

Review

A Review of Hydrogen Production Methods and Power Electronics Converter Topologies for Green Hydrogen Applications

Goncalo Rego , Joao Rocha, Jose A. Faria, Joao L. Afonso  and Vitor Monteiro * 

ALGORITMI Research Centre, LASI, University of Minho, 4800-058 Guimarães, Portugal; pg50403@alunos.uminho.pt (G.R.); pg50485@alunos.uminho.pt (J.R.); pg50512@alunos.uminho.pt (J.A.F.); jla@dei.uminho.pt (J.L.A.)

* Correspondence: vmonteiro@dei.uminho.pt

Abstract: Hydrogen has been receiving a lot of attention in the last few years since it is seen as a viable, yet not thoroughly dissected alternative for addressing climate change issues, namely in terms of energy storage, and therefore, great investments have been made towards research and development in this area. In this context, a study about the main options for hydrogen production, along with the analysis of a variety of the main power electronics converter topologies for such applications, is presented as the purpose of this paper. Much of the analyzed available literature only discusses a few types of hydrogen production methods, so it becomes crucial to include an analysis of all known types of methods for producing hydrogen, according to their production type, along with the color code associated with each type, and highlighting the respective contextualization, as well as advantages and disadvantages. Regarding the topologies of power electronics converters most suitable for hydrogen production, and more specifically, for green hydrogen production, a list of them was analyzed through the available literature, and a discussion of their advantages and disadvantages is presented. These topologies present the advantage of having a low ripple current output, which is a requirement for the production of hydrogen.

Keywords: hydrogen; green hydrogen; hydrogen colors; alternative fuels; energy; power electronics converters



Citation: Rego, G.; Rocha, J.; Faria, J.A.; Afonso, J.L.; Monteiro, V. A Review of Hydrogen Production Methods and Power Electronics Converter Topologies for Green Hydrogen Applications. *Energies* **2024**, *17*, 5579. <https://doi.org/10.3390/en17225579>

Academic Editor: Riccardo Berta

Received: 20 September 2024

Revised: 25 October 2024

Accepted: 31 October 2024

Published: 8 November 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Hydrogen (H_2) is known today as the most abundant element in the universe [1], and it has many uses that range from ammonia production for fertilizers, to cyclohexane utilized in the plastic industry, or methanol, applied in pharmaceuticals. It can also be part of the hydrogenation process that occurs in oils, in order to form fats, such as margarine. For glassmakers, H_2 creates a protective atmosphere, and it can even be used for manufacturing silicon chips. There is also the classic example of the airships, which took advantage of hydrogen's low density to propel zeppelins. It is known, however, that this no longer happens due to the Hindenburg disaster [2]. Automobile companies are investing their efforts into developing vehicles fueled by H_2 , such as the Mirai model, by Toyota, or the Clarity Fuel Cell model, by Honda [3,4]. The H_2 used in these vehicles can be used in fuel cells (FCs), which take advantage of H_2 's chemical energy, and through an electrode, an electric current is generated, allowing the motor on these vehicles to rotate, making the car move [5]. Even though H_2 is used in the automotive industry, via FC stacks, it can also be used in internal combustion engines [6]. The operational principle of H_2 in this type of engine is similar to the engines fed by fossil fuels [3], such as gasoline or diesel, and there are companies like Keyou that specialize in converting diesel engines into H_2 internal combustion engines in a cheap manner, smoothing the transition from a polluting way of transportation into a cleaner one [7].

H₂, however, is still not as reliable as other fuels, like diesel or gasoline, for example [8], and its adoption still requires major efforts for such a transition to happen, in order to lower costs and to boost the investigation in this area [9,10]. The whole infrastructure needs adjustments since H₂ does not present the same characteristics as these other energy carriers [11]. Such changes refer to two specific cases. The first case refers to alterations in terms of gas storage. Previous fueling stations can be repurposed, but with changes to the conditioning of the H₂ in the underground tanks and in the pump supply system, since gas pressure, temperature, and stability are not the same when compared to other fuels [12]. The second case refers to repurposing and minor adaptations to the preexisting natural gas infrastructure. In Europe, there has been an effort to understand the viability and feasibility of reusing the well-developed and widespread pipeline systems for natural gas. This method presents advantages, besides the preexistence of the transporting infrastructure, such as the easily achievable very high energy transportation, thanks to the lower density of H₂ compared to methane [13]. When comparing the energy flow of both gases through a pipeline, H₂'s outputted volume can be nearly three-fold that of methane, under a given period, at the same pressure, achieving only a slightly reduced energy density, which means that the transition from natural gas to H₂ has a low impact on the capacity of a pipeline to transport energy [7,9,10,14–16].

In [16], an analysis of the differences between vehicles with distinct types of engines under several test conditions is presented. Their driving range, fuel consumption, and the amount of carbon dioxide (CO₂) emitted per vehicle type were compared, and the conclusions are summarized in Figure 1.

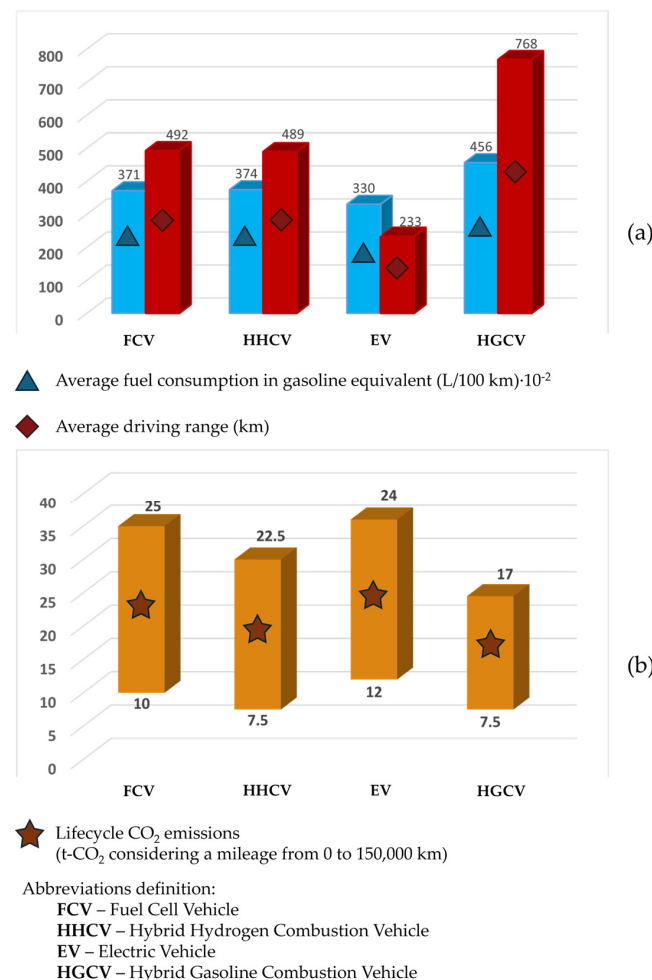


Figure 1. (a) Comparison of fuel consumption and driving range between the analyzed vehicles; (b) differences in lifecycle CO₂ emissions associated with each vehicle type.

Besides the transportation sector, H_2 has been receiving special attention in energy-heavy industries, such as the steelmaking industry, and it accounts for the list of biggest pollutants, through all types of industry [17,18]. Thus, there has been evidence that an energy transition in this sector is crucial for climate targets to be achieved [18], which has led to a growing interest in H_2 , since it can be implemented as an eco-friendlier fuel, without major changes to existing hardware, such as furnaces and ovens [19]. It should be noted, however, that the required H_2 must be produced through processes that use clean energy, such as that produced from renewable energy sources (RESs), which means that for the whole process to be sustainable and to have minimal environmental impact, green hydrogen (G- H_2) must be considered.

RESs are known to have a deep “flaw”, which is their variance through time, and one of the solutions proposed was the use of energy storage systems [20,21]. These include batteries, supercapacitors, and gases, for example. H_2 is a type of gas that can be used for this end; therefore, it is crucial to study its capabilities as a solution for the energy storage problem. Green hydrogen stands out as a solution for this problem since there is a major utilization of what could otherwise be lost energy. Therefore, G- H_2 is seen as a key driver of the energy transition [20].

To this extent, there is a strong need for the development of solutions that allow such technological advancements, namely in the power electronics (PE) field. In order to interface the many components of a power grid, whether it is part of a major grid or part of an islanded grid, there is always the need for PE, and in the case discussed in this paper, the transfer of energy from its source to the electrolyzers that produce H_2 requires several PE converters that work symbiotically as a single converter. Figure 2 displays the relationship established between the energy sources, which for G- H_2 must be renewables, the PE converter, and finally the electrolyzer. This presents an example application of the G- H_2 production and utilization, where PE is at the core of the operation. Another utilization for the produced G- H_2 is also depicted by fuel cells.

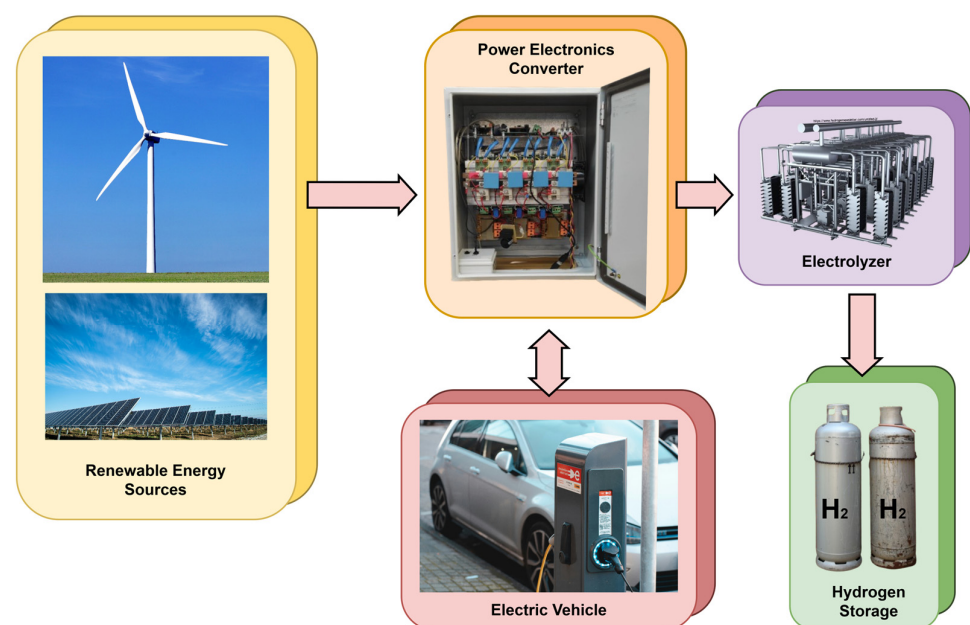


Figure 2. Diagram of a G- H_2 use case, from its energy source to the production and storage, or for usage of the gas itself.

This paper presents various contributions, namely the following: (i) outlining the various types of H_2 according to their production type, along with the color code associated with each type; (ii) regarding G- H_2 , the specific and main PE converter topologies that allow for its production are presented and described, along with the characteristics that make

them suitable for G-H₂ production; (iii) the principle of operation of the PE converters, including a comparison based on advantages and disadvantages, is presented. After this introduction, the second section is dedicated to an introduction to H₂ and its possible applications, as well as an enumeration of the various H₂ production methods, along with the color code associated with each type. Section 3 describes some PE converter topologies associated with the production of H₂, as well as the characteristics that make them suitable for G-H₂ production. A comparison of all the converters is presented in Section 4, according to their advantages and disadvantages. Lastly, in Section 5, conclusions about the discussed methods for H₂ production and the PE converter topologies are drawn.

2. Hydrogen: Classification and Associated Color Code

Before showcasing the different existing methods for H₂ production, a note of warning must be made about the different types of hydrogen since there are three variants; that is, hydrogen can be categorized in its isotopes, namely Protium (¹H), Deuterium (²H), and Tritium (³H), and they all refer to the chemical element hydrogen, with the same number of protons, but with 0, 1, or 2 neutrons, respectively. With this being said, in this paper, the term hydrogen or H₂ will always represent the most abundant isotope, which is Protium, and the molecule composed of two Protium atoms [22].

In recent years, H₂ has been appraised as a sustainable alternative for the decarbonization of a multitude of processes, from transportation to energy production, or energy-dense industries, such as the steel industry [23,24]; it has a variety of applications, and when it is burned or used in fuel cells, the only byproduct is pure drinkable water. Therefore, in this regard, H₂ has an advantage, when compared to fossil fuels [25]. The latter produce hazardous and pollutant byproducts when they are burned to produce energy and are considered key drivers of global warming, which in turn leads to negative impacts on the environment, its inhabitants, and the ecosystem as a whole [26,27]. There are, however, some constraints related to the production methods of H₂, and to assess this issue, a color code for different types of H₂ was developed [28,29].

H₂ itself is a colorless gas, but there are around ten color codes for identifying H₂, and these refer to the source or the process used to produce it, more specifically green, blue, grey, brown or black, turquoise, purple, pink, red, and white, and they refer to a way of categorizing H₂ concerning its origin, method of production, monetary and energy costs for its production, and life cycle emissions [26,30]. Table 1 showcases the different categories created for H₂ according to several specifications. These are the most common H₂ production methods since they have already been used to produce H₂ on an industry level [31]; therefore, not all colors are addressed in this table.

Table 1. Main pathways for H₂ production.

Type	Source	Process	Min. Energy Inputs (kWh/kg)	Conversion Efficiency (%)	Average Cost (£/kg)	Life Cycle CO ₂ Emissions (kgCO ₂ /kg)
Black/Brown [23,25,26,28]	Coal	Gasification	~40	60	3.4	>18
Grey [17,23,24,27,28]	Methane	SMR ¹	10.8	65–80	1.7	>12
Blue [17,32,33]	Methane	SMR + CCS ²	~14	47–62	2–2.5	3.5–5
Pink [34–36]	Water	Nuclear Electrolysis	~47.8–51.3	85–90	~3.3–6	0.559
Turquoise [17,37–39]	Methane	Plasm Pyrolysis	9–16	14–56	~2	3–4
Green [17,20,30,33,40,41]	Water	Electrolysis	55	60–70	5–7	4–5

¹ SMR—Steam Methane Reforming. ² CCS—Carbon Capture and Storage.

In [26], the characteristics of each of these colors of H₂ are discussed and presented, along with a benignity assessment of each of them. In [33], a differentiation of the various colors of H₂ is made, reinforcing the weight that most conventional practices for H₂ production have in the transitional phase of H₂, namely coal and gas burning. In [32], the authors discuss the production of blue H₂ as a key for the growth of the H₂ market. They emphasize the evolution and improvement of techniques that aim for the production of H₂ in recent years, as well as a comparison between H₂ and natural gas, in terms of their advantages and disadvantages as fuels and energy carriers. Lastly, they refer to CCS as being essential for the implementation of blue H₂.

2.1. Black/Brown Hydrogen

Black and brown H₂ are similar since they are both produced from coal. The only difference is the type of coal that is used; for the first case, black bituminous coal is used to produce energy from its burning, whereas for brown coal (thereby the name), lignite is used instead [23,25]. This method of production is, on one hand, the cheapest, since coal prices are low, but on the other hand, it has the biggest environmental impact when compared to other methods of H₂ production, since burning coal is responsible for the emission of large amounts of greenhouse gases, aggravating global warming through air pollution [26,28].

2.2. Grey Hydrogen

The most common method of producing H₂ is through the SMR process, and more than 80% of H₂ is produced through it [23]. At the beginning of the process, natural gas and other hydrocarbons that contain methane are injected into the steam enclosure, where heating and sulfur removal processes happen. When heated, the mixture produces the desired H₂. Some extra procedures are used to produce more pure H₂, such as the water shift gas reaction [27]. The advantages of this method are the already existing infrastructure and its lower cost. However, SMR has an enormous presence among the biggest pollutant industrial processes, accounting for almost 3% of the global industrial sector CO₂ emissions; therefore, it is not an alternative to be looking at in the future, since it does not meet the net-zero carbon targets [42,43].

2.3. Blue Hydrogen

To produce blue H₂, it is necessary to capture and store the carbon emitted upon the burning of natural gas. This method allows for this H₂ to be labeled as low-carbon, since most of the produced CO₂ is then captured and stored in underground caves [32]. This method is hailed as more expensive than the black/brown H₂ type; however, with the CCS strategy, the carbon offset is lower, making it an environmentally friendly option [17]. It is not, however, the greenest, because the captured carbon cannot be kept forever, and there will always be leaks, which leads to an increase in the overall carbon footprint of this alternative [33].

2.4. Pink Hydrogen

There are numerous ways to produce energy, and besides the ones mentioned above, or RESs, there is one energy production method that stays in between, and it is nuclear energy (NE). The use of nuclear reactions to produce energy is no novelty, and this energy can also be used to produce H₂ [34]. Pink H₂ is produced through the electrolysis of water, and the energy is sourced from nuclear power plants. There are trade-offs when using NE to produce H₂. In terms of pollution caused, none of it directly affects the environment; i.e., the byproduct of producing this energy is water vapor, which is innocuous to the atmosphere but can contribute to the heating of nearby rivers and water reservoirs, leading to a less positive influence on the local ecosystem. Another great issue related to the use of nuclear power refers to the residues since these are practically impossible to decompose in nature and present a biohazard because of the radiation they produce, as well as their

toxicity, when in contact with living beings. Thus, the production of pink H_2 must be thoroughly calculated so that no greater risks arise [35,36].

2.5. Turquoise Hydrogen

For the production of turquoise H_2 , the process of methane (CH_4) pyrolysis via thermal plasma is used. That is, through the burning of CH_4 , using hot plasma, it is possible to produce H_2 with a high degree of purity [37]. This method has many advantages, such as being a lower-energy-density process, when compared to other processes, such as SMR, or water electrolysis. Furthermore, its usage and production can be accelerated, considering the already existing natural gas infrastructure [17,37]. Another advantage presented by turquoise H_2 is its byproduct: high-value black carbon. Upon burning one molecule of methane, it is possible to produce two molecules of H_2 and one molecule of carbon, which can later be used in a multitude of processes and/or products, including as a pigment, as a filler for rubber-making, for pencil-making, as artificial diamonds for industrial tools, and even for gunpowder, among others [38,39,44,45].

2.6. Green Hydrogen

Lastly, concerning the major types of H_2 , there is G- H_2 . This is the most environmentally friendly type of H_2 since it is produced from RESs through the electrolysis process [41]. This is an energy-dense process, which may represent a downside; however, since this is a cleaner process, it beats all the other H_2 production methods, because no harmful gases or chemicals are released into the atmosphere and surrounding ecosystems [30,33]. G- H_2 is deeply associated with the decentralization of energy production since for it to be more sustainable and reliable and for the whole production and usage process to be more efficient, G- H_2 must be produced near its final application equipment, namely electric vehicle (EV) charging stations and ammonia and fertilizer production, or simply to produce H_2 to be stored as an energy carrier, for example [17,40]. Many projects, namely in Europe, intend to accelerate the transition to G- H_2 through a goal set for 2030 that relies upon importing 10 million tons of G- H_2 for use in traditionally fossil-fuel-reliant sectors, such as heavy industry and transportation [46].

2.7. Purple Hydrogen

The production of purple H_2 foresees the usage of nuclear power, heat, and H_2O through electrolysis and thermolysis processes. It has similarities to the production of pink H_2 ; however, they differ, since pink H_2 does not rely on heat to be manufactured [40].

The vast majority of purple H_2 projects are located in the USA and in the UK. Even though China only has one purple H_2 project, its announced capacity surpasses all the other preexistent infrastructure, with a theoretical maximum capacity of 39.37 kilotons per annum (ktpa), and it is expected to begin its activity in 2025. This is a huge difference from the average purple H_2 project, which outputs around 0.6 ktpa. It is also estimated that a 1 GW reactor could provide 150 ktpa of H_2 production, whereas a 3 GW one could generate enough H_2 to heat 1 million homes or to feed 40,000 H_2 buses [47].

2.8. Red Hydrogen

Just like pink and purple H_2 , red H_2 is produced using nuclear energy. This particular type of H_2 is produced solely from the resulting heat of nuclear energy production, through the thermolysis of water [40]. There is, however, another difference, which relates to the type of nuclear reactor that is used for the production of red H_2 . To be able to produce red H_2 , a new generation of reactors must be used, and they differ from previous reactors in terms of size and power; i.e., they are smaller and less powerful. This allows higher temperatures than those in classic reactors to be attained. In terms of perspective, the newer reactor power plants will output from 30 MW to 100 MW of thermal power, whereas bigger and older nuclear power plants output approximately 100 times more thermal power. The

problem is that older nuclear reactors are less efficient; therefore, the implementation of these newer reactors could be transformative to this H₂ production method [48].

2.9. White Hydrogen

H₂ can also be produced naturally. White H₂ refers to the gas that is produced from natural processes and kept in underground deposits. This hydrogen is seen as bliss since it is produced naturally without any kind of interference from humans. However, there are downsides to it, such as its extraction, which accounts for possible gas leaks that are dangerous, since H₂ is flammable, and the environmental impact associated with it, considering that these natural H₂-occurring areas need to be exploited, and therefore, heavy-duty machinery will induce both controlled and uncontrolled damage to the structures that keep the gas stored; a further downside is its bioavailability, since naturally formed H₂ cannot be found in all parts of the world, and natural H₂ reserves are not equally accessible and do not grant the same extraction conditions [49,50].

2.10. Yellow Hydrogen

Yellow H₂ is defined as a derivate of G-H₂ since it is produced from RESs; however, in this case, the only source that can be accounted for is solar energy. Through the use of solar panels, electricity is produced, and when it is fed to the electrolyzer, H₂ is produced, without the release of CO₂ or other harmful gases to the atmosphere [51]. There is, however, not much consensus on the definition of the origin of yellow H₂, and some authors claim that it may also be produced from electrolysis, but with its energy directly sourced from the power grid [26].

3. Power Electronics Converter Topologies for Green Hydrogen Production

G-H₂ stands out as an environmentally friendly alternative to fossil fuels since through its use, no pollutant components are emitted to its surroundings, either through its use via fuel cells or by simply burning it, as is done with other fuels, such as diesel or gasoline. The use of H₂ requires, nonetheless, a high degree of purity, i.e., a purity level superior to or equal to 98%; therefore, the equipment responsible for such production must be capable of outputting top-grade H₂ [52,53].

For this to be possible, every step of the production process must be performed in such a way that the H₂ is as pure as possible. The electrolysis process leads to the fissure of the H₂O molecules into their components, namely oxygen (O₂) and H₂, by means of large amounts of electric current [54]. Considering this, it is necessary to think of ways to minimize the losses that occur amidst the energy conversion process and to grant the required conditions for the electrolyzers to work, namely in terms of adequate current and voltage. PE is evident from the beginning to the end of the production process, and thus an alternative to fight energy conversion losses is proposed by using PE converters. These systems are key to having high-quality H₂, and there are many PE converters that allow the production of G-H₂. PE converters are an essential part of an electrolysis system since their purpose is to be able to provide the electrolyzer with all its electricity needs, despite the power grid it may be inserted on, either as part of a bigger power grid or as an islanded grid [55]. These converters will be further analyzed.

Considering the aforementioned, some authors have already addressed the current ripple influence on the electrolyzers. In [56], an analysis of how important and relevant the current ripple is to the performance of an electrolyzer, namely a proton exchange membrane (PEM) electrolyzer, is presented. With the results presented in their work, the authors concluded that efficiency is reduced proportionately to the increase in the current ripple since it increases the power consumption of the electrolyzer. In terms of the amount of H₂ that is produced, they stated that it stays constant since this value is solely affected by the average of consumed current, which stays constant no matter the amount of ripple that the current may have. Thus, the lower amount of ripple leads to a reduction in the power consumption from the electrolyzer's perspective. In [57], the authors established that there

is a proportional relationship between the watt-hour efficiency of the H_2 production process and the quotient I_{AVG}/P_{AVG} . Another aspect could be considered for the improvement of the power conversion efficiency, namely through the usage of soft switching; however, in the context of this paper, this feature is not an object of analysis [58].

G- H_2 can be compared to pink H_2 , given the fact that a major similarity between both production methods can be identified, namely the fact that both methods rely on the electrolysis of water. However, they differ in terms of power, since a nuclear power plant with commercially available reactors may produce as much as 1500 MW [41], whereas for G- H_2 production, a standardized electrolyzer stack coupled to RESs could output only about 10 MW [59]. This leads to the conclusion that PE converter topologies may be similar, independently of the application; however, considering the power required for each method, there must be an adjustment of the type of components that ensure the correct operation of both electrolyzers. Thus, this section analyzes converters that can be employed for an electrolyzer and, more specifically, for electrolyzers whose energy is produced from RESs, in order to produce G- H_2 .

3.1. Power Electronics Converter Topologies

For a certain converter to be deemed suitable for G- H_2 production, some technical aspects must be considered, since H_2 production requires lower voltages and higher current values; i.e., for PEM electrolyzers that present an electrode area of around 1500 cm², current density may vary between 900 A and 3000 A, whereas the voltage range is limited to 1.4 V to 2.5 V [54,60,61]. Other aspects must be taken into account when considering PE converter topologies for their integration with electrolyzers, such as, and foremost, a low output current ripple, diminished electromagnetic interferences, higher power density, reduced costs, high conversion ratio, reliability, and the efficiency of the electrolysis process, according to the technique applied [62]. Electrolyzer efficiencies may vary from 50% to 83% in PEM electrolyzers and may vary for other technologies, such as alkaline water electrolysis (50% to 78%), anion exchange membranes (57% to 59%), and solid oxide electrolysis cells (about 89%), which means that if the H_2 -producing element has such values of efficiency, it is crucial to increase the efficiency of the PE converters as much as possible, in order to feed the electrolyzer units, and thus, this presents a prerequisite for appointing certain PE converter topologies, such as the ones described in this paper, as adequate for H_2 production [60,61,63].

To produce hydrogen using electrolysis, only dc current can be used, and since the intended application cases are RESs, to produce G- H_2 , their coupling is made to a dc bus. The usage of dc has benefits when compared to ac, namely in terms of efficiency, reliability, the integration of battery systems and RESs, and ultimately, the elimination of frequency issues, which lead to transmission losses [63].

There are many power electronics converters that can be applied in H_2 production, and thanks to continuously growing investment and investigation in this area, this number is continuously growing. Thus, a selection of PE converter topologies is dissected in this work for the sake of understanding their position among the remainder by the analysis of their benefits and demerits.

3.1.1. Dual Active Bridge Converter

In [64], the authors discuss a dual active bridge (DAB) converter as a way to interface a high-voltage DC bus with an electrolyzer. This PE converter is pictured in Figure 3.

However, to handle the high currents typical in such systems, an alternative approach is proposed, namely by using these converters as modules, that is, to allow the high currents to flow through n converters. This approach is used to minimize losses as well. The authors analyzed three different configurations for these modules, namely by changing their configuration on the high-voltage (HV) and low-voltage (LV) sides.

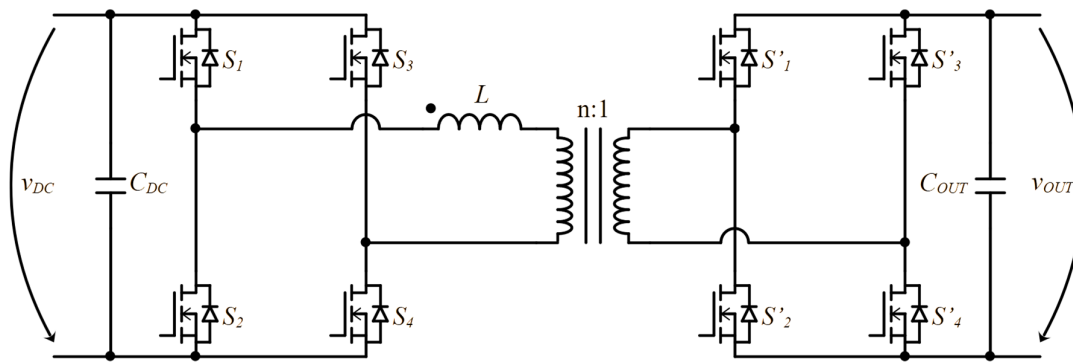


Figure 3. Dual active bridge converter.

Series HV Side and Parallel LV Side (SHV-PLV)

As the number of modules (n) increases in this configuration, the amount of current and voltage on each is decreased by a factor of $1/n$, which is beneficial, since the workload is divided, allowing for an extended lifetime of the switching elements. Such a configuration can be seen in Figure 4.

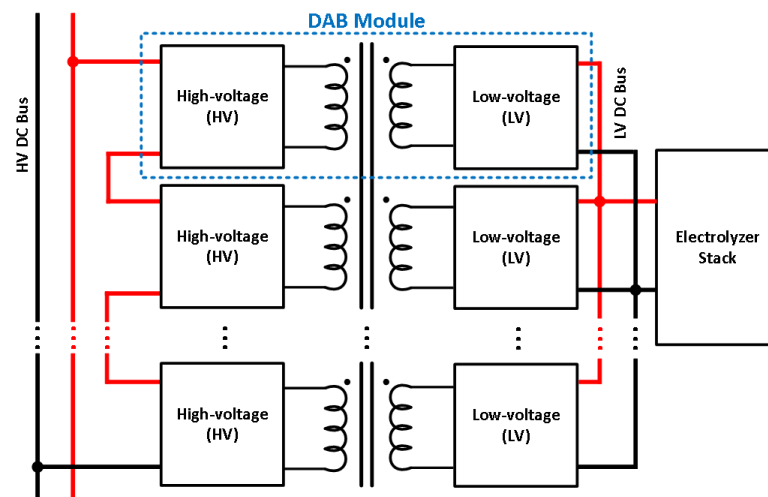


Figure 4. Series HV and parallel LV configuration.

Parallel HV and LV Sides (PHV-PLV)

The configuration seen in Figure 5 presents the same advantage in terms of current distribution through the modules as the previous configuration. However, the voltage rating of each bridge switch must match the DC grid voltage. It is even possible to activate or deactivate each of the modules individually when in operation in order to increase the system's efficiency.

Dedicated DAB Module for Each Electrolyzer Stack

In such a configuration, each DAB module concentrates its effort on a single electrolyzer stack, as per Figure 6. The power rating for each system is given by $(1/n)^{th}$ of the given system power. Since each module is independent, the overall system efficiency can be altered for the required specifications. This configuration has the downside of being a more expensive approach, since the more stacks there are, the more DAB modules are required, and these modules must be able to handle higher currents on their own since no current is divided through the other modules, as they are separated (on the LV side).

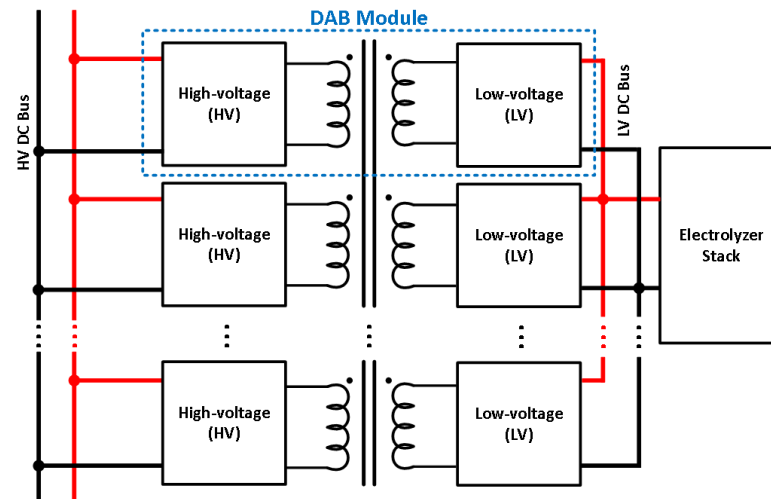


Figure 5. Parallel HV and LV configuration.

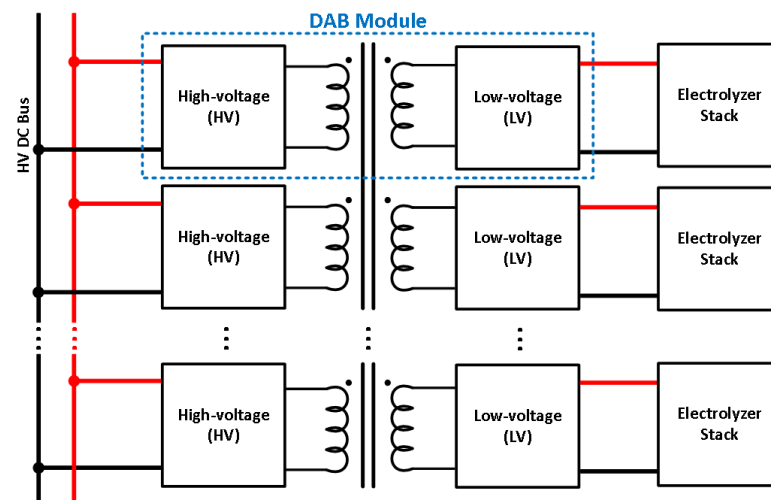


Figure 6. Dedicated DAB converter for each electrolyser stack.

Other studies, such as [65], suggest the implementation of the DAB using dual phase shift as a way to reduce conduction and switching losses, presenting results for a 10 kW converter with a current output of 25 A and efficiencies from 94.0% to 97.6%. The low current ripple of the analyzed topology implementation was not mentioned in the paper; however, this work presented a relevant study of the implementation of the DAB. In [66], the authors analyzed the influence of phase shift modulation on the same converter, and its performance was assessed under high-current applications, and like the work described in [65], they concluded that standard single-phase shift does not present advantages. This specific paper analyzed the influence of trapezoidal and triangular modulation schemes and concluded that despite the increased computational effort to control the converter, conduction and switching losses were minimized, which improved the overall efficiency of the converter.

As the energetic paradigm shifts towards powerful and more efficient electrical systems, the use of innovative converter topologies to suppress the prevailing energy needs is crucial.

In [67], the authors stated that multilevel converters may be the appropriate solution since a large number of semiconductors are used. Such a characteristic is beneficial because voltage can be divided by all semiconductors, which means that smaller semiconductors can be implemented, allowing a reduction in losses and an increase in the system's lifetime. Contrarily, the increase in power levels will also cause associated costs to rise. One major

benefit of using multilevel converters is their control algorithm, which allows for more voltage levels at the output of the converter, resulting in improvements in power quality.

When compared to traditional topologies, multilevel converters permit the escalation of the system's power without changing the maximum current value while still enhancing power quality, namely by reducing harmonic distortion and voltage transients, in AC grid-tied systems. These modifications provoke a faster dynamic response from the converter and allow the increase in the switching frequency of the semiconductors, therefore reducing the size of the passive elements in the converter. The number of levels available at the output of the converter also increases. There is, nonetheless, an aggravation in the system, for example, in the control complexity, due to the larger number of semiconductors.

Multilevel converter topologies are seen as very adequate for uses such as bipolar grids, a structure for possible adoption in active buildings, in the context of smart grids. Bipolar grids are gifted with great flexibility, and their implementation surges as a response to the fast-paced evolution of loads and electrical appliances that are coupled to the power grid. The insertion of additional voltage levels through this type of converter allows an increase in the conversion's efficiency and controllability when a grid failure occurs [67,68].

Stacked and interleaved converters are known for their better efficiency, considering that ripple frequency is higher, proportionately to the number of ramifications of the converter connected in parallel, leading to a reduction in stress on the power semiconductors, as well as conduction loss minimization. The complexity of the system is also aggravated thanks to the increase in semiconductors. Despite that, the size of the passive components is diminished since the ripple frequency is higher [69].

3.1.2. Standard Buck Converter

Most converters applied in electrolysis systems are buck-type, and this subsection will analyze them according to the existing variants. Buck converters are suitable for a wide range of applications, including renewable energy applications and steelmaking, which is an energy-dense process, or for use in G-H₂ production, which in reality is an amalgamation of both these categories [55,67,70].

The buck converter, as depicted in Figure 7, stands out as an easy-to-implement solution given its simplicity, as well as being less expensive and easier to control. On the other hand, the buck converter has limitations, namely the introduction of current ripple at the output. This fact requires the implementation of procedures that limit it and the unavoidable increase in the inductance value, as well as the associated switching losses and overall costs [55]. For low-cost applications, it still may be considered to be a viable option, despite these less beneficial characteristics. To overcome common hurdles of the buck converter, the authors of [71] proposed an improved buck converter with the ability to withstand a step-down ratio of 18:1 under a high switching frequency (1 MHz), while ensuring a low current ripple.

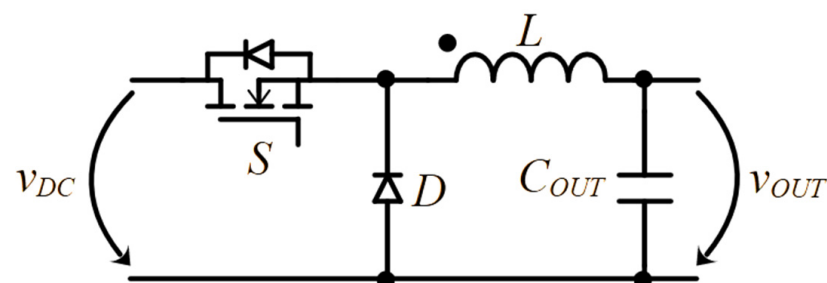


Figure 7. Standard buck converter.

3.1.3. Synchronous Buck Converter

Other authors proposed an alternative electrolysis system, pictured in Figure 8 and described in [72]. The experiment had the goal of producing G-H₂, and their choice for the DC/DC synchronous buck converter was very well thought through. The voltage output

of renewable sources and storage systems nears 12 V, in their case, 2 V. The effectiveness of the converter at low output voltage is diminished, whereas the output current is high. Such phenomena occur thanks to voltage drops across the converter, namely the diode; therefore, the suggested methodology involved removing the freewheeling diode and replacing it with a semiconductor. A MOSFET was chosen because it has a reduced voltage drop. In conducting mode, the semiconductor acts like a small resistance benefiting from the absence of a voltage drop, contrarily to IGBTs and diodes, which translates into an improvement in efficiency [67,72].

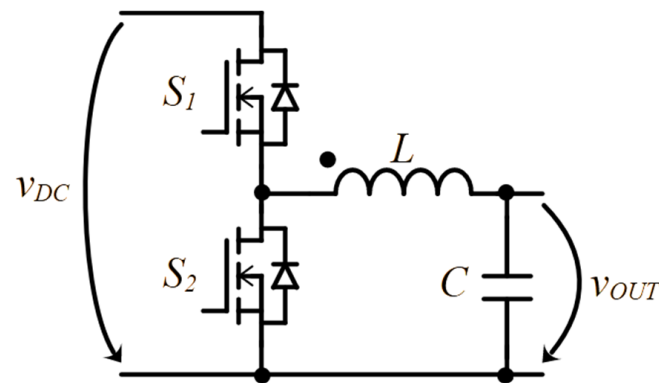


Figure 8. Synchronous buck converter.

An efficiency analysis then concluded that the conduction voltage drop of the synchronous switch is lower than the one that occurs in diodes such as the Schottky ones, reinforcing their choice of using a synchronous converter as opposed to a regular one [72].

Similarly, the authors of [73] highlight the advantages of the synchronous buck converter in high-switching-frequency applications, revealing a high transient response in the output voltage. Other advantages associated with high-frequency synchronous buck converters include a reduction in the cost and an improvement in the converter's performance.

3.1.4. Stacked Buck Converter

The authors of [69] showcased their implementation of a stacked interleaved buck converter, in contrast to a synchronous boost converter. The purpose of their investigation was to improve the converter's transient response, control method, and output current ripple through dead-time modulation, which had the objective of adjusting two equivalent waveforms, from the primary and secondary arms of the converter, in order to reduce the output current ripple [69]. Firstly, they stated the three main categories for techniques that aim to eliminate the output current ripple, namely multi-phase buck converters in parallel inter-switched, coupled inductors, and stacked architectures. Each of these categories is summarized in Table 2.

Table 2. Standard current ripple elimination effect technique comparison.

Technique	Advantages	Disadvantages
Multi-phase buck Converters	Increased current ripple frequency. Reduced capacitance of the input capacitor.	Current ripples will only cancel each other out to a certain degree. Limited duty-cycle range.
Coupled Inductors	Full duty-cycle range.	The increase in the inductance leads to a direct reduction in the transient response speed of the converter.
Stacked architecture	Acceleration of rising and falling slope of the output current with both arms of the bridge converter turned on, improving transient response.	Dead time of the switching signals and parasitic capacitance of switching elements negatively affect the ripple elimination effect.

The work described in [69] takes aim at a converter like the one depicted in Figure 9. The implemented coupled inductor has the principle of producing two opposite-phased currents through L_s and L_p in order to eliminate the overall current ripple since they complement each other. The converter working principle is based on this proposition, and it will be further analyzed.

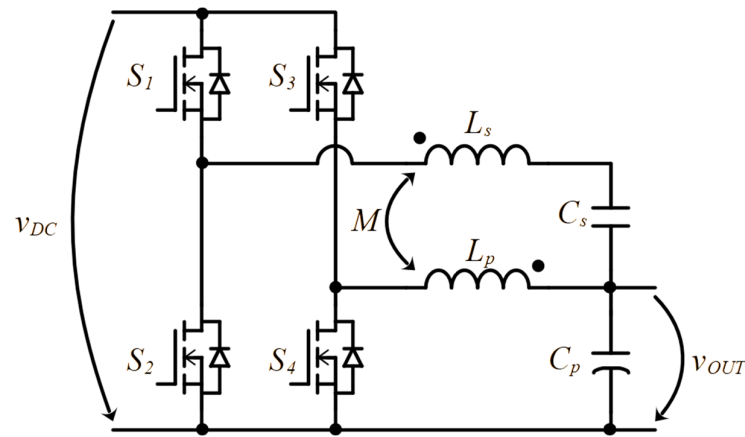


Figure 9. Stacked buck converter.

The stacked buck converter (SBC) presents advantages in terms of current ripple elimination, through the use of a coupled inductor (M), since there is no major detriment in the ability to reduce the current ripple by reducing the inductance value. The authors also claimed that by lowering the capacitance value of C_s , in order to increase the converter's transient response, there would be an increase in the current ripple, which is contradictory, since the objective was to produce a low ripple current that would feed the electrolyzer. To overcome this hurdle, they suggested that using an overlapping activity on both arms, i.e., having both arms turned ON at specific times, could improve the system's transient response, without prejudice to the capacitance values, which translated into a decrease in the current ripple elimination ability. Through this method, both a satisfactory transient response and a cleaner ripple output were assured [69].

Other authors have also presented works about this converter, such as in [74] where several requirements were emphasized from the electrolyzer point of view. These were low output current ripple, an adequate dynamic response that ensured the electrolyzer's reliability, and high energy efficiency. In this work, a theoretical analysis of the converter was presented, including the dynamic model of the electrolyzer unit and the control system design. The authors state that this topology, under the implemented control algorithm, can compensate the output ripple independently from the applied duty cycle, as well as protecting against overvoltage surges, while increasing the electrolyzer's performance. Their design can also be scaled to higher voltages. Lastly, they state that an inconvenience in increasing the power of the topology is the limitation imposed by the inductors, as the available values in the market are yet not high enough to meet such high-power demands.

3.1.5. Quadratic Buck Converter

Another topology that has been analyzed in different studies is the quadratic buck converter (QBC). This topology presents advantages not only through the reduction in the output current ripple, but also by presenting high efficiency values. In [75], it is stated that upon the design of a QBC, satisfactory results were obtained in terms of output current ripple since an efficiency of 82% was obtained. It was also mentioned that even though a simpler control method was employed, the steady-state output regulation was superior to what was expected, as was the transient response, which was faster than predicted. For the performed study, a QBC like the one presented in Figure 10 was implemented.

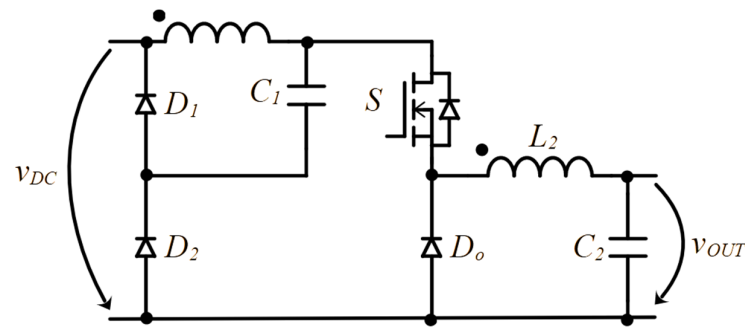


Figure 10. Quadratic buck converter.

A different approach to the QBC implementation is presented in [76], in terms of control methodology; the authors declare that through the implementation of dynamic modeling of the QBC with the state-space averaging technique, it is possible to obtain a more precise model when compared to the previous ones. Their model accounts for the influence of equivalent series resistances of the capacitors in the circuit, as well as the inductors, contrarily to previous studies which have neglected such variables, considering having an ideal converter.

From another perspective, the authors of [77] showed how reconfigurable QBCs specifically applied to electrolyzers can prove to be adequate, given their low voltage and high current outputs. This reconfigurable technique allows for a safer power distribution since in this way, the system is capable of protecting the life cycle of a load that would otherwise be negatively impacted during an unexpected and unwanted shut-down.

3.1.6. Superimposed Quadratic Buck Converter

Another work was developed, and in [78], an unusual alternative is showcased: a quadratic buck converter according to a superimposed topology for overcoming very high step-down ratios (in the studied case, 48 V to 1 V). Such an approach, in combination with an adequate quadratic conversion ratio, allows for a reduction in the time spent ON by the converter. The distribution of power under parallel paths with reduced RMS current allows for a peak efficiency of 94%. This topology receives its name from the superimposed LC filters applied, as per Figure 11, and is also able to minimize the output current ripple. To optimize the system, a complementary switching scheme and a duty-ratio-based inductor size improvement technique were introduced.

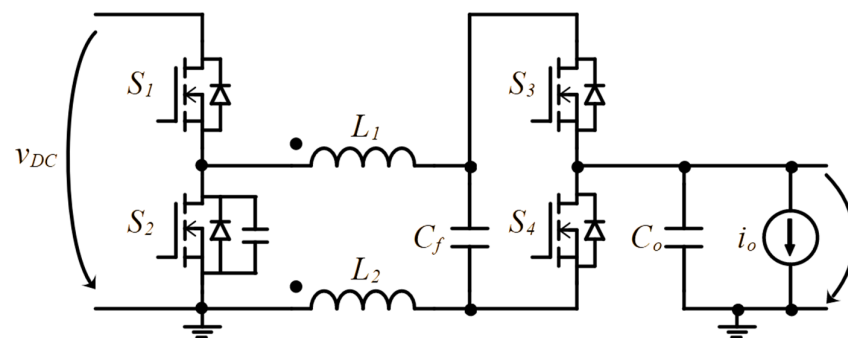


Figure 11. Superimposed quadratic buck converter.

4. Comparison

For the sake of better understanding each converter's strengths and weaknesses, and why some may be used in certain situations while others are more adequate for a different scope of application, Table 3 is presented, and it profiles a brief summary of the advantages and disadvantages of each of the aforementioned topologies. All the analyzed converters have the ability to reduce the system's current ripple; therefore, this is a common advantage,

and since the objective of this paper is to showcase different types of converters for G-H₂ production, this characteristic is seen as preconceived; otherwise, the converters would not be profiled.

Table 3. Comparison of the analyzed PE converter topologies.

Converter Topology	Advantages	Disadvantages
DAB (SHV-PLV) [64–68]	- Modular/scalable. - Current is divided through the various modules. - Withstands high DC input voltage. - Ensures galvanic isolation between the input and the output.	- Higher associated costs. - Harder to implement control algorithms as the number of modules increases, since there is a need to synchronize them.
DAB (PHV-PLV)	- High number of semiconductors allows for a reduction in losses.	
Dedicated DAB		
Standard Buck [55,67,70,71]	- Simplicity of implementation and compactness. - Inexpensive. - Easy to control. - Efficient, even if not as much as the other converters. - Stable output voltage.	- Necessity of implementing current-ripple-limiting techniques and increasing the inductance value, as well as switching losses. - Efficiency drop at lower loads.
Synchronous Buck [55,67,72,73]	- High efficiency. - Low output voltages benefit the performance. - Improved transient response. - Has the ability to handle higher currents.	- Does not ensure isolation between input and output. - Does not present an advantage in terms of voltage drop ratio, compared to regular buck converters.
Stacked Buck (SBC) [55,69,74]	- Improved transient response and efficiency. - Fast dynamic response. - Scalability and modularity. - Ability to have both semiconductors conducting (switched ON) at the same time.	- Increased complexity of the control algorithm, since a bigger number of semiconductors is being used. Higher costs are also associated. - Lighter loads lead to a reduction in efficiency.
Quadratic Buck (QB) [75–77]	- High efficiency—82%. - Simple control algorithm can ensure superior steady-state output regulation. - High voltage step-down ratios. - Fast transient response. - Can be more accurate if non-ideal parameters are accounted for.	- Augmented costs due to the implementation of multiple MOSFET switches. - Potential increase in electromagnetic interferences with the increase in switching stages. - Lower power levels lead to reduced efficiency.
Superimposed QB [55,78]	- Allows for very high step-down ratios. - Reduction in the ON time of the converter leads to better energy management and less losses. - Peak efficiency of 94% thanks to the parallel distribution of power. - Duty-ratio-based inductor size improvement technique can be employed.	- Control requirements are complex. - Higher cost, complexity, and number of components. - Efficiency is prejudiced at light loads.

It is important to highlight that in this efficiency assessment, the semiconductors of each converter are considered ideal. Also, considering the application scope of the power converters, there was a need to include the electrical model of the electrolyzer in the simulations, which is displayed in Figure 12, along with the values of the components that compose this model. Therefore, it was possible to analyze the behavior of the distinct power converters with a more realistic electrical model of the electrolyzer, as opposed to the use of a resistor, which is the simplest model but does not guarantee as much accuracy

(although it is used in some studies available in the literature). Through the analysis and comparison of several other papers [79–83], the mentioned values were found, and they are displayed in Figure 12.

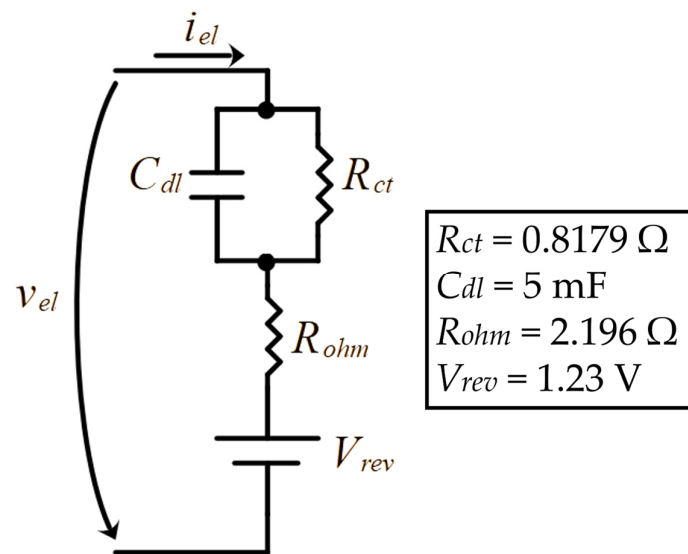


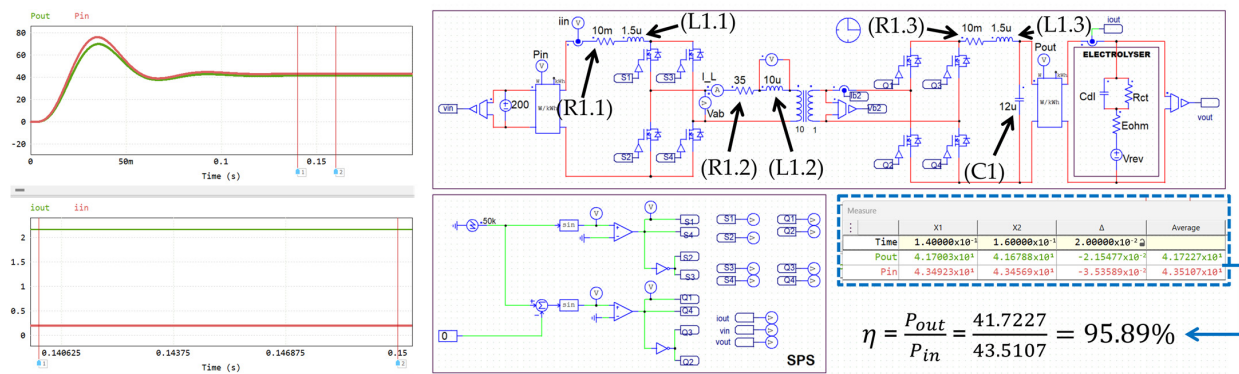
Figure 12. Electrolyzer model and its characteristics.

According to the aforementioned, some simulation results are presented in order to demonstrate the advantages/disadvantages of the analyzed converters, along with a simplified assessment of each converter's efficiency under the circumstances specified in each converter diagram, shown in Figure 13.

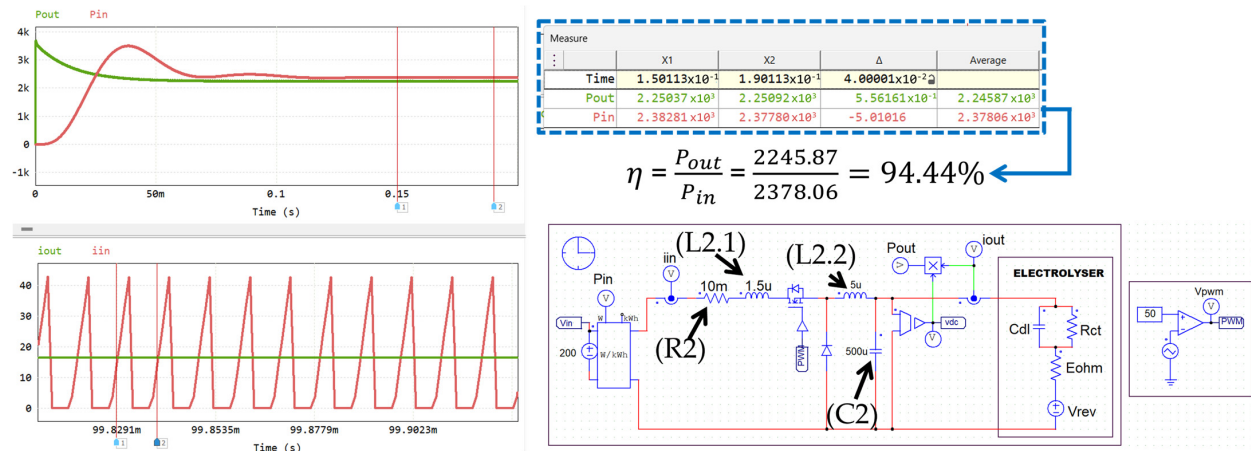
Table 4 presents the values used in the simulations of the analyzed PE converter topologies.

Table 4. Passive element values used in the simulation process.

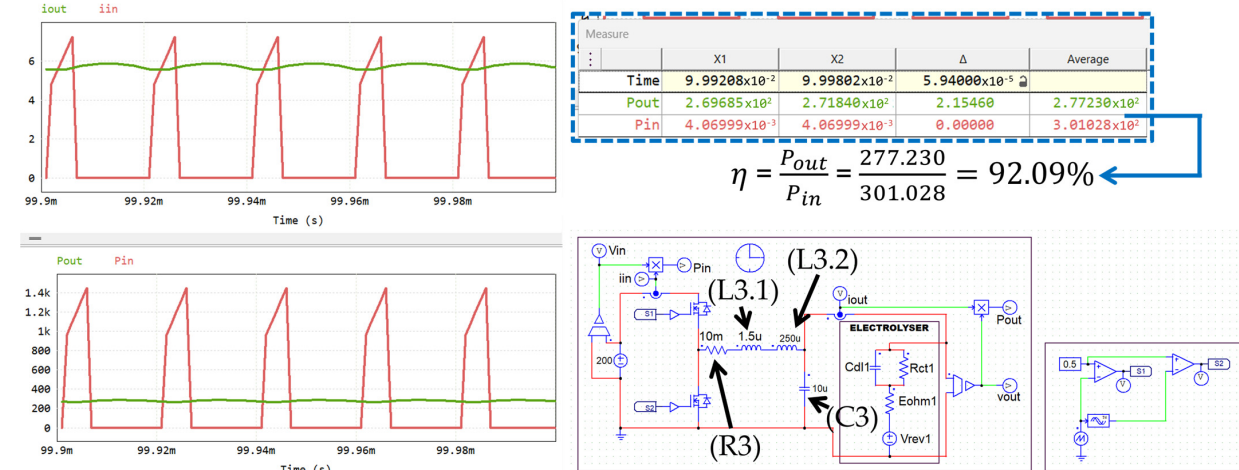
Converter Topology	Resistors	Capacitors	Inductors
(a) Dual Active Bridge	R1.1 = 10 mΩ	C1 = 12 μF	L1.1 = 1.5 μH
	R1.2 = 35 Ω		L1.2 = 10 μH
	R1.3 = 10 mΩ		L1.3 = 1.5 μH
(b) Standard Buck	R2 = 10 mΩ	C2 = 500 μF	L2.1 = 1.5 μH
			L2.2 = 5 μH
(c) Synchronous Buck	R3 = 10 mΩ	C3 = 10 μF	L3.1 = 1.5 μH
			L3.2 = 250 μH
			L4.1 = 1 μH
(d) Stacked Buck	R4.1 = 10 mΩ	C4.1 = 10 μF	L4.2 = 1 μH
	R4.2 = 10 mΩ	C4.2 = 200 μF	Ls = 100 μH
	R5 = 10 mΩ	C5.1 = 330 μF	Lp = 100 μH
			M = 5 μH
(e) Quadratic Buck	R5 = 10 mΩ	C5.2 = 110 μF	L5.1 = 6 μH
		C6.1 = 0.33 μF	L5.2 = 1.5 μH
			L5.3 = 50 μH
(f) Superimposed Quadratic Buck	R6 = 10 mΩ	C6.2 = 1 μF	L6.1 = 1.5 μH
		C6.3 = 680 μF	L6.2 = 200 μH
			L6.3 = 200 μH



(a)



(b)



(c)

Figure 13. Cont.

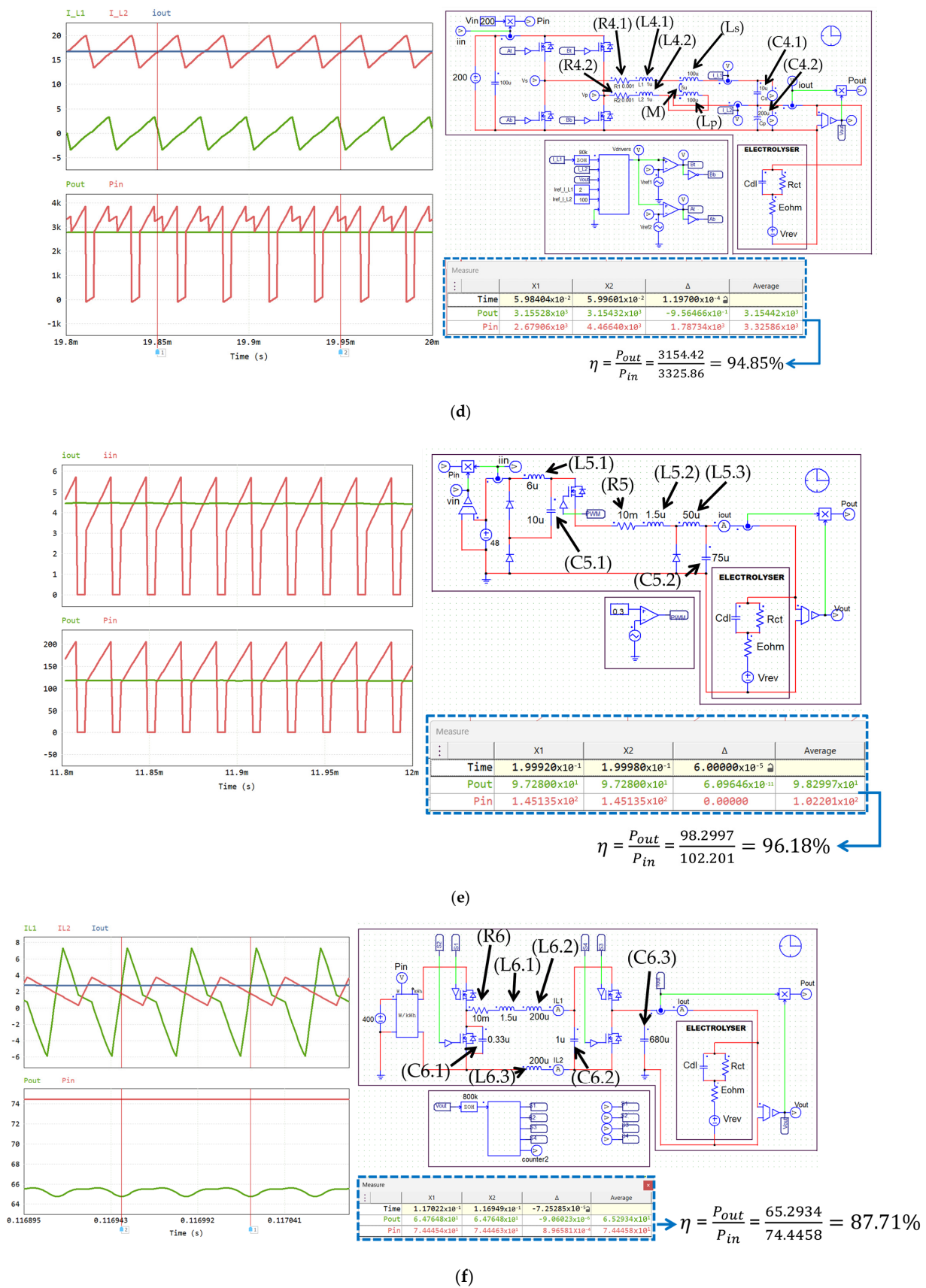


Figure 13. Simulation results: (a) dual active bridge converter; (b) standard buck converter; (c) synchronous buck converter; (d) stacked buck converter; (e) quadratic buck converter; (f) superimposed quadratic buck converter.

5. Conclusions

Hydrogen alone will not solve the problems that the world faces regarding greenhouse gas emissions, but it can be part of the solution, through the investigation, development, and deployment of more sustainable solutions for hydrogen production, storage, and usage. The use of renewable energy sources is highly dependent on the evolution of energy storage techniques, and H_2 is presented as a promising alternative since it is the most abundant element in the universe. Considering this statement, it becomes imperative that engineers and researchers worldwide determine the best ways to make the most out of this gas, without harming the planet that we live on and at the same time ensuring benefits similar to those that we have been enjoying, such as energy and resources, that are traditionally produced/obtained from fossil fuels or in ways that are negative for the environment.

There are several ways to produce H_2 , and the main ones are analyzed and presented in detail, with a focus on their advantages and disadvantages, which is an important output to highlight since they are summarized and compared in this review paper. Some of these technologies for producing H_2 are still in a preliminary stage, which means that there is much more room to either strengthen our knowledge of these newer technologies or to expand the other techniques that have already been industrialized and find better ways to use them in order to have more efficient and effective methods of producing this promising gas. As concerns G- H_2 , it is expected that through more research, development, and investment, its costs will decrease to prices that are the same as, if not lower than, the price of H_2 produced from fossil fuels. This would then lead to the worldwide adoption of H_2 in various industries and processes, as aforementioned, with the objective of reaching the 55% minimum reduction in CO_2 emissions in 2030 and the net-zero carbon goals set for 2050.

Power electronics technologies for G- H_2 production are indispensable, and their weaknesses and strengths have been analyzed. This work intended to emphasize the role of power electronics, and the main focus of this review was related to the production of G- H_2 . Thus, no topology was referred to as the best or the worst, because the suitability of a topology depends on the final application, the available means, and the manufacturing costs, among other factors. One distinguished and important factor to be noted is that all the aforementioned power electronics converter topologies ensure low output current ripple, either intrinsically or through the application of external filters to limit it. Regarding the power electronics converter topologies, the standard buck, the dual active bridge (including different configurations according to different contexts), the synchronous buck, the stacked buck, the quadratic buck, and the superimposed quadratic buck were presented in detail. A comprehensive comparison between all of them was established. The standard buck converter is also featured in this review paper because, even though it may be a less effective converter due to the fact that it still introduces ripple in the output current, through the implementation of filters, it can still have a decent behavior, and thereby, when its reduced cost is considered, it still may be seen as a viable option for simpler applications.

Funding: This paper is supported by the Alliance for the Energy Transition (56) co-financed by the Recovery and Resilience Plan (PRR) through the European Union. This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the R&D Units Project Scope: UIDB/00319/2020. Gonçalo Rego has a scholarship with the reference ATE_BI_2024_01_CALG (1).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. U.S. Department of Energy Los Alamos National Laboratory. Periodic Table of Elements: Los Alamos National Laboratory. Available online: <https://periodic.lanl.gov/1.shtml> (accessed on 27 October 2023).
2. Royal Society of Chemistry. Hydrogen—Element Information, Properties and Uses | Periodic Table. Available online: <https://www.rsc.org/periodic-table/element/1/hydrogen> (accessed on 27 October 2023).
3. Turoń, K. Hydrogen-powered vehicles in urban transport systems—Current state and development. *Transp. Res. Procedia* **2020**, *45*, 835–841. [CrossRef]

4. Manoharan, Y.; Hosseini, S.E.; Butler, B.; Alzhahrani, H.; Senior, B.T.F.; Ashuri, T.; Krohn, J. Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect. *Appl. Sci.* **2019**, *9*, 2296. [\[CrossRef\]](#)
5. Fan, L.; Tu, Z.; Chan, S.H. Recent development of hydrogen and fuel cell technologies: A review. *Energy Rep.* **2021**, *7*, 8421–8446. [\[CrossRef\]](#)
6. Yip, H.L.; Srna, A.; Yuen, A.C.Y.; Kook, S.; Taylor, R.A.; Yeoh, G.H.; Medwell, P.R.; Chan, Q.N. A review of hydrogen direct injection for internal combustion engines: Towards carbon-free combustion. *Appl. Sci.* **2019**, *9*, 4842. [\[CrossRef\]](#)
7. Fernandes, F.A. O Engenheiro Que está a Converter Motores a Diesel Para Hidrogénio—Expresso. Available online: <https://expresso.pt/iniciativaseprodutos/projetos-expresso/lideres-da-transicao/2023-11-07-O-engenheiro-que-esta-a-converter-motores-a-diesel-para-hidrogenio-9b7a5a9f> (accessed on 13 November 2023).
8. Ji, M.; Wang, J. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *Int. J. Hydrogen Energy* **2021**, *46*, 38612–38635. [\[CrossRef\]](#)
9. Kim, C.; Cho, S.H.; Cho, S.M.; Na, Y.; Kim, S.; Kim, D.K. Review of hydrogen infrastructure: The current status and roll-out strategy. *Int. J. Hydrogen Energy* **2023**, *48*, 1701–1716. [\[CrossRef\]](#)
10. Bairrão, D.; Soares, J.; Almeida, J.; Franco, J.F.; Vale, Z. Green Hydrogen and Energy Transition: Current State and Prospects in Portugal. *Energies* **2023**, *16*, 551. [\[CrossRef\]](#)
11. Mazloomi, K.; Gomes, C. Hydrogen as an energy carrier: Prospects and challenges. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3024–3033. [\[CrossRef\]](#)
12. Hydrogen for Mobility—The Challenge of Refueling. Available online: <https://www.reuters.com/plus/acumen-stories/cop-28/hrs> (accessed on 6 September 2023).
13. Repurposing Gas Infrastructure for Hydrogen. Available online: <https://www.siemens-energy.com/global/en/home/stories/repurposing-natural-gas-infrastructure-for-hydrogen.html> (accessed on 6 September 2023).
14. Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure: Overview of Existing Studies and Reflections on the Conditions for Repurposing. 2021. Available online: https://acer.europa.eu/sites/default/files/documents/Publications/Transporting%20Pure%20Hydrogen%20by%20Repurposing%20Existing%20Gas%20Infrastructure_Overview%20of%20studies.pdf (accessed on 30 October 2024).
15. Adam, P.; Heunemann, F.; Engelshove, S.; von dem Bussche, C.; Thiemann, T. Hydrogen Infrastructure-the Pillar of Energy Transition The Practical Conversion of Long-Distance Gas Networks to Hydrogen Operation. 2020. Available online: <https://www.nowega.de/wp-content/uploads/200915-whitepaper-h2-infrastructure-EN.pdf> (accessed on 30 October 2024).
16. Naganuma, K.; Sakane, Y. Examining Real-Road Fuel Consumption Performance of Hydrogen-Fueled Series Hybrid Vehicles. *Energies* **2023**, *16*, 7193. [\[CrossRef\]](#)
17. Hermesmann, M.; Müller, T.E. Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. *Prog. Energy Combust. Sci.* **2022**, *90*, 100996. [\[CrossRef\]](#)
18. Gielen, D.; Taibi, E.; Miranda, R. *Hydrogen: A Renewable Energy Perspective*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019.
19. Neuwirth, M.; Fleiter, T.; Manz, P.; Hofmann, R. The future potential hydrogen demand in energy-intensive industries—A site-specific approach applied to Germany. *Energy Convers. Manag.* **2022**, *252*, 115052. [\[CrossRef\]](#)
20. Sayed, E.T.; Olabi, A.G.; Alami, A.H.; Radwan, A.; Mdallal, A.; Rezk, A.; Abdelkareem, M.A. Renewable Energy and Energy Storage Systems. *Energies* **2023**, *16*, 1415. [\[CrossRef\]](#)
21. Faria, J.A.; Novo, M.; Dias, J.; Barros, L.A.M.; Pinto, J.G. Development of a Power Electronics Interface between an Energy Storage System and the Power Grid. In Proceedings of the 8th International Young Engineers Forum on Electrical and Computer Engineering, YEF-ECE 2024, Caparica, Portugal, 5 July 2024; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2024; pp. 57–62. [\[CrossRef\]](#)
22. Hydrogen—Isotopes, Deuterium, Tritium | Britannica. Available online: <https://www.britannica.com/science/hydrogen/Isotopes-of-hydrogen> (accessed on 20 September 2024).
23. Younas, M.; Shafique, S.; Hafeez, A.; Javed, F.; Rehman, F. An Overview of Hydrogen Production: Current Status, Potential, and Challenges. *Fuel* **2022**, *316*, 123317. [\[CrossRef\]](#)
24. Qazi, U.Y. Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications; Challenges and Expected Opportunities. *Energies* **2022**, *15*, 4741. [\[CrossRef\]](#)
25. Gürtekin, E. Biological Hydrogen Production Methods. 2014. Available online: <https://i-sem.info/PastConferences/ISEM2014/ISEM2014/papers/A10-ISEM2014ID80.pdf> (accessed on 30 October 2024).
26. Ajanovic, A.; Sayer, M.; Haas, R. The economics and the environmental benignity of different colors of hydrogen. *Int. J. Hydrogen Energy* **2022**, *47*, 24136–24154. [\[CrossRef\]](#)
27. Stenina, I.; Yaroslavl'tsev, A. Modern Technologies of Hydrogen Production. *Processes* **2022**, *11*, 56. [\[CrossRef\]](#)
28. Nnabuiife, S.G.; Darko, C.K.; Obiako, P.C.; Kuang, B.; Sun, X.; Jenkins, K. A Comparative Analysis of Different Hydrogen Production Methods and Their Environmental Impact. *Clean Technol.* **2023**, *5*, 1344–1380. [\[CrossRef\]](#)
29. Razi, F.; Hewage, K.; Sadiq, R. A comparative exergoenvironmental evaluation of chlorine-based thermochemical processes for hydrogen production. *Int. J. Hydrogen Energy* **2023**, *48*, 37108–37123. [\[CrossRef\]](#)
30. Gorji, S.A. Challenges and opportunities in green hydrogen supply chain through metaheuristic optimization. *J. Comput. Des. Eng.* **2023**, *10*, 1143–1157. [\[CrossRef\]](#)

31. Ammonia Production | Encyclopedia MDPI. Available online: <https://encyclopedia.pub/entry/1129> (accessed on 14 September 2024).
32. Massarweh, O.; Al-khuzaei, M.; Al-Shafi, M.; Bicer, Y.; Abushaikh, A.S. Blue hydrogen production from natural gas reservoirs: A review of application and feasibility. *J. CO₂ Util.* **2023**, *70*, 102438. [CrossRef]
33. Arcos, J.M.M.; Santos, D.M.F. The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production. *Gases* **2023**, *3*, 25–46. [CrossRef]
34. Alabbadi, A.A.; Obaid, O.A.; AlZahrani, A.A. A comparative economic study of nuclear hydrogen production, storage, and transportation. *Int. J. Hydrogen Energy* **2024**, *54*, 849–863. [CrossRef]
35. Yildiz, B.; Kazimi, M.S. Efficiency of hydrogen production systems using alternative nuclear energy technologies. *Int. J. Hydrogen Energy* **2006**, *31*, 77–92. [CrossRef]
36. Ji, M.; Shi, M.; Wang, J. Life cycle assessment of nuclear hydrogen production processes based on high temperature gas-cooled reactor. *Int. J. Hydrogen Energy* **2023**, *48*, 22302–22318. [CrossRef]
37. Diab, J.; Fulcheri, L.; Hessel, V.; Rohani, V.; Frenklach, M. Why turquoise hydrogen will Be a game changer for the energy transition. *Int. J. Hydrogen Energy* **2022**, *47*, 25831–25848. [CrossRef]
38. Gautier, M.; Rohani, V.; Fulcheri, L. Direct decarbonization of methane by thermal plasma for the production of hydrogen and high value-added carbon black. *Int. J. Hydrogen Energy* **2017**, *42*, 28140–28156. [CrossRef]
39. Alhamed, H.; Behar, O.; Saxena, S.; Angikath, F.; Nagaraja, S.; Yousry, A.; Das, R.; Altmann, T.; Dally, B.; Sarathy, S.M. From methane to hydrogen: A comprehensive review to assess the efficiency and potential of turquoise hydrogen technologies. *Int. J. Hydrogen Energy* **2024**, *68*, 635–662. [CrossRef]
40. Ishaq, H.; Dincer, I.; Crawford, C. A review on hydrogen production and utilization: Challenges and opportunities. *Int. J. Hydrogen Energy* **2022**, *47*, 26238–26264. [CrossRef]
41. Dincer, I. Green methods for hydrogen production. *Int. J. Hydrogen Energy* **2012**, *37*, 1954–1971. [CrossRef]
42. Dincer, I.; Rosen, M.A.; Al-Zareer, M. 3.11 Chemical Energy Production. *Compr. Energy Syst.* **2018**, *3*, 470–520. [CrossRef]
43. Soltani, R.; Rosen, M.A.; Dincer, I. Assessment of CO₂ capture options from various points in steam methane reforming for hydrogen production. *Int. J. Hydrogen Energy* **2014**, *39*, 20266–20275. [CrossRef]
44. Carbon | Facts, Uses, & Properties | Britannica. Available online: <https://www.britannica.com/science/carbon-chemical-element> (accessed on 16 September 2024).
45. Carbon—Element Information, Properties and Uses | Periodic Table. Available online: <https://www.rsc.org/periodic-table/element/6/carbon> (accessed on 16 September 2024).
46. The Value of Green Hydrogen Trade for Europe—RMI. Available online: <https://rmi.org/insight/the-value-of-green-hydrogen-trade-for-europe/> (accessed on 16 September 2024).
47. Purple Hydrogen: Is Nuclear Back on the Rise?—Energy Monitor. Available online: <https://www.energymonitor.ai/analyst-comment/purple-hydrogen-nuclear-back-rise/?cf-view> (accessed on 17 September 2024).
48. What Is Red Hydrogen? Interview with Our DirectIndustry Expert—DirectIndustry e-Magazine. Available online: <https://emag.directindustry.com/2023/02/15/what-is-red-hydrogen-interview-with-our-directindustry-expert-small-nuclear-reactor-smr-htgr-httr-japan-france/> (accessed on 17 September 2024).
49. Blay-Roger, R.; Bach, W.; Bobadilla, L.F.; Reina, T.R.; Odriozola, J.A.; Amils, R.; Blay, V. Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113888. [CrossRef]
50. White Hydrogen: 5 of the Most Critical Questions Answered | World Economic Forum. Available online: <https://www.weforum.org/agenda/2024/08/white-hydrogen-5-critical-questions-answered/> (accessed on 16 September 2024).
51. Incer-Valverde, J.; Korayem, A.; Tsatsaronis, G.; Morosuk, T. Colors' of hydrogen: Definitions and carbon intensity. *Energy Convers. Manag.* **2023**, *291*, 117294. [CrossRef]
52. Yang, Y.; Wang, G.; Zhang, L.; Zhang, S.; Lin, L. Comparison of Hydrogen Specification in National Standards for China. In *E3S Web of Conferences*; EDP Sciences: Les Ulis, France, 2019. [CrossRef]
53. Reporting Instructions Hydrogen-Annual Data V 1.1 2023. Available online: <https://ec.europa.eu/eurostat/documents/38154/16135593/Hydrogen+-+Reporting+instructions.pdf/> (accessed on 30 October 2024).
54. Kumar, S.S.; Himabindu, V. Hydrogen production by PEM water electrolysis—A review. *Mater. Sci. Energy Technol.* **2019**, *2*, 442–454. [CrossRef]
55. Lei, J.; Ma, H.; Qin, G.; Guo, Z.; Xia, P.; Hao, C. A Comprehensive Review on the Power Supply System of Hydrogen Production Electrolyzers for Future Integrated Energy Systems. *Energies* **2024**, *17*, 935. [CrossRef]
56. Buitendach, H.P.C.; Gouws, R.; Martinson, C.A.; Minnaar, C.; Bessarabov, D. Effect of a ripple current on the efficiency of a PEM electrolyser. *Results Eng.* **2021**, *10*, 100216. [CrossRef]
57. Górecki, K.; Górecki, P.; Zarebski, J. Electrical model of the alkaline electrolyser dedicated for SPICE. *Int. J. Circuit Theory Appl.* **2018**, *46*, 1044–1054. [CrossRef]
58. Gautam, D.S.; Bhat, A.K.S. A comparison of soft-switched DC-to-DC converters for electrolyzer application. *IEEE Trans. Power Electron.* **2013**, *28*, 54–63. [CrossRef]
59. Chen, M.; Chou, S.F.; Blaabjerg, F.; Davari, P. Overview of Power Electronic Converter Topologies Enabling Large-Scale Hydrogen Production via Water Electrolysis. *Appl. Sci.* **2022**, *12*, 1906. [CrossRef]
60. Kumar, S.S.; Lim, H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep.* **2022**, *8*, 13793–13813. [CrossRef]

61. Guo, X.; Zhu, H.; Zhang, S. Overview of electrolyser and hydrogen production power supply from industrial perspective. *Int. J. Hydrogen Energy* **2024**, *49*, 1048–1059. [\[CrossRef\]](#)
62. Guilbert, D.; Collura, S.M.; Scipioni, A. DC/DC converter topologies for electrolyzers: State-of-the-art and remaining key issues. *Int. J. Hydrogen Energy* **2017**, *42*, 23966–23985. [\[CrossRef\]](#)
63. Prabhala, V.A.; Baddipadiga, B.P.; Fajri, P.; Ferdowsi, M. An overview of direct current distribution system architectures & benefits. *Energies* **2018**, *11*, 2463. [\[CrossRef\]](#)
64. Deshmukh, R.S.; Shekhar, A.; Bauer, P. Adaptive Modularity for Power Electronics Based Electrolysis Systems for Green Hydrogen. In Proceedings of the 2022 IEEE 20th International Power Electronics and Motion Control Conference, PEMC 2022, Brasov, Romania, 25–28 September 2022; Institute of Electrical and Electronics Engineers Inc.: Brasov, Romania, 2022; pp. 508–515. [\[CrossRef\]](#)
65. Huang, T.W.; Kuo, S.H.; Wang, C.C.; Chiu, H.J. High Power Dual Active Bridge Converter in Wide Voltage Range Application. In Proceedings of the 2021 International Conference on Fuzzy Theory and Its Applications, iFUZZY 2021, Taitung, Taiwan, 5–8 October 2021; Institute of Electrical and Electronics Engineers Inc.: Taitung, Taiwan, 2021. [\[CrossRef\]](#)
66. Krismer, F.; Round, S.; Kolar, J.W. Performance Optimization of a High Current Dual Active Bridge with a Wide Operating Voltage Range. In *2006 37th IEEE Power Electronics Specialists Conference*; IEEE: New York, NY, USA, 2006.
67. Coelho, S.; Machado, J.; Monteiro, V.; Afonso, J.L. Power electronics technologies for renewable energy sources. In *Recent Advances in Renewable Energy Technologies*; Elsevier: New York, NY, USA, 2022; Volume 2, pp. 403–455. [\[CrossRef\]](#)
68. Sadigh, A.K.; Dargahi, V.; Abarzadeh, M.; Dargahi, S. Reduced DC voltage source flying capacitor multicell multilevel inverter: Analysis and implementation. *IET Power Electron.* **2014**, *7*, 439–450. [\[CrossRef\]](#)
69. Huang, C.C.; Liu, Y.C.; Lin, C.C.; Ni, C.Y.; Chiu, H.J. Stacked buck converter: Current ripple elimination effect and transient response. *Energies* **2021**, *14*, 64. [\[CrossRef\]](#)
70. Baharudin, N.H.; Mansur, T.M.N.T.; Hamid, F.A.; Ali, R.; Misrun, M.I. Performance Analysis of DC-DC Buck Converter for Renewable Energy Application. *J. Phys. Conf. Ser.* **2018**, *1019*, 012020. [\[CrossRef\]](#)
71. Liu, Q.; Qian, Q.; Shi, L.; Xu, Q.; Ding, S.; Sun, W. An improved Buck converter with high frequency and high step-down ratio for auxiliary power supply applications. *IET Power Electron.* **2023**, *16*, 2638–2649. [\[CrossRef\]](#)
72. Şahin, M.E.; Okumuş, H.I.; Aydemir, M.T. Implementation of an electrolysis system with DC/DC synchronous buck converter. *Int. J. Hydrogen Energy* **2014**, *39*, 6802–6812. [\[CrossRef\]](#)
73. El-Zanaty, M.; Orabi, M.; El-Sadek, M.Z. Review of Synchronous Buck Converter Design Optimization. In Proceedings of the 2008 12th International Middle East Power System Conference, Aswan, Egypt, 12–15 March 2008; IEEE: New York, NY, USA, 2008.
74. Guilbert, D.; Sorbera, D.; Vitale, G. A stacked interleaved DC-DC buck converter for proton exchange membrane electrolyzer applications: Design and experimental validation. *Int. J. Hydrogen Energy* **2020**, *45*, 64–79. [\[CrossRef\]](#)
75. Trakuldit, S.; Tattiwong, K.; Bunlaksananusorn, C. Design and evaluation of a Quadratic Buck Converter. *Energy Rep.* **2022**, *8*, 536–543. [\[CrossRef\]](#)
76. Karaket, K.; Bunlaksananusorn, C. Electrical Power Systems Modeling of a Quadratic Buck Converter. *IEEE Trans. Aerosp. Electron. Syst.* **2011**, *41*, 1450–1456.
77. Gorji, S.A. Reconfigurable Quadratic Converters for Electrolyzers Utilized in DC Microgrids. *IEEE Access* **2022**, *10*, 109677–109687. [\[CrossRef\]](#)
78. Kwak, J.W.; Ma, D.B. Superimposed Quadratic Buck Converter for High-Efficiency Direct 48V/1V Applications. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition—APEC, Orlando, FL, USA, 19–23 March 2023; Institute of Electrical and Electronics Engineers Inc.: Orlando, FL, USA, 2023; pp. 2253–2259. [\[CrossRef\]](#)
79. Majumdar, A.; Haas, M.; Elliot, I.; Nazari, S. Control and control-oriented modeling of PEM water electrolyzers: A review. *Int. J. Hydrogen Energy* **2023**, *48*, 30621–30641. [\[CrossRef\]](#)
80. Yodwong, B.; Guilbert, D.; Phattanasak, M.; Kaewmanee, W.; Hinaje, M.; Vitale, G. Proton Exchange Membrane Electrolyzer Modeling for Power Electronics Control: A Short Review. *C* **2020**, *6*, 29. [\[CrossRef\]](#)
81. Guilbert, D.; Vitale, G. Dynamic emulation of a PEM electrolyzer by time constant based exponential model. *Energies* **2019**, *12*, 750. [\[CrossRef\]](#)
82. Hernández-Gómez, Á.; Ramirez, V.; Guilbert, D. Investigation of PEM electrolyzer modeling: Electrical domain, efficiency, and specific energy consumption Investigation of PEM electrolyzer modeling: Electrical domain, efficiency, and specific energy consumption' Angel. *Int. J. Hydrogen Energy* **2020**, *45*, 14625–14639. [\[CrossRef\]](#)
83. Ganeshan, I.S.; Manikandan, V.V.S.; Sundhar, V.R.; Sajiv, R.; Shanthi, C.; Kottayil, S.K.; Ramachandran, T. Regulated hydrogen production using solar powered electrolyser. *Int. J. Hydrogen Energy* **2016**, *41*, 10322–10326. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.