat Transfer	
J	Current density	(A m _{MCE} ⁻²)
MCE	Molten Carbonate Electrolyzers	
MCFC	Molten Carbonate Fuel Cells	
OE	Oxygen Electrode	
р	power density	$(W m_{MCE}^{-2})$
Р	Power	(W)
PV	Photovoltaic Panels	
Q	Heat	(W)
SOE	Solid Oxid Electrolyzer	
SOFC	Solid Oxide Fuel Cells	
V	Volage	(V)
WGS	Water Gas Shift	

Subscript

el	electrical
р	peak
syn	syngas
th	thermal
х	reaction

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