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Anion exchange membrane: a valuable perspective in emerging technologies of low temperature water electrolysis

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Abstract

When powered by renewable energy source, efficient and low-cost water electrolysis may be a sustainable way to produce *green H₂*, making it competitive with respect to *grey H₂* from fossil fuels. In the present paper the urgency of improving the efficiency of the water electrolysis process has been highlighted, analyzing the recent progress in the scientific field. Anion Exchange Membrane Water Electrolysis (AEMWE) has been indicated as a new generation technique where the advantages of Alkaline (AWE) and Proton Exchange Membrane (PEM) Water Electrolysis (WE) could be joined. The combination of bibliometric and bibliographic analyses has been used to evaluate the temporal evolution of the research, and to identify the topics of recent investigation, and possible future developments.

Introduction

In the context of the 2020 Strategic Energy Transition Program, Europe identified green H₂ as the most compatible option with the climate neutrality goal and decided to increase its production, from today's 2% up to 13-14% by 2050. For H₂ to contribute to climate neutrality, its use must reach an industrial scale and its production must be completely decarbonized. In fact, to date, H₂ is still largely produced from natural gas or coal, resulting in an annual release of 70-100 Mton CO₂ in Europe [1]. Therefore, changing the production method is considered an indispensable strategy for the environmental sustainability.

Considering the current world situation, following such a strategy is even more important and urgent, since the availability of natural gas could be severely compromised. In most European countries, to cope with this emergent situation it has already been decided to reactivate the coal power plants, which will obviously slow down the goal of decarbonization. In this context, improving the exploitation of renewable energy sources becomes even more urgent. However, due to the intermittent nature of the renewable energy sources, a mismatch between supply and demand is originated, thus requiring an effective storage system. Among different clean storage solutions, green H₂ has been identified as the best candidate because it can be efficiently produced from water electrolysis (WE) powered by the renewable energy surplus [2]. Moreover, green H₂ represents a key element also for decarbonization of different civil and industrial sectors: it can be efficiently transformed in electrical energy by fuel cells, making it possible to compensate for the non-continuous availability of the renewable sources.

In these last years, the attention of the scientific community has been focusing on the electrochemical water splitting and several efforts are being made to increase the efficiency of the process and lower its costs. As for now, mainly due to the high costs of electrode materials and membrane separators, *green H₂* from WE is not yet competitive with *grey H₂* from steam reforming of fossil fuels, mainly natural gas. *Green H₂* is expected to be competitive by 2030-2040, although this economic forecast is likely to be affected by new political and economic scenarios as well as by the volatility of the markets of electricity and natural gas [3,4].

The present paper aims to examine the progress of the research on low-temperature WE during the last two years, identifying possible suggestions to address the future work. Starting from recent data (Key Performance Indicators) made available by specific companies and technical centers, we also tried to see how much scientific work agrees with the needs of the technical sector.

In the scientific context, based on data derived from the SCOPUS database, the work has been organized with a first bibliometric analysis, which is especially useful to underline or visualize the state of the knowledge, its possible evolution, and the emerging trends. The VOSviewer software [5,6] has been used to express the results with a map presentation, from which an immediate view of the data can be obtained. Zooming and scrolling functionalities offered by this software are especially useful for exploring larger networks consisting of hundreds or thousands of nodes.

Of note, a preliminary bibliometric analysis can be advantageous compared to a direct bibliographic analysis [7] as, the bibliographic search results are conditioned by the specific query and the related combination of keywords (KW) used in it. The use of a preliminary bibliometric analysis can instead help to better identify the sectors of interest.

A map presentation of data is used in the VOSviewer software, where: i) each node of the map is associated with a KW; ii) the node size depends on the number of times the KW is mentioned in the articles; iii) the distance between the nodes gives an idea of the connection between the different KWs; iv) the number of links starting from each node gives a measure of the relations between the different connected topics; v) the number of times that a couple of KWs is co-cited (total link strength TLS) indicates its relevance in the scientific field.

Among the different bibliometric analyses [5], in the present work the co-occurrence analysis has been performed, based on the number of times that the KWs co-occurred in the examined articles. The so-called overlay visualization has been used to present the results: a score is attributed to the items, evaluated as the average publication year (APY) of the papers where the related KWs appeared; different colors of the clusters allowed deriving indication of the topics which are currently under study.

Bibliometric analysis results

Data for the following surveys was retrieved from SCOPUS. The search was updated on March 25, 2022. Due to the continuous updating of records on SCOPUS, if the same search were to be performed on a different date, it would probably yield slightly different results.

The initial query Q1 was performed against the fields *keyword*, *title* and *abstract*, using the SCOPUS function "TITLE-ABS-KEY".

Q1: "TITLE-ABS-KEY (hydrogen AND "water electrolysis") AND (LIMIT-TO (DOCTYPE, "ar")) AND PUBYEAR > 2019

Among the different kinds of documents, only the articles have been considered and the reviews have been filtered out to avoid overlapping of information with respect to the original papers. Moreover, to better focus on papers specifically addressed to the selected topics, we decided to base the analysis not on the generic KWs, but only on those specifically indicated by the authors.

The results of the first *co-occurrence* analysis of KWs performed on the query Q1 are shown in figure 1.

As can be observed, among the yellow nodes (representing the items from papers with a more recent APY), the presence of words related to the topics under consideration is highlighted.

For example, the KW green H₂ (APY = 2020.95) is connected to KWs such as anion exchange membrane (APY = 2021.07), and PEM (APY = 2021.00). Among the yellow nodes we also note electrolyzer (APY = 2021.00), linked to solar energy (APY = 2021.00), and overpotential (APY = 2021.14).

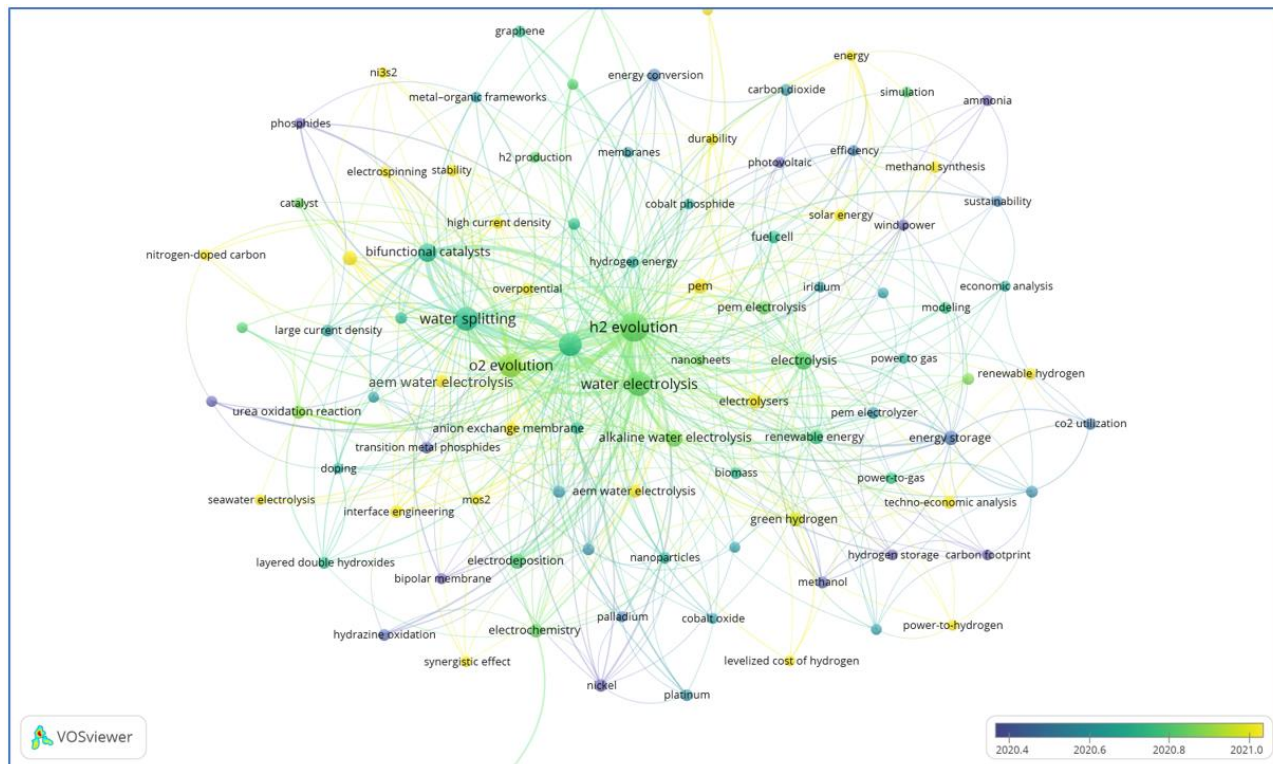


Figure 1 - Co-occurrence map of the KWs with minimum occurrence of 5 in the 1414 articles derived from the query Q1. The color of item is associated to the APY of all the articles in which the related KW has been used. An interactive visualization of the map is available at <https://bit.ly/3P2Pw0y> where the overlay visualization function can be selected. Accessed date: 25 March 2022.

Such nodes as water splitting, water electrolysis, H₂ evolution, and O₂ evolution, have the largest size, as they are more frequently used as KWs. Moreover, near to these nodes, also the term bifunctional catalyst appears to be relevant, with a value APY= 2020.70, less recent than the previous ones, but certainly of high relevance (the node has in fact 30 connections and a TLS = 134). The term alkaline electrolysis also appears with a slightly lighter green (APY = 2020.85).

The query Q2 has been used to investigate on the membranes used in the WE process for H₂ production.

Q2: (TITLE-ABS-KEY ("exchange membrane") AND TITLE-ABS-KEY ("water electrolysis") AND TITLE-ABS-KEY (hydrogen)) AND (LIMIT-TO (DOCTYPE, "ar"))

To derive indication on both the type of membranes and the past and recent use of them, this survey was carried out without time limitations.

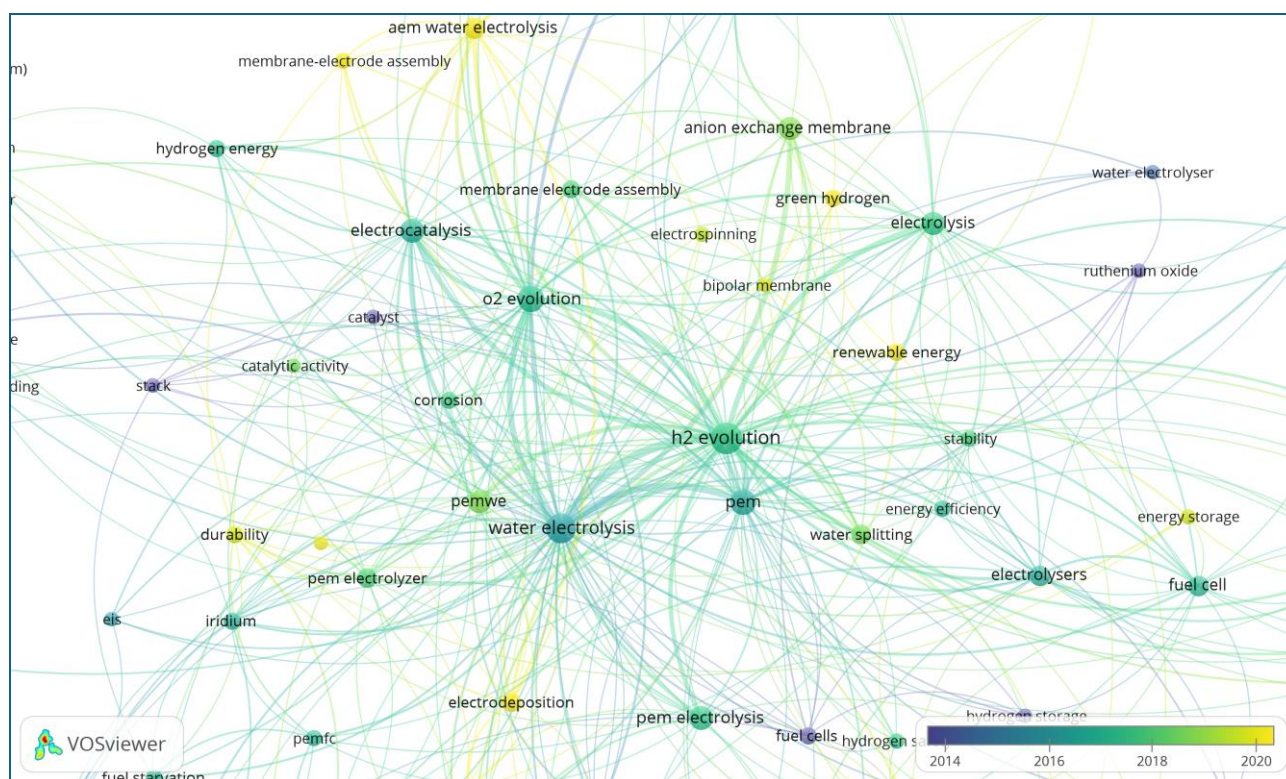


Figure 2 – Zoomed detail of the co-occurrence map of the KWs with minimum occurrence of 3 in the 516 articles derived from the query Q2. The color of item is associated to the APY of all the articles in which the related KW has been used. Full version of the map, and its interactive visualization is available at <https://bit.ly/3MbaBEg> where the overlay visualization function can be selected. Accessed date: 25 March 2022.

The map in figure 2 clearly shows how PEMs have been in use the longest time (dark green node, APY=2016.47); terms such as AEM water electrolysis (APY=2020.15), anion exchange membrane (APY=2018.60), and bipolar membrane (APY=2019.67) correspond to yellow or light green nodes in the map, confirming the more recent interest of the research community on these topics.

Q3: (TITLE-ABS-KEY (hydrogen) AND TITLE-ABS-KEY (water electrolysis)) AND PUBYEAR > 2019 AND AUTHKEY ("bifunctional catalyst" OR "bipolar membrane") AND (LIMIT-TO (DOCTYPE, "ar"))

Q4: ((TITLE-ABS-KEY ("exchange membrane") AND TITLE-ABS-KEY ("water electrolysis") AND TITLE-ABS-KEY (hydrogen)) AND PUBYEAR > 2019) AND AUTHKEY ("anion exchange membrane") AND (LIMIT-TO (DOCTYPE,"ar"))

On the bases of the previous results, the following final queries Q3 and Q4, have been used to select the final papers, object of the present review. In detail, 17 and 29 papers resulted from Q3 and Q4, respectively.

Analysis and discussion of data

Before moving on to the analysis and discussion of the data derived from the selected articles, the main Key Performance Indicators (KPI) (table 1) were derived from the reports of the EU Clean Hydrogen Partnership (Strategic Research and Innovation Agenda 2021-2027 [8]), and of the International Renewable Energy Agency (Green Hydrogen cost reduction scaling up Electrolyzers to meet the 1.5°C Climate Goal [3]) to compare scientific activities and technical data. Data in Table 1 show the SoA (state of the art at 2020) and the medium (2030) and long-term forecasts (2050); for the last three KPIs in the table, *Degradation*, *Capital Costs* and *Critical Raw Materials* (CRMS, as defined in the table caption) only estimates for the near future are available.

	PEMWE			AWE			AEMWE		
Parameter	SoA	2030	2050	SoA	2030	2050	SoA	2030	2050
Nominal Current Density (A/cm ²)	1-2	3	4-6	0,2-0,8	1	>2	0,2-2	1,5	>2
Operating Temperature (°C)	50-80	-	80	70-90	-	>90	40-60	-	80
Cell Pressure (bar)	≤30	-	>70	<30	-	>70	<35	-	>70
Load Range (%)	5-120	-	300	15-100	-	5-300	5-100	-	5-200
Electrical Efficiency (stack) (kWh/kg H ₂)	55	48	<42	50	48	<42	55	48	<42
Lifetime (stack) (hours)	50000-80000	-	100000-120000	60000	-	100000	>5000 ⁴	-	100000
Cold start (to nominal load) (minutes)	< 20	-	<5	<50	-	<30	<20	-	<5
Degradation (%/1000 h) ¹	0,19	0,12	-	0,12	0,1	-	>1	0,5	-
Capital costs (€/kW) ²	900	500	-	600	400	-	1000	300	-
Use of Critical Raw Materials (mg/W) ³	2,5	0,25	-	0,6	0	-	1,7	0	-

1: Stack degradation is defined as the percentage loss of efficiency when operating at nominal capacity

2: Capital costs are estimated assuming a 100 MW plant for a single company, and a lifetime of 10 years operating at steady state. End of life is considered to be reached when there is a 10% increase in the energy required for hydrogen production.

3: The CRM considered are: Ru in the anode and Pt in the cathode for PEMWE; Ru in the cathode for AWE; Ir in the anode and Pt in the cathode for AEMWE

4: Lifetime value for AEMWE for 2020, was > 5000 h according to [3], however recently the company Enapter has claimed lifetime values for their AEM systems of >35000 at 55°C operation time [www.enapter.com]

Table 1- *KPI values for the different low temperature water electrolysis technologies [3,8]1): Stack degradation defined as percentage efficiency loss when run at nominal capacity; 2): Capital cost are based on 100 MW production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby end of life is defined as 10% increase in energy required for production of hydrogen; 3):The critical raw materials considered are: Ru in the anode and Pt in the cathode for PEMWE; Ru in the cathode for AWE; Ir in the anode and Pt in the cathode for AEMWE*

KPI values are related to the three WE processes, alkaline water electrolysis (AWE), proton exchange membrane WE (PEMWE) and anion exchange membrane WE (AEMWE) considered in this work.

Based on data from the examined articles, figure 3 summarizes the main pros (green) and cons (red) of the two most popular systems, namely AWE and PEMWE, with the AEMWE as the main solution for an efficient and less expensive process.

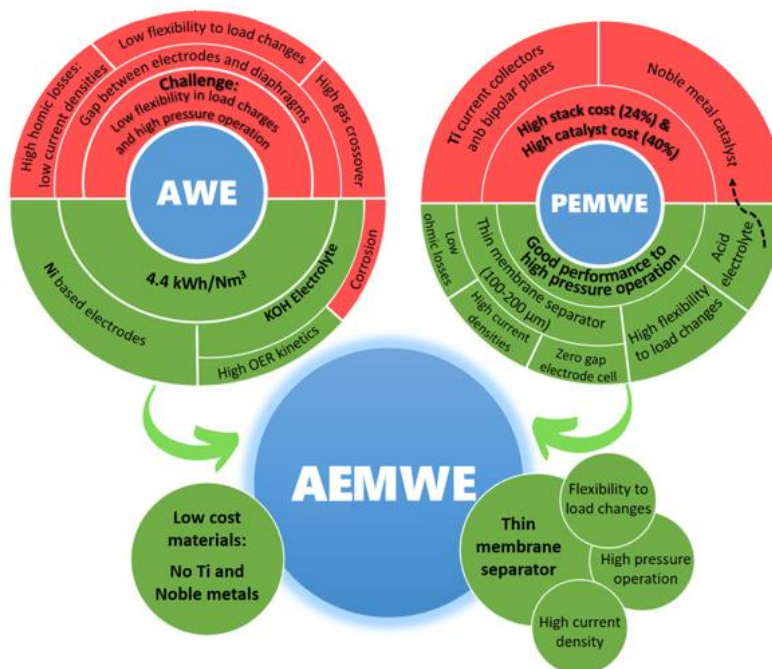


Figure 3 – Schematic representation of anion exchange membrane WE (AEMWE) that combines advantages of the alkaline (AWE) and PEM water electrolysis (PEMWE).

AEMWE is considered as a next generation technology that combines the low cost and stability of the electrodes of AWE with the dynamic response and high current densities of PEMWE [9,10*]. The membrane electrode assembly (MEA) configuration of the PEMs and the use of non-precious metal catalysts and less costly cell components may result in a cheaper hydrogen production [11*]. Moreover, in recent years increasing attention has been paid to replace the separator with polymer membranes, such as the polymeric anion-exchange membrane (AEM) or the ion-solvating membrane, because it allows using pure water or low concentrated electrolytes [12*,13].

However, as it is also evident from data in table 1, some of the current technological advances on AEMWE are declared to be further back than those on Alkaline and PEM electrolysis; AEMWE is still limited to a much narrow range of power input in comparison with the other technologies, so that it is far from large-scale application [3].

The following discussion has been focused on the critical aspects highlighted in the examined papers mainly related to the efficiency and stability of the membrane electrode assemblies (MEA), in terms of both membrane and electrode catalysts.

Commercial membranes used in AEMWE

Membrane	Company	Chemical Structure base	Reference
Sustanion	Dioxide Materials (USA)	Hydrocarbon based membranes with imidazolium groups	[9]
Orion TM1	Orion Polymer (USA)	Hydrocarbon-based membranes with quaternary ammonium groups	[14,15]
Fumasep FAA3	Fumatech (Germany)	Polyaromatic polymer with ether bonds in the main chain, and quaternary ammonium groups attached to the main chain	[16,17]
AEMION	Ionomr (Canada)	Methylated poly-benzimidazolium	[18]
Piperlon	Versogen (USA)	Poly(aryl piperidinium) membrane	[12]
A201	Tokuyama (Japan)	Hydrocarbon-based membranes with quaternary ammonium groups	[19]

Tab.2. Main characteristics of anionic commercial membranes used for AEM.

Table 2 summarizes the most common commercial AEMs used in the experimental cells reported in the examined papers. Their performance is highly dependent on the operative parameters (circulating liquid, type of binder, catalyst, etc.) so that the need of a standard protocol is highlighted [20*].

Ion conductivity is one of the critical points of the membranes, directly related to their thickness. Since the transport of hydroxyl ions is slower than that of protons [21], the AEMs demonstrate an ionic conductivity lower than the PEM, thickness being the same. To compensate for this lack, possible remedies are reported such as: i) lower thicknesses (usually ranging from 10-50 μm [22*]) and suitable reinforcement to compensate the poor mechanical stability [12]; ii) KOH solutions instead of pure water [14,23,24]; iii) higher working temperatures to improve both the AEM conductivity and the HER / OER kinetics.

However, high temperature operation can cause severe chemical damage in AEM undermining its stability and limiting its application on a large scale [22*]. For this reason, porous diaphragms are still used in AWE commercial cells: issues of low conductivity remain especially when not concentrated solutions are used, as well as H₂ crossover to anodic compartment when low current density is used. To face these problems porous diaphragms have been proposed [13]. High performance is measured, which is comparable to that of AEM electrolyzer using noble materials.

Concerning high pressure operation, in AWE, due to the use of diaphragms, the whole system is pressurized [3], while for AEMWE and PEMWE, differential pressure mode is preferred (30-70 bar for PEM) [3]. However, this option also involves some challenges, such as lower mechanical stability of the membranes and H₂ crossover. This last point has been little studied, especially in AEMWE. Recently, it has been shown that AEMWE systems can be as safe as PEM [25], with H₂ crossover as low as 0.16 times that of PEM systems. Several strategies are proposed to avoid H₂ crossover [3]: development of suitable porous transport layers (PTLs) to give consistency to thin membranes; development of thicker advanced membranes; increasing catalyst loading (prioritizing non-critical raw materials).

In AEMWE, the stability of the membrane and catalyst layers is a well-recognized key issue. This is especially important with KOH electrolyte, as the main degradation mechanism consists of hydroxide attack of the polymer backbone, with membrane collapse and dissolution of the catalyst layer, so the presence of soluble ionomers in the catalyst layer becomes critical. Electrochemical stability under oxidizing potentials with different electrolytes and phenyl oxidation during the operation of AEMWE were also found as significant causes of performance decay [26,27]. The performance of the MEA is strongly linked to the mechanical and chemical properties of the ionomer: its amount should be sufficiently high to guarantee the durable adhesion between PTL's, catalyst layers and membrane, but at the same time, excess of load should be limited to avoid possible swelling effects [14,17,28*-31*]. For example, a load of 15% of ionomer (Fumatech) resulted the optimal amount to improve the performance of Ni-Fe anodes [17]. It should be also noted that the anion exchange ionomers lead to lower HER performance in comparison with Nafion ionomer. In addition, the type of cations in the electrolyte and their concentrations also greatly affect the final performance [9*]. Apart from amount of ionomer, the main approaches to face degradation are cross-linking chemical methods or operating using only pure water (which can lead to a durability beyond 5000 hours). However, all these alternatives imply a reduction of efficiency [3].

The development of high-performance electrodes is another essential point to achieve economical hydrogen production using the AEMWE technology [32]. Different combinations of metals are extensively investigated to seek active catalysts for both OER and HER which, depending on the operative conditions, may be favored at different extent [17,33,34*]. However, due to the unfavorable kinetics of O₂ evolution, the main attention in the examined articles was always aimed at implementing the performance of the anodes. In some cases, the addition of molecules susceptible to oxidation, as sacrificial agents, is considered a possible solution to this problem. Among the different compounds proposed in the past, such as methanol, ethanol, hydrazine, 5-hydroxymethylfurfural, urea was considered as an ideal alternative due to its characteristics of abundance and low cost [35]. Owing to the lower thermodynamic oxidation potential, Urea oxidation reaction (UOR) has been proposed to replace the OER [36,37] in WE thus allowing the energy consumption to be lowered.

Developing efficient and sustainable OER catalysts is crucial to achieve higher cell efficiencies [38-40]. Due to the four electrons needed to produce one molecule of oxygen, several intermediate single electron states are involved, leading to a build-up of energy barriers and thus slowing the reaction kinetics, which is seen as the major source of energy loss. For example, Fe has been reported to be OER promoter for Ni and Co catalysts. The introduction of iron dopants in Co-based metal organic frameworks anodes increased the metal-O active sites, reducing the adsorbed binding energy of *O and *OOH intermediates. The related OER electrocatalytic activity outperformed the response of IrO₂ for OER in AEM conditions [33]. A home-made AEMWE cell was assembled with the Co/Fe (1:1)-MOF as the OER catalyst and commercial Pt/C as the HER catalyst, which exhibited a low overpotential of 490 mV at a large current density of 500 mA cm⁻², outperforming the cell with commercial IrO₂ as the OER catalyst [33].

Most of the solutions proposed in this regard are aimed at electrodes based on non-noble transition metals (carbides, nitrides, phosphides and chalcogenides) [41-44]. In fact, although IrO₂ or RuO₂-based catalysts generally show low overvoltage for HER and OER, respectively, the scarcity and cost of these electrocatalysts hinder their practical applications [45,46].

Recent studies reported that Ni and Co, either single or combined, are attractive elements for catalytic HER in alkaline electrolyte owing to their moderate hydrogen binding energy, which

provides suitable adsorption of the OH⁻ and H_{ads} intermediates. However, their effectiveness remains lower than that of Pt, so that combination with other metal components may be needed; moreover, both are earth-abundant metals, but Co is classified as CRM due to the high supply risk [31,33,34,47]. NiCu metal mixed oxides showed high HER performance, comparable with Pt, indicating their suitability to replace it [31]. The combination of Ni with La-Ce oxides (LCO) as cocatalysts, also allowed to improve Ni durability and the HER activity in AEMWE, where LCO acts as an electron donor forming a heterostructure with Ni [34].

Only in some cases, the use of noble metals is still considered. In particular, the least expensive Ru, combined with other metals and suitable porous supports [48] provided significant advantages when used as the cathode in the AEMWE: good performances were obtained, higher than those of the AEMWE with commercial Pt/C cathodes. Ru-doped bimetallic phosphide (Ru-NiCoP) deposited on Ni foams, possesses high conductivity and open channels within the interconnecting networks, so that it can facilitate electron transport and stabilize the working electrode to resolve the influence of bubbles generated during water splitting [49*].

The stability of the electrodes during long term operation is indicated as a further problem that limits the large-scale application of the WE process. Particle loss and delamination of the catalyst layer during operation have been indicated as degradation dynamics [31]. The problem is reported both with Pt group and non-noble metals, especially in terms of their possible stability in acid and alkaline environments [50,51]. Indeed, since HER and OER have different reaction pathways, usually a good catalyst for HER does not work well in OER and vice versa. Therefore, it is still very difficult to design and prepare a catalyst capable of simultaneously promoting HER and OER catalysis in the same electrolyte [52]. The methods of catalyst synthesis and pretreatment have been indicated very influential on the catalyst performance and structural modifications [53].

Bifunctional catalysts, able to activate oxidative and reductive processes in the meantime, possibly coupled with bipolar membrane (BPM), may be considered to increase efficiency and stability in the different reaction environments.

BPM consists of a cation exchange membrane permselective to cations (e. g., H⁺) adjoining with an anion-exchange membrane permselective to anions (e. g., OH⁻), enabling to employ acid-alkaline dual electrolytes in the cathodic and anodic compartments of a single cell, respectively [30,54]. The cathodic HER and anodic OER take place under conditions kinetically favorable for each reaction. Depending on the orientation of the BPM within the electrical field (forward or reverse bias), the water splitting may be facilitated via electrochemical neutralization and the required external electrical energy input may be reduced [55*]. Of note, very different potential values were reported [49*] for water electrolysis accomplished with the two configurations to deliver 10 mA cm⁻²: 1.72 V in the reverse bias configuration, and 1.01 V in the forward bias configuration. In such a way the BPM-based asymmetric water electrolysis would perform better than WE with noble metal electrocatalysts.

Moreover, bifunctional catalysts with high catalytic activity and durability at large current density (≥ 500 mA cm⁻²) are in demand to further reduce the cost and improve practicality [56,57]. Different proposals are reported to overcome the problems related to their effective use on large scale.

Investigation on the performances of bifunctional electrodes, is mainly based on the exploitation of the synergistic effects between the materials with various scales, to optimize the adsorption strength of intermediates on different active site [51,58]. In detail, the suggested actions may be highlighted as in the following list:

-i) *Crystalline and amorph structures combination*: the amorph phase demonstrated larger electrochemical surface area, over crystalline materials, and rich coordinatively unsaturated sites resulted effective centers improving the catalytic activity [50,52,59,60].

-ii) *Multi-metal oxide combination*: the diversity of metal compositions can offer more possible approaches to design catalysts. The synergy between different components can improve the electronic structure to achieve ideal adsorption/desorption sites enhancing the catalytic activity for OER and/or HER [28,31,50,57].

-iii) *Preparation method of the final structure*: Electrodeposition of the catalyst has been individuated as one of the most convenient over conventional synthesis techniques because of advantages including low cost, ease operation and low temperature requirements [57,61]. Moreover, it can be carried out directly on the porous support to obtain the gas diffusion layer, without the addition of binders [59].

-iv) *Selection of the best support*: improved gas diffusion layers and thinner membranes are indicated as crucial points for future improvements of the WE [12]. The support on which the active phase of the catalyst is prepared has a great effect on the performance. Different systems can be realized depending on whether the catalyst is coated onto the membrane or onto the PTL. The structural properties of PTL, such as pore size, porosity, and permeability, significantly influence the electrolysis performance [62]. The surface functionalization of carbon supports with conducting polymers demonstrated improved conductivity through π - π conjugation also providing more accessible active sites for electrochemical surface reaction [63]. This could increase the electron transfer rate over the active sites of the catalyst, then leading to improved OER performance.

Combination of BPM and bifunctional catalyst, constituted by a dual-phase cobalt phosphide-cobalt ditelluride nanowires, in the forward bias configuration, has been assessed as "*great promise as an alternative to the-state-of-art AWE and PEMWE technologies, which may allow for the large-scale production of hydrogen with minimum energy consumption*"[55].

Conclusions and future perspectives

Bibliometric analysis allowed identifying the various sub-topics of the scientific research on problems related to the cost of the WE process. The visualization of the data, weighted on the APY of the related articles, allowed evaluating the temporal evolution of the research and to identify the topics of recent investigation. Focusing the following bibliographic research on the most relevant papers published on the last two years was then possible.

From the analysis of the articles examined in this review, AEM technology emerged as a future candidate which combines the advantages and reduces the disadvantages of both PEMWE and AWE, this also in agreement with some technical data. Capital costs and use of critical material in AEMWE are technically expected to be more convenient than for PEMWE and AWE. However, the urgency to limit the Degradation and improve the efficiency of the process clearly emerged.

In most of the studies examined, the technologies were validated at laboratory scale and only in one case it concerned a pilot scale processes [64*]. Thus, the main fields where the action should be addressed on to make the process applicable on a large scale have been highlighted. In most cases, actions aimed to improve the performance of the anodes are emphasized, since the kinetics of O₂ evolution reaction is known to be the slowest one. Future studies to increase the catalytic activity and the performance of polyfunctional catalysts would be welcomed.

The possibility of carrying out the process under conditions such that both semi-reactions are favored is also of great interest. Such a process would require the use of bipolar membranes (anionic and cationic exchange membranes combination): coupled with bifunctional catalysts they would allow the large-scale production of hydrogen with minimum energy consumption. The possible increase in costs could be compensated by the increase in the kinetics of the overall process.

As a final consideration, we would like to specify that especially in such sectors where the number of publications is currently growing exponentially, the results of the analysis can significantly change over the course of months or even weeks. For this reason, rather than definitive conclusions or absolute numbers, the results of this survey should be considered as general trend or general suggestions to be used as indication on the possible ways where the next studies should be addressed.

Declaration of competing interest

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

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