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# Electrical Energy Conversion for Low Temperature Electrolysis - Challenges and Future Trends

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Abstract—Low temperature electrolysis brings the possibility of achieving the production of fuels and chemical feedstocks without any carbon footprint. Power electronic converters are vital components of future electrolyser systems in terms of overall cost and efficiency. This paper presents the current state of art in power electronics for low temperature electrolysis and all the major steps of designing an electrolysis system are discussed from the modeling of electrolysers to the system architecture. The most promising routes are pointed out and backed up with results from both experimental and theoretical studies found in the literature.

Index Terms—Renewable energy, electrolysis, solar fuel, modeling, power electronics

# I. INTRODUCTION

The target on which the energetic industry is basing its development in the coming years has two main opposing aspects: on one hand there is the promise of energy for all mankind considering the disparity that almost one billion people still lack access to electricity [1], and on the other hand there is the dire need to reduce emissions which contribute to the global warming effect, leading to breathing-related illnesses, loss of flora and fauna to name a few. The commonly agreed upon solution is a transition away from fossil fuel based production towards renewable, carbon-neutral or even carbon-negative technologies. Water vapor is the most potent greenhouse gas, but its concentration in the atmosphere is mainly determined by temperature and is out of human control. It is also shortlived with only nine days of residence in the atmosphere [2] so the focus of the energy transition for a sustainable future is directed towards the reduction of CO2 emissions. Other greenhouse gasses exist, but due to the fact that carbon dioxide represents three-quarters of the total greenhouse gas emissions [3], it has almost all the attention of the energy transition initiatives.

The main driver of reducing  $CO_2$  emissions is the renewable electric energy, however there are limitations in the extent of penetration within the energy sector. A need for energy-dense fuels, chemicals and other carbon-based materials will still exist and further increase in the future so a solution for closing the carbon loop has to be implemented. One important link of the loop is the conversion of  $CO_2$  into useful products, which can be done in two ways:

- The indirect route (CO<sub>2</sub> is not directly converted using electricity)
- The direct route (CO<sub>2</sub> is directly converted through electrolysis)

Many established  $CO_2$  conversion processes also require hydrogen. Hydrogen can be obtained by the decomposition of water through electrolysis, as described by (1):

$$2 H_2O(l) \rightarrow 2 H_2(g) + O_2(g).$$
 (1)

Considerable effort and advancements have been made to efficiently obtain  $H_2$  from wind, solar or other renewable electrical energy source. Industrial solutions for MW scale are available [4] and state-of-the-art proton exchange membrane (PEM) technologies yield efficiencies of around 70% [5].

The indirect route involves the use of a carbon source molecule which is converted through processes other than direct conversion using electricity. The greatest example is the century-old process first reported by Sabatier in 1902 [6] that can be used for the sustainable production of methane, described by (2).

$$\mathrm{CO}_2 + 4 \operatorname{H}_2 \to \mathrm{CH}_4 + 2 \operatorname{H}_2\mathrm{O}.$$
 (2)

The  $CO_2$  methanation process is particularly attractive due to  $CH_4$  selectivity of up to 99%.

The direct route involves the electrochemical reduction of carbon dioxide, also known as CO2 electrolysis to convert  $CO_2$  into chemicals and fuels. This is an attractive route for the renewable production of base chemicals because CO2 electrolysis allows for the production of several various substances like carbon monoxide, formic acid, formaldehyde, methanol, methane, ethanol or ethylene. The CO2 reduction reaction potential is in the same range as that for hydrogen evolution reaction (HER) so the two reactions are usually in competition and it ultimately leads to low faradaic efficiency [7]. It was discovered in 1985 that copper (Cu) has the ability to electrochemically reduce CO2 to hydrocarbons like methane and ethylene with relatively good faradaic efficiencies, appointing Cu as good catalyst for  $CO_2$  electrolysis. The direct route asks for the study of electrochemical reactions which may turn out to be more efficient than well-established multi-step reactions,

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but generally the mechanistic pathways are more complicated and hard to discover, as the work of Kortlever et al. shows [8].

Attention is rightfully directed towards up-scaling the processes of converting the biggest contributor to global warming,  $CO_2$ , into an energy-dense fuel which is compatible with the existing energetic infrastructure. It is the aim of this study to show the power electronics design challenges associated with up-scaling existing and forthcoming electrolysers.

This paper is organised as follows: in Section II, an application example of a solar fuel production plant and its operation is discussed. Section III introduces a typical thermodynamic model for low-temperature water electrolysis and describes how different inter-connection architectures of electrolysis cells influence the overall system. Furthermore, a literature review of inter-connection methods for renewable systems is presented. Section IV enumerates the power supply types suitable for electrolysis with performance indicators for each. The paper is concluded in Section V.

# II. ELECTROCHEMICAL PLANT

As an application example, the system proposed by Smith et al. is considered [9]. It is capable of producing methanol taking in only atmospheric air, water and electricity generated by photovoltaic (PV) panels with a grid connection being here provided only as back-up. Neglecting the electrical energy production, there are four main processing steps towards the production of green methanol: first, atmospheric air capture, which is estimated to require 13 kJ/mol CO<sub>2</sub> for state of the art technology [10]; in this case a KOH aqueous solution is used to catch the  $CO_2$  molecules which is then regenerated in a bipolar membrane electrodialysis (BPMED) step requiring 215 kJ/mol  $CO_2$  so that the capture solvent can be recycled. The third step of the process involves the splitting of water into  $H_2$  and  $O_2$  and the electrochemical reduction of  $CO_2$ giving CO and O<sub>2</sub>, both being very energy-demanding with 816 kJ per equivalent mol of  $CO_2$  for the  $H_2O$  electrolysis considering the 2:1 ratio of  $H_2$  to CO required to produce methanol, and 404.3 kJ/mol of  $CO_2$  for the  $CO_2$  electrolysis.



Fig. 1. Schematic of a methanol electrochemical plant for the production of over  $340 \, \text{kg}$  of methanol per day assuming a 12 hours daily operation.

These values are obtained from the theoretical energy required for the reactions assuming a 70% efficiency of the electrolyser itself both in the case of water and  $CO_2$ . The final step of the process is a standard methanol synthesis process which requires no considerable electrical energy consumption. The described plant schematic can be seen in Fig. 1 and it can produce over 340 kg of methanol/day assuming a daily continuous operation of 12 hours. For this application isolated DC-DC converters are used to efficiently adapt and deliver the energy generated by the solar panels to the electrolysers, which is intrinsically DC. The plant is assumed to have a battery energy storage system (BESS), which is capable of providing constant power to the electrolysers. In order to keep the costs of research and development of such a system low, each major building block of the system can be replaced with a hardware-in-the-loop (HIL) emulator that has the same electrical characteristics as the real device [11], [12].

# III. ELECTRICAL CONVERSION

The electrical power supply is responsible for the power conditioning and is one of the vital components of any electrolyser owing to the following reasons: firstly, its defining purpose is to convert the electrical input which can be a traditional AC grid connection or a renewable energy source to a useful form for the electrolysis process, namely DC with the appropriate voltage and current capabilities; secondly, it is one of the notable constituents of the overall system capital expenditure (CAPEX), with a fraction of about 15% [13]; thirdly, it provides means of controlling the electrical power quality at the electrolyser level which can influence the overall system efficiency and fourthly, its electrical conversion efficiency plays a role in the price of the final product on the grounds that the cost of electricity is most influential, in the case of hydrogen electrolysis it is responsible for 70-90% of the total operating costs [14].

#### A. Electrolyser model

When considering a large scale electrolyser system, it is compulsory to consider the electrical characteristics of a single electrolyser cell for determining the restrictions set by the load on the power supply. In the case of water electrolysis, the reaction described by (1), there are three main types of electrolysers: alkaline water electrolsers in which the electrochemical reaction occurs in an aqueous electrolyte which usually contains KOH at about 30 wt% and the recombination of  $H_2$  and  $O_2$  is stopped by an ion-exchange membrane; proton exchange membrane electrolysers (PEMEC) in which the electrodes are separated by a proton conductive membrane and the high-temperature solid oxide electrolysers (SOEC), in which the electrolyte used is a solid oxide or ceramic and is usually more economic to run due to the fact that part of the energy supplied is in the form of heat that is cheaper than electricity. Electrical models have been developed for all these types of electrolysers, the most researched being the alkaline [15]–[19] as a result of it being the most mature technology, followed by the PEMEC [20]-[22] and SOEC.

For an electrochemical reaction to take place, heat and voltage have to be applied to the electrolytic cell, the minimum electric voltage is given by [21]:

$$U_{\rm rev} = \frac{\Delta G}{z F},\tag{3}$$

where z is the number of moles of electrons transferred for one mol of product (z = 2 for  $H_2$ ), F is the Faraday constant (96 485 C mol<sup>-1</sup>) and  $\Delta G$  is the Gibbs free energy which is given by:

$$\Delta \mathbf{G} = \Delta \mathbf{H} - T \,\Delta \mathbf{S},\tag{4}$$

where  $\Delta H$  is the enthalpy change, T is the absolute temperature and  $\Delta S$  is the entropy change. In the case of water splitting, at standard pressure and temperature (101.325 kPa and 298.15 K), the reversible voltage is  $U_{rev} = 1.229$  V. On the other hand, if the heat required for the electrochemical process is provided also by means of electricity, which is the case of PEM and alkaline electrolysers, then this thermal energy  $T \Delta S$ shall be included in the minimum voltage calculation, bringing forth the notion of thermoneutral voltage. In the case of water splitting,  $U_{tn} = 1.481$  V:

$$U_{\rm tn} = \frac{\Delta H}{z F}.$$
 (5)

The voltage of an electrolytic cell supplied with a current for electrolysis is given by:

$$U_{\rm cell} = U_{\rm rev} + U_{\rm ohm} + U_{\rm act},\tag{6}$$

where  $U_{\rm rev}$  is the reversible voltage,  $U_{\rm ohm}$  is a purely resistive voltage caused by ohmic losses within the cell,  $U_{\rm act}$  is the activation voltage caused by electrode kinetics and it has a logarithmic dependency of the cell current [15]. These are commonly named overpotentials in literature on the grounds that they are an addition to the ideal reversible voltage and contribute to a lower efficiency of the cell.

The equivalent electric model of an electrolytic cell is presented in Fig. 2, where the activation overpotential is divided in two parts, one for the anode  $U_{\rm act,a}$ , and one for the cathode  $U_{\rm act,c}$ . This is explained by the physical structure of electrolyser cells, which have one anode and one cathode, and by the different activity rate at each of the two electrodes. The capacitors model the effect of the double-layer formation at the boundary between the electrolyte and the anode/cathode.



Fig. 2. Electrical model of a water electrolyser



Fig. 3. Qualitative I-V curve of a water electrolyser, adapted from [15]

During steady state the capacitors behave as open circuit and only the parallel current sources have an influence in the cell [17]. The voltage across them is given by (7) and (8):

$$U_{\rm act,a} = s \, \ln\left(\frac{1}{t} \, i_{\rm act,a} + 1\right),\tag{7}$$

$$U_{
m act,c} = v \, \ln\left(rac{1}{w} \, i_{
m act,c} + 1
ight),$$
(8)

where s, t, v and w are temperature dependent parameters. The temperature dependency of these parameters and that of the ohmic resistance is quadratic [15]:

$$s(T) = s_1 + s_2 T + s_3 T^2, \ t(T) = t_1 + t_2 T + t_3 T^2,$$
 (9)

$$v(T) = v_1 + v_2 T + v_3 T^2, w(T) = w_1 + w_2 T + w_3 T^2,$$
 (10)

$$r(T) = r_1 + r_2 T + \frac{r_3}{T} + \frac{r_4}{T^2},$$
 (11)

where T is the electrolyser temperature, and the parasitic resistance in Fig. 2 is given by  $R_{\rm ohm} = \frac{r}{A}$ ; A is the cell area.

It is important to note that in the dynamic behavior of the cell, the  $i_{Cdl,a}$ ,  $i_{Cdl,c}$  currents do not participate in the hydrogen and oxygen production.

In Fig. 3 the qualitative behavior of an electrolyser cell can be observed, where at a higher temperature temp 2 > temp 1 a decrease in voltage can be observed which also leads to a decrease in power consumption. The parameter values are obtained from literature and correspond to an alkaline water electrolyser [15]. This behavior is due to the increased reaction activity and the increased electrolyte conductivity [19].

If all the supplied energy is in the form of electrical energy, which is the case for alkaline and PEM water electrolysers (usually not the case of SOEC), then the specific energy consumption  $E_s$  of an electrolyser can be defined as:

$$E_{\rm s} = \frac{\int_0^t I_{\rm E} U_{\rm E} \,\mathrm{d}t}{\int_0^t f_{\rm H_2} \,\mathrm{d}t},\tag{12}$$

where  $I_{\rm E}$ ,  $U_{\rm E}$  and  $f_{\rm H_2}$  represent the electrolyser current, voltage and production rate, respectively.

The *energy efficiency* of the electrolysis process, taking into account all the above described losses, can be calculated with respect to the hydrogen higher heating value by:

$$\eta_{\rm E} = \frac{\rm HHV_{\rm H_2}}{E_{\rm s}} \, 100 \, [\%]. \tag{13}$$

 $\rm HHV_{H_2}$  represents the heat of combustion of  $\rm H_2$  in which the water vapor, if produced, is condensed and the additional heat of condensation is included [23].

# B. System architecture

In order to design a conversion system with high efficiency, both converter topology and system architecture need to be discussed. The unification of the electrolyser stack size and working parameters of the electrical power supply serves as the principal aspect of the overall system efficiency and investment value. One can define four main architecture types for electrolysis systems which will be described in the following:

#### Direct/independent connection

This architecture implies that electrolyser cells are directly connected to the electrical energy source, in other words they are independent from one another. In this way, each cell can be controlled to operate at its optimal power and any fault on the electrolyser side would not propagate to other cells. This architecture is appealing for standalone systems with renewable-based electrical energy generation because it allows for operation at the maximum power in all conditions by use of, for example, module level converters for PV panels, see Fig. 4 [24]. Direct coupling between PV modules and electrolysers without additional conversion stages can be considered, as the lower number of conversion stages and lack of a battery energy storage system BESS, which is popular in standalone systems theoretically leads to higher conversion efficiency and lower system cost [25]-[27]. The arrangement should be so that the static I-V curve of the water electrolyser should match the maximum power point (MPP) curve of the solar panel configuration [28], [29].

However, control systems for the flow of water and outtake gasses still have to be implemented and experiments show that even if solar-to-hydrogen efficiencies of 8.5 % were recorded, a converter stage with maximum power point tracking (MPPT) algorithm provides better energy efficiency by about 14.5 %



Fig. 4. Standalone module-level PV connection.



Fig. 5. Independent connection architecture with shared AC or DC bus.



Fig. 6. Parallel connection architecture.

[30]. One other way of connecting the individual cells or stack of cells is by a shared DC or AC bus within the plant, as shown in Fig. 5.

# Parallel connection

Studies have pointed out that the selectivity of reaction products for  $CO_2$  electrochemical reduction heavily depends on the cell voltage, thus one of the options for up-scaling an electrolysis system is to connect the electrolysers in parallel (cf. Fig. 6) [8], [31], [32]. In this way the cell voltage and implicitly the electrolysis reaction can be controlled, this connection is analogous with the extension of the electrode surface and essentially linearly increasing the production rate. The production rate of a given electrolysis process is given by

$$f = \eta_{\rm F} \frac{j_{\rm cell} \, A_{\rm cell}}{\rm z \, F} \tag{14}$$

where f is the production rate (mol s<sup>-1</sup>) of the electrolysis product, for example  $f_{\rm H_2}$  in the case of water splitting or  $f_{\rm CO}$  in the case of CO<sub>2</sub> electrochemical reduction,  $\eta_{\rm F}$  is the Faraday efficiency of the reaction,  $j_{\rm cell}$  is the current density (A cm<sup>-2</sup>), A<sub>cell</sub> is the effective cell area (cm<sup>2</sup>), z is the number of moles of electrons transferred and F is the Faraday constant (96 485 C mol<sup>-1</sup>).

For the power supply, up-scaling such a system entails the necessity of providing the entire system with a voltage equal to the cell voltage, in the range of 3 V for low-temperature  $\text{CO}_2$  electrochemical reduction, and a current intensity proportional to the system power. It is easy to observe that such an architecture is very limited because it quickly leads to unrealistic current requirements for high-power systems (e.g. 3.33 MA for a 10 MW system). The implementation of this connection type is not used in practice due to the low capacity of up-scaling to high power.

# Series connection

Stacking up the electrolyser cells in series (cf. Fig. 7) is one other method of up-scaling and its essential benefit over the parallel connection is that it can be provided with a higher voltage level, resulting in a lower current intensity value when system power is accounted for. Both power supply and connecting wires' conduction losses are greatly reduced due to the proportionality to the square of the effective current value  $I_{\rm RMS}^2$ .

The series connection also has limits as small voltage imbalances that can be observed among a string of seriesconnected electrolyser cells can add up to large imbalances in a stack with large number of cells and as stated in the previous section, the selectivity of the electrochemical reaction is strongly dependent on the cell voltage.

Limiting factor for this architecture is also the gas-pressure equalization within the cells, in the case of alkaline electrolysers [33], and the overall stack voltage which should be kept low enough to avoid discharges and the danger of explosions (for hydrogen systems). This architecture is used in most high power commercial water electrolysers [14], [15], [34], [35].

# Mixed connection

A combination of the previous architectures should be considered for high power electrolysis units (cf. Fig. 8). Connecting multiple strings in parallel allows for higher power systems with a low component-count. The supplied current will be higher than what is required for a single seriesconnected stack because the limiting requirement for stack voltage, but lower than the parallel scheme.

Just as the series connection, this architecture is also limited by the overall stack voltage and input gas-pressure equalization. Modular mixed connection systems have been proposed in literature, where each module comprised of a stack or series connection of stacks is independently operated by DC-DC converters [36]. This allows for system control strategies such as selective shut-down of modules with the purpose of an efficient system operation under variable power conditions ( also known as load-following operation).

#### **IV. CONVERTER TOPOLOGY**

The electrolyser power conditioning is handled by the power electronics converters, which in the case of high power



Fig. 7. Series connection architecture.



Fig. 8. Mixed connection architecture.

systems can be branched into two main groups, mainly: grid frequency power supply (GFPS) and switched mode power supply (SMPS). The first is characterized by grid frequency converters working at the AC grid frequency of 50 or 60 Hz which usually require a large and heavy grid transformer and the second is characterized by the use of switching devices working at frequencies much higher than the AC grid frequency, typically higher than the human hearing threshold of around 20 kHz [37]. One necessary safety precaution from the ISO22734:2020 standard for hydrogen generators using water electrolysis and the ISO19880-1:2020 standard for gaseous hydrogen fueling stations is that frames and enclosures that can become energized under first fault conditions shall be grounded. In this scenario the power electronics must include galvanic isolation to separate the electrolyser from the input electrical source.

Industrial power electronics systems are usually designed for high voltage and low current in order to minimize ohmic losses and to allow for reasonable conductor size. Further, high power industrial consumers generally have an inherent AC character, for instance industrial electric drives, unlike the DC character of the electrolyser. Indeed there are many applications requiring a DC power supply, like data centers, telecoms equipment [38], household appliances and electronic devices, but their power levels are lower than what is required for electrolysis. As a result, in very high power electrolyser units the supply can be thyristor-based since thyristors can cope with large currents and generally require a relatively low number of additional components, leading to reduced cost and high efficiency.

#### A. Grid frequency power supply

Most high power electrolysers are grid-connected and their power supply is mainly composed out of a grid frequency transformer which is connected to the grid either directly or through a semi-controllable ac-ac voltage controller and a rectifier stage.

This is shown in Fig. 9 as the anti-parallel thyristors which can control the root-mean-square (RMS) value of the AC voltage through their firing angle and implicitly the output voltage and the hydrogen production. For the low-power electrolysers (5 kW and below) a single phase grid connection is sufficient, while for high power units the three-phase system is preferable. The transformer provides galvanic isolation and



Fig. 9. Example of three-phase grid frequency power supply for high power electrolysers.

reduces the grid voltage to a level suitable for the electrolyser stack. It is then rectified by a simple diode rectifier, in the case that an AC-AC voltage controller stage is used, or a semicontrolled rectifier. The semi-controlled rectifier has a diode and a thyristor in each leg, the latter being able to generate a controlled DC output voltage in order to achieve the desired hydrogen production.

This type of power supply provides a 6-pulse voltage with high amplitude and low-frequency harmonics which require bulky and costly passive filters at the grid side [14]. Multipulse techniques, like the 12-pulse rectifier, are commonly used by industry to reduce the total harmonic distortion ratio (THD) but higher number of pulses are not ordinarily used because they lead to higher cost and lower reliability [39], [40]. For alkaline water electrolysers, data based on a 2.8 kW electrolyser built by McPhy, shows that for a simulated 1 MW electrolyser, the 6-pulse grid frequency power supply can require a specific energy consumption of up to 14% higher than an insulated gate bipolar transistor (IGBT)-based switched-mode power supply (SMPS) buck converter and a 12-pulse rectifier can lead to an increase of up to 9% in specific energy consumption compared to the reference IGBT converter [34]. This result is in line with other conclusions from literature which suggest that grid frequency harmonics do not contribute to the generation of more hydrogen [14], [41]. Combinations of passive and active filters like the distribution static compensator (DSTATCOM) can improve the harmonic distortion and power factor PF of a high power electrolyser (1 MW) grid connection with values reaching 4.5% and 0.98 for the THD and (PF), respectively. The drawbacks of such solutions is a decrease in reliability and increase in cost, i.e., the capital cost of an active filter being about 5 times higher than the same rating of passive filter [35].

# B. Switched mode power supply

This type of power supply is based on fully controllable switching devices, like IGBTs or metal-oxide field effect transistors (MOSFETs) which transfer the energy between the passive elements, i.e., inductors and capacitors, at high frequency. The main advantages of this type of converters is a stable output voltage and the reduction of the AC filtering requirement, i.e. weight and volume, for compliance with grid standards. The galvanic isolation can also be provided by a higher frequency transformer which will considerably reduce the size and weight of this component when compared to the



Fig. 10. Three-phase switched mode power supply for electrolysers.



Fig. 11. Example of full bridge configurations that can be used for electrolysis. Herein, multiple alternative implementations of phase-shift (forward-type) converters are shown for deriving DC-DC or AC-DC power conversions.

grid-frequency transformer solutions. A typical high power multi-stage SMPS is structured as in Fig. 10, where the grid rectifier stage (left) is usually made with diodes because the power flow for an electrolyser application is unidirectional and the inverter stage is made with IGBT or MOSFET, depending on the particular application parameters.

Full-bridge inverter is used for high power rating because it can deliver twice the power of a half-bridge inverter at the expense of higher number of switching components [42]-[44]. The AC input can also be directly connected to a fourquadrant inverter which eliminates the need for the input rectifying stage [45]. On the secondary side of the highfrequency transformer, the voltage and current are rectified and filtered in order to provide a low-harmonic content output to the electrolyser. Furthermore, the rectifying stages can be implemented with fully controllable switches either to obtain power factor correction, in the case of grid rectification, or for better efficiency through synchronous rectification. The described full-bridge configurations are represented in Fig. 11, where any of the primary side variations can be coupled with any of the secondary side, depending on the type of input connection, output power and electrolyser stack connection architecture.

The hydrogen production is dependent on the mean current supplied, so the SMPS-type with low-harmonic output is best suited for the electrolysers. As showed by Ursua, Sanchis and Marroyo [14], [46], the use of a high power buck converter offers better system efficiency than a commercial GFPS in the case of a 5 kW H2 IGEN 300/1/25 alkaline water electrolyser by about 7%, with 80.3% system energy efficiency in the case of SMPS and 73% in the case of GFPS, despite the fact that the power supply efficiency of the buck converter (87%) is lower than that of the GFPS (89.6%). This is backed up by the the work of Koponen et al. [34], which concluded that a similar buck-type converter leads to a specific energy consumption reduction of 9% compared to a traditional 12-pulse thyristor rectifier. The effect of power quality in that study is more important than the converter losses, as these represent less than 3% of the energy consumption.

SMPS-type converters, unlike GFPS, can perform DC-DC energy conversion and are thus necessary and were used for integration with DC energy sources like PV, fuel cells or DC grids without additional rectifying stages [47], [48].

Efficiency of the SMPS can generally be improved by techniques for the elimination of switching losses of the active devices, formally known as soft-switching. In literature a zero voltage switching (ZVS) converter for a water electrolysis application rated at 7.2 kW was designed, simulated and tested and achieved a conversion efficiency of just over 90% [44], [49]. In other work, a 5.5 kW soft switching phase-shifted full-bridge converter was designed and tested for a water electrolysis application which yielded an efficiency of 94.3%, while a similar 1 kW converter with current doubler rectifier for hydrogen production was designed and tested with an efficiency of over 95% [50], [51].

An electrolyser solely connected to renewable energy sources is forced to work in a variable power mode due to the typical intermittent energy production, this regime may positively affect the lifetime of the electrolyser according to some studies [52], while other studies state that this influence is detrimental to lifetime [17], [53]. While the effect of intermittency on water electrolysers is still a subject of debate, techniques for independent operation of an electrolysis system with multiple electrolyser modules is a good solution for driving parts of the system at nominal power, where the efficiency is best. A multi-port converter with independent control of multiple solid oxide fuel cell (SOFC) stacks was proposed and validated by Lin et al. [54].

#### V. CONCLUSION

The challenges of designing an electrical energy conversion system for low temperature electrolysis were presented in this paper. A solar fuel production plant was used as an example of different electrolysis processes to present four inter-connection architectures. A general thermodynamic model was presented which hints the electrical behavior of water electrolysers and forms the basis of creating electrolysis emulators with the objective of creating a platform for safe and reliable testing of power supplies designed for electrolysis. It was highlighted that power quality is essential to the performance of the system and SMPS-type converters are preferred because they can provide current which is practically free of harmonic content. Some converter topologies are more suitable for a certain type of architecture, i.e., direct three-phase AC inverter for a grid-connected system, current-doubler secondary for parallel cell connection, multi-port converter for independent connection architecture. Various topologies for electrolysis and their performance indicators were presented, but a comprehensive comparison between SMPS-type converter topologies paired with different electrolysis system architectures is absent from literature, this will be the focus of a future work by the authors of this paper.

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