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Review

Renewable Energy Potentials and Roadmap in Brazil, Austria, and Germany

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Abstract: The emerging energy transition is particularly described as a move towards a cleaner, lower-carbon system. In the context of the global shift towards sustainable energy sources, this paper reviews the potential and roadmap for hydrogen energy as a crucial component of the clean energy landscape. The primary objective is to present a comprehensive literature overview, illuminating key themes, trends, and research gaps in the scientific discourse concerning hydrogen production and energy policy. This review focuses particularly on specified geographic contexts, with an emphasis on understanding the unique energy policies related to renewable energy in Brazil, Austria, and Germany. Given their distinct social systems and developmental stages, this paper aims to delineate the nuanced approaches these countries adopt in their pursuit of renewable energy and the integration of hydrogen within their energy frameworks. Brazil exhibits vast renewable energy potential, particularly in wind and solar energy sectors, positioning itself for substantial growth in the coming years. Germany showcases a regulatory framework that promotes innovation and technological expansion, reflecting its highly developed social system and commitment to transitioning away from fossil fuels. Austria demonstrates dedication to decarbonization, particularly through the exploration of biomethane for residential heating and cooling.

Keywords: renewable energies; hydrogen energy; energy policy; energy transition

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1. Introduction

One major challenge today is developing clean fuels and alternative energy sources. This is due to the increase in world energy demand generated by the increase in population [1] and the growing pressure to control polluting emissions [2]. Fossil fuels, including petroleum, natural gas, and coal, account for over 80% of global energy consumption [3]. The depletion of finite fossil fuels represents a critical issue that needs to be overcome to achieve a sustainable energy future [4].

Renewable energy sources have the potential to fulfill approximately two-thirds of the worldwide energy demand. Previous assessments of future energy scenarios have demonstrated that it is technically feasible to enhance energy accessibility, air quality, and energy security concurrently, all while mitigating the risks of adverse climate change [2].

In the context of renewable energy, hydrogen (with the molecular formula H_2) serves as a carrier of environmentally sustainable energy [5]. Hydrogen as an alternative energy carrier has been extensively examined, particularly to produce electricity via fuel cells, which results in zero local pollution, as the sole byproduct generated is pure water [6].

Hydrogen and fuel cell technologies provide individuals with an enhanced spectrum of options during the transition to a low-carbon economy, owing to their comparable performance, operational characteristics, and user experience in comparison to fossil-fuel technologies [7]. The integration of hydrogen and fuel cell technologies stands out as a promising avenue to tackle the challenges associated with transitioning towards sustainable energy solutions, underscoring their potential to play a pivotal role in a broader spectrum of low-carbon initiatives.

In recent years, hydrogen has garnered recognition as a promising alternative to meet the escalating global energy demand, primarily attributable to its high energy efficiency. It can provide three times more energy than gasoline combustion per unit mass [8] and possesses an impressive energy storage capability, as evidenced by calculations indicating that 1 kg of hydrogen contains approximately 120 megajoules (equivalent to 33.33 kWh) of energy [3].

A broad consensus affirms the substantial potential of generating hydrogen from renewable energy sources such as solar and wind for advancing global sustainability [9]. In this context, processes utilizing renewable sources constitute a focal point in current research endeavors, encompassing areas such as water and biomass utilization. This focus arises from their capability to yield CO_2-free hydrogen, commonly referred to as green hydrogen. The primary procedural pathways for H_2 production from renewable sources involve electrolysis and thermochemical processes.

In the literature, numerous studies have delved into the technical–economic analysis of hydrogen production utilizing various renewable sources, including wind and solar [10]. Current initiatives aimed at advancing the utilization of green hydrogen in the energy transition are gaining momentum worldwide, with a significant focus on large-scale and energy-efficient electrolysis, as emphasized by the International Renewable Energy Agency [11].

This study is dedicated to conducting a thorough literature review of scientific publications related to hydrogen production and energy policies, with a specific emphasis on renewable energy. The investigation centers on the contexts of Brazil, Austria, and Germany, scrutinizing their respective policies within the realm of renewable energy. Brazil, on one side, and Austria/Germany (as examples of Europe), on the other, represent two completely different economic and political markets. This contrast provides an opportunity to examine the issues and solutions related to hydrogen usage from different perspectives, offering a broader view of the topic.

The primary objective of this study is to offer a comprehensive overview of the existing literature, shedding light on key themes, trends, and research gaps in the scientific discourse regarding hydrogen production and energy policy, particularly within the specified geographic contexts. This study aims to explore the significance of hydrogen in energy systems and underscore its crucial role in achieving a sustainable energy future. It also involves examining fresh policy suggestions and identifying specific opportunities and obstacles within the selected nations.

The study is conducted through a literature review of technical-scientific articles related to the research topic, obtained from the Scopus and Web of Science databases. Using the R programming language and the RStudio development interface, bibliometric analysis is performed with bibliometrix (R Language), ensuring the consolidation of documents without duplication for subsequent analysis.

This paper is organized into distinct sections. Section 2 conducts a comprehensive review of relevant publications to elucidate the role of hydrogen production in the global energy system. Section 3 delves into decarbonization energy policies, examining the varied approaches adopted in different regions. Section 4 explores sustainable pathways for the hydrogen sector, specifically focusing on America and Europe, providing insights into innovative strategies and initiatives. Section 5 concludes the paper.

2. The Role of Hydrogen Production in the Global Energy System: A Review of Relevant Publications

Figure 1 illustrates a comprehensive overview of global research publications on hydrogen production, showcasing the contributions of various countries to this pivotal field of study. The data presented in the figure span from 2018 to 2022, reflecting the global landscape of scientific production during this period. Notably, China emerges as the frontrunner, with an impressive 4554 publications, underscoring its significant commitment to advancing hydrogen production technologies. Following closely, the United States has produced 964 publications, highlighting its robust research ecosystem in this domain. India, South Korea, Turkey, Iran, and Canada also demonstrate substantial engagement, with 843, 724, 546, 505, and 498 publications, respectively.

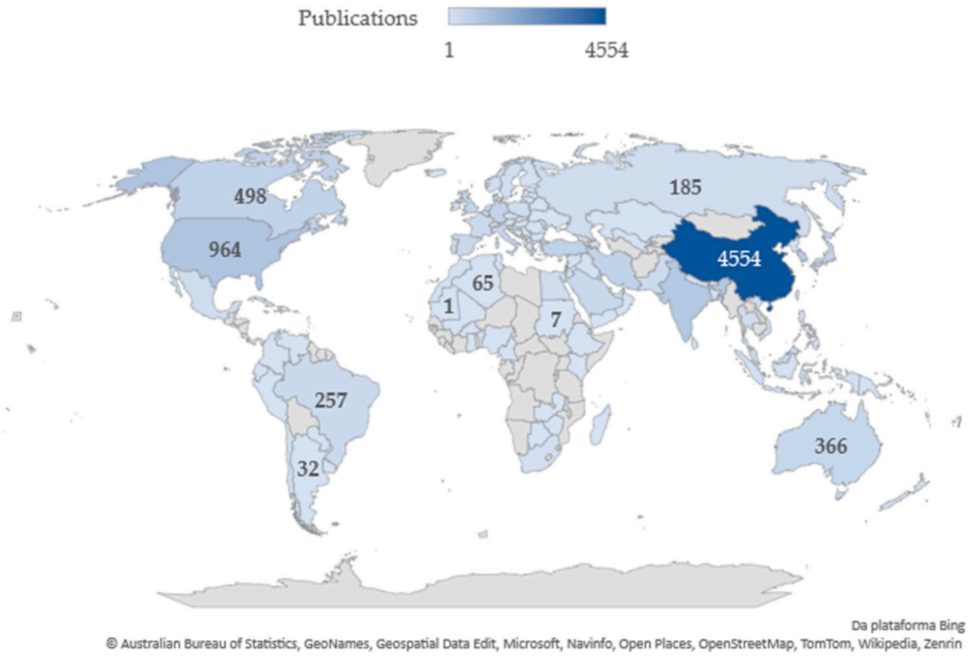

Figure 1. Global hydrogen production research publication landscape (data from Scopus 2018–2022).

The data presented in this figure reveals the global landscape of research activities in the field of hydrogen production, including the number of publications per country. China's dominant position in publications reflects its proactive approach to hydrogen-related research, likely driven by its growing interest in sustainable energy solutions. This preeminence can be ascribed to various factors, including China's substantial investment in research and development, governmental initiatives aimed at fostering clean energy technologies, and the country's extensive reservoir of resources and infrastructure.

Conversely, the robust presence of the United States accentuates its unwavering dedication to scientific progress, particularly in the domain of clean energy technologies. Leveraging a resilient research ecosystem comprising top-tier universities, research institutions, and significant private sector investments, the United States remains at the forefront of scientific innovation. Furthermore, supportive government policies and funding mechanisms further bolster the nation's leadership in scientific research endeavors.

The disparities observed in research activity levels among other nations carry significant implications for global collaboration, knowledge dissemination, and technological advancement. Countries with comparatively lower research activity may encounter hurdles in accessing the latest breakthroughs, potentially impeding their capacity for technological innovation and implementation. Therefore, prioritizing international cooperation and forging strategic partnerships becomes imperative in redressing these disparities and propelling progress toward sustainable energy solutions on a worldwide scale.

Similar reviews focusing on other countries have been conducted, providing insights into their respective research landscapes. For instance, a comprehensive analysis of hydrogen production research in China by Chai et al. (2021) and Ren et al. (2020) revealed the country's dominant position in this field, driven by its proactive approach to sustainable energy solutions [12,13].

Furthermore, a study by Li et al. (2020) examined hydrogen-related research activities in the United States, particularly in the context of paths to low-cost hydrogen energy at a scale for transportation applications, and also included a comparison with China [14]. This analysis highlights the nation's enduring commitment to scientific advancements, particularly in clean energy technologies.

Currently, several processes take place in the production of hydrogen (e.g., electrolysis and gasification), varying according to the raw material used. The raw materials most frequently utilized in the production of hydrogen are essentially fossil fuels (e.g., natural gas, oil, and coal), biomass, and water. The most interesting hydrogen production process in a world where sustainability and sustainable production are sought is electrolysis, which is the breakage of water molecules, using various renewable sources (e.g., wind, hydroelectric and solar energy).

Currently, about half of the world's hydrogen production is from natural gas, and most of the industrial-scale production is by the steam reforming process (48% of the world's total hydrogen production) or as a by-product of petroleum refining and chemical compound production [15]. It underscores the need for accelerated efforts in transitioning to more sustainable and environmentally friendly hydrogen production methods.

There are five main forms of hydrogen production [16,17], as shown in Figure 2. Green hydrogen is produced from electrolysis using renewable electricity generation sources. Gray hydrogen is produced from steam methane reforming. Blue hydrogen is produced using fossil sources utilizing capture and storage of CO_2 techniques [18]. Brown hydrogen is produced by coal gasification. White hydrogen consists of the electrolysis of water using electricity generated from different energy sources [16].

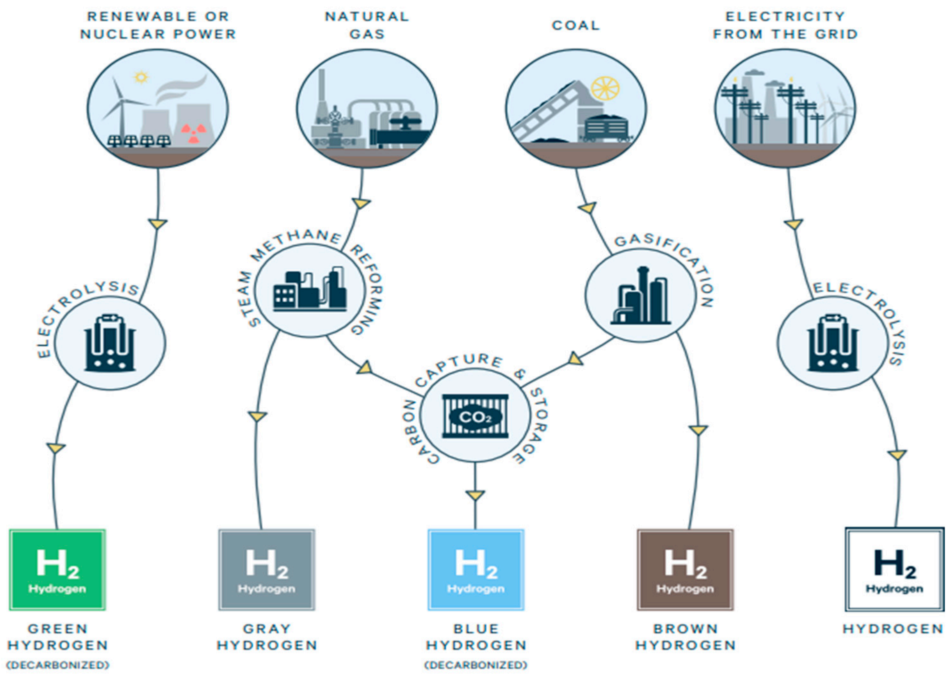

Figure 2. Different forms of hydrogen production [17].

The TreeMap visualization in Figure 3 offers a comprehensive view of the most crucial keywords and their frequencies within a compilation of articles from the period 2018–2022 on the subject of hydrogen production. Table 1 represents the association of keywords with hydrogen production methods. Collectively, these keywords portray a multidisciplinary approach to advancing hydrogen production technologies, driven by a commitment to sustainable and environmentally responsible energy solutions. Notably, the fraction of references corresponding to "fermentation", "electrolysis", and "carbon dioxide" each equals 6% of the total number of references, indicating a shared emphasis on diverse hydrogen production methods and a commitment to addressing environmental concerns, particularly carbon emissions. "Catalyst activity", "hydrogen generation", and "electrocatalysts", each at 5%, underscore the pivotal role of catalysts in enhancing the efficiency of hydrogen production processes.

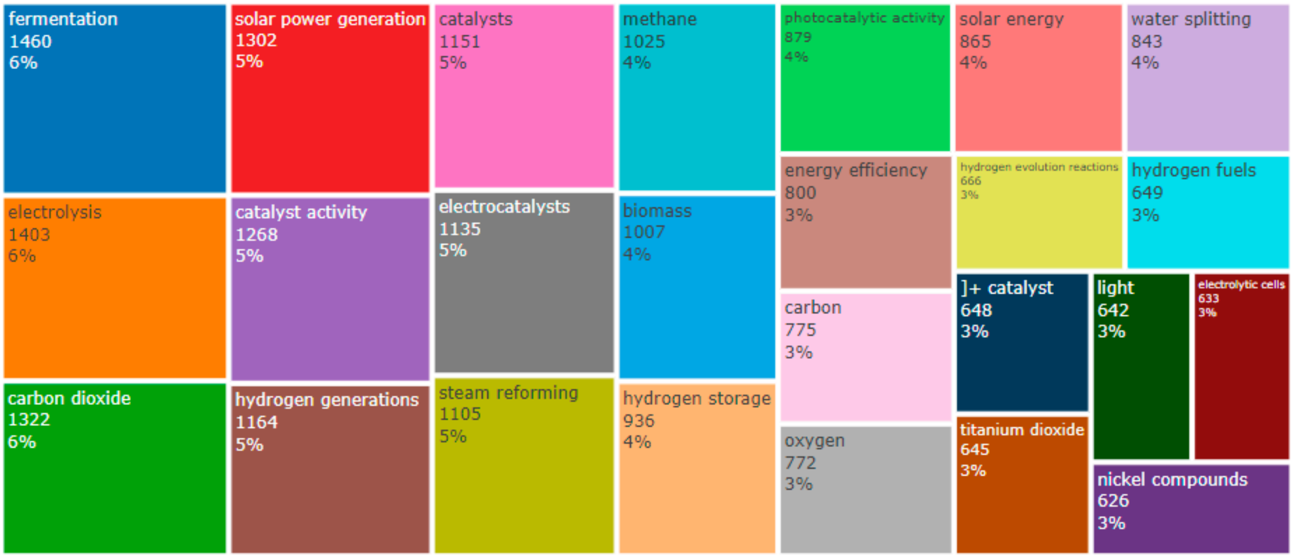

Figure 3. Relevant keywords regarding hydrogen production, 2018–2022 (Scopus).

Table 1. Association of keywords with hydrogen production methods.

Related Keywords	Forms of Hydrogen Production					Description	References
	Green	Gray	Blue	Brown	White		
Fermentation	x	x				Several studies in the literature employ fermentation processes for the development of sustainable technologies for H_2 production, while others view it as gray.	e.g., [19,20]
Electrolysis	x					Among several hydrogen production methods, eco-friendly and high-purity hydrogen can be obtained through water electrolysis.	[21]
Carbon dioxide		x	x			Gray hydrogen is produced through steam methane reforming (SMR), while blue hydrogen is derived from SMR with CO_2 capture and storage (CCS).	[18]
Catalyst activity	x	x	x	x	x	Catalyst activity can be assessed in various hydrogen processes, including gray, white, blue, brown, and green processes.	[22–25]
Hydrogen generations	x	x	x			Hydrogen generation technology assumes a central role in determining the course of hydrogen utilization, exerting a profound influence on its multifaceted applications across diverse sectors.	[18,26–28]
Electrocatalysts	x					Developing cost-effective electrocatalysts for green water electrolysis is a topic of significant research interest.	[25]
Steam reforming		x				SMR of natural gas is currently the most mature and extended technology for gray hydrogen production.	[18]

Table 1. *Cont.*

Related Keywords	Forms of Hydrogen Production					Description	References
	Green	Gray	Blue	Brown	White		
Methane		x	x			SMR processes can give rise to gray hydrogen or blue hydrogen when carbon capture is employed, with several studies evaluating the catalytic effect with methane reforming.	[18,29–32]
Biomass	x		x			Blue-green pathways offer numerous benefits and warrant serious consideration in the global decarbonization effort, particularly when utilizing microorganisms such as microalgae and cyanobacteria, which are significant sources of biohydrogen.	[26–28,33]
Hydrogen storage	x	x	x	x	x	The hydrogen storage technology is crucial for the advancement of this technology, being linked to its entire production chain.	[18,26–28]
Photocatalytic activity	x					Using a photocatalyst empowers prospective applications for the evolution of green hydrogen. Photocatalytic H_2 production is proven to be one of the cleanest methods for harvesting both hydrogen and oxygen.	[34]
Energy efficiency	x	x	x	x	x	Energy efficiency is linked to the entire production process. In alkaline electrolysis, for instance, the energy efficiency is approximately 70–80%.	[21,33]
Titanium dioxide	x					Titanium dioxide (TiO_2) is a promising candidate for photocatalytic H_2 production due to its favorable properties, including a large band gap, low cost, non-toxicity, and chemical stability.	[35]

"Steam reforming" and "methane" at 5% and 4%, respectively, suggest research into alternative hydrogen production methods and the utilization of methane as a feedstock. "Biomass" and "hydrogen storage" at 4% each highlight the importance of sustainable feedstock and efficient storage solutions. The keywords "photocatalytic activity" and "energy efficiency" at 4% and 3%, respectively, showcase the pursuit of energy-efficient and environmentally friendly hydrogen production through photocatalysis and carbon-related innovations. The presence of "solar energy" and "titanium dioxide" at 3% each signifies interest in harnessing solar energy for water splitting, often utilizing titanium dioxide as a photocatalyst.

Hydrogen plays a crucial role in energy transition due to its transport capacity. It can be conveyed using intermediate energy carriers such as ammonia, methylcyclohexane, methanol, and others [36]. H_2 is widely recognized as a high-potential energy vector in the advancement of clean energy.

The primary challenge associated with this alternative is the low energy density of the fuels and the challenges of producing the fuels and transforming them back to hydrogen [36]. Nevertheless, with the development of energy policies and cooperation agreements among countries aiming to decarbonize their energy sources, it is possible to overcome the technological challenges associated with the transportation and storage of hydrogen. This progress may pave the way for a scenario in which new transportation and storage technologies will be developed.

3. Decarbonization Energy Policies

3.1. European Landscape

In the dynamic landscape of European energy policies, key directives and agreements have played pivotal roles in shaping the transition towards renewable energy sources (RES) and decarbonization. The 2009 Renewable Energy Directive (RED1) and the Fuel Quality Directive (FDQ) stand out as fundamental policy references at the European Union (EU) level, outlining a framework (Directive, 2009/28/EC [37], 2009/30/EC [38], European Commission) to stimulate the utilization of renewable energy sources in transport [39].

However, the journey towards a sustainable energy future faced new challenges in 2015. A directive aiming to mitigate indirect land use change for biofuels and bioliquids (EU, 2015/1513 [40]) introduced complexities to the targets set by RED1 and FDQ, reflecting the evolving nature of EU energy policies [39].

On the global stage, the Conference of the Parties in December 2015 resulted in the historic Paris Agreement, where 195 countries collectively committed to urgent climate action. This agreement set the ambitious goal of limiting global warming to well below 2 °C, with efforts to restrict it further to 1.5 °C. Nationally Determined Contributions (NDCs) emerged as a tangible outcome, with countries pledging initiatives such as increased use of RES, enhanced energy efficiency, and reduced CO_2 emissions in various sectors, including transport and waste management [41].

Building on these commitments, the European Commission proposed a revised Renewable Energy (RE) directive in November 2016 as part of the Clean Energy for All European Package (RED2). The recast RE directive, effective since December 2018, signifies a significant stride towards positioning the EU as a global leader in renewable energy, establishing a target of a minimum 32% share of RE by 2030 (Directive, 2018/2001/EU [42]) [39].

Within the European context, the transport sector poses a significant challenge, primarily reliant on fossil fuels, thereby jeopardizing efforts to maintain global warming within safe limits [43]. To address this, stringent criteria have been set to ensure that only bioenergy sources meeting sustainability standards receive financial support for bioenergy consumption, contributing towards EU RES targets and national obligations [44].

However, integrating second-generation biofuels, such as bioethanol and biodiesel, presents a nuanced challenge due to potential conflicts with land and water use for food supply [39]. Amidst these policy frameworks and challenges, the European Union faces a substantial obstacle to supply security. More than half of the energy demand is met through imports, with crude oil constituting over 90% and natural gas 66%, amounting to a significant economic risk exceeding EUR 1 billion per day [45]. This emphasizes the need for holistic and resilient strategies to address the complex interplay of energy security, sustainability, and decarbonization in the European context.

3.1.1. Austria

In a landmark decision in 1978, Austrians, through a democratic referendum, banned the use of nuclear power, positioning wind and solar power as the exclusive options for significant expansion in low-carbon power generation [46,47]. Moreover, measures introduced in 1998, such as requiring grid operators to accept electricity from renewable sources, laid the groundwork for the nation's enduring dedication to renewable electricity. This commitment gained further momentum in 2002 by adopting Austria's climate strategy as a nationwide plan, aligning with international agreements such as the Kyoto Protocol. Under this protocol, Austria pledged to reduce greenhouse gas emissions by 13% below 1990 levels by 2008–2012 [48]. This pivotal moment set Austria on a path towards a nuclear-free and environmentally sustainable energy future. The cornerstone of this transition is the Green Electricity Act [49] of 2002, which, when amended in 2012, defined ambitious installation targets for solar photovoltaic and wind power, reflecting Austria's commitment to harnessing renewable energy [49].

The inception of the "Green Electricity Act" in 2002 marked Austria's inaugural step toward boosting the share of non-hydro RES. This policy, coupled with a lucrative feed-in tariff, successfully attracted investments, fostering the growth of renewable energy deployment [50]. In the realm of electricity generation and supply, the Green Electricity Act played a pivotal role in shaping Austria's renewable energy landscape. The Act not only introduced feed-in tariff schemes but also incentivized investments through grants and green electricity bonuses, propelling the integration of high-efficiency co-generation installations into the RE sector [48]. Austria's steadfast commitment to the Green Electricity

Act showcases its dedication to sustainable, low-carbon energy solutions, steering the nation towards a greener and more resilient energy future.

According to the Integrated National Energy and Climate Plan for Austria 2021–2030, the significance of RE sources in achieving climate targets is underscored by the spatial reference to the availability of renewables in Austria [51]. Recognizing the pivotal role of renewable heating systems, Austria implemented measures in its 2010 Energy Strategy, emphasizing the imperative to accelerate building refurbishment and replace fossil-based heating systems with sustainable alternatives. In a bid to incentivize the use of biofuels, Austria's Mineral Oil Act of 2007 granted tax concessions for fuels with a biofuel share of at least 6.6% and 4.6% for diesel and petrol, respectively. However, the subsequent fuel ordinance amendment in 2008 imposed limitations, capping the biodiesel share in the fuel supply at a maximum of 7% [48].

To provide a clear and stable framework for renewable energy deployment, Austria enacted the RES legislation in July 2011, known as Ökostromgesetz 2012. This legislation marked a significant milestone by introducing long-term deployment perspectives with concrete target values, ensuring a stable legal framework for renewable energy initiatives until 2020 [52]. In synthesizing these measures, Austria demonstrates a comprehensive and forward-looking approach to integrating renewable energy into its national energy strategy, reflecting its commitment to sustainability and climate goals.

Austria is steadfast in its commitment to achieving 100% renewable energy in its electricity mix by 2030 through the visionary "Mission 2030" [53]. In tandem, the government plans to generate an additional 27 TWh of electricity each year from renewable sources, culminating in a total of 78.3 TWh of renewable electricity generation in 2030 [47]. Austria's climate policy, a linchpin of Mission 2030, targets a substantial 36% reduction in greenhouse gas emissions by 2030 compared to 2005 levels. This strategic initiative not only guides investments in the energy sector but also aligns with Austria's broader goals of decarbonization, showcasing its dedication to global environmental sustainability [54].

In the broader context, Austria's commitment echoes the concrete policy actions of the European Council, which, in 2014, adopted the 2030 climate and energy framework, a significant stride towards fulfilling the Paris Agreement [39,55]. Going beyond traditional energy policies, Mission 2030 places a strong emphasis on social affordability and participatory governance. By 2030, Austria envisions meeting all of its electricity demands from domestic renewable sources, with a specific focus on wind energy [47]. Key factors for social and public acceptance are outlined, including the evaluation of economic rationality, such as levelized costs of energy generation. The strategy encourages collaborative efforts for effective social solutions and advocates for good governance principles, ensuring transparent access to information and awareness-raising measures [54].

Moreover, Austria stands as a pioneer in advancing energy flexibility through initiatives such as the Climate and Energy Fund, which prioritizes bottom-up approaches, local governance, and stakeholder engagement, empowering laypeople in decision-making for energy sector decarbonization [54]. According to the Climate and Energy Fund, this commitment is exemplified by the fund's long-standing support for sustainable energy activities at grassroots levels in municipalities and regions [56]. The synergy between Mission 2030 and the Climate and Energy Fund underscores Austria's holistic and innovative approach, reaffirming its dedication to a sustainable, inclusive, and flexible energy future.

On a broader scale, the main Swiss energy policy, Energy Strategy 2050 (Energiestrategie 2050), outlined in the Energy Law (Energiegesetz, EnG), defines ambitious targets for the expansion of the RE sector [57,58]. With Switzerland adopting the Energy Strategy 2050 in 2016 [58] and Austria amending its ÖSG in 2012, both countries are navigating evolving policy landscapes. Caution is advised in changing the current policy system to avoid disadvantaging community energy initiatives, considering the nascent nature of Community Renewable Energy (CRE) investments. A case from Germany illustrates how policymakers can create an advantageous framework for CRE projects, even amid policy changes [59].

The policies implemented by Austria to promote renewable energy adoption have demonstrated significant progress towards achieving a transition to a low-carbon energy system. The decision to ban nuclear power in 1978, followed by subsequent legislative measures such as the Green Electricity Act of 2002, underscore Austria's commitment to renewable energy development. These policies have successfully incentivized investments in renewable energy deployment, resulting in tangible outcomes such as increased installation of solar photovoltaic and wind power systems.

Additionally, the implications of Austria's renewable energy policies extend beyond its borders, aligning with broader European and international climate and energy frameworks. The synergy between Austria's Mission 2030 and initiatives such as the Climate and Energy Fund highlights its holistic approach towards sustainable energy development. However, ongoing evaluation and adaptation of policies will be necessary to address evolving challenges and ensure the long-term success of Austria's transition to a renewable energy-based economy.

To mitigate these challenges, collaborative efforts between government agencies, private sector stakeholders, and civil society organizations can foster transparency, accountability, and stakeholder participation in decision-making processes related to energy development projects. Furthermore, promoting public awareness and education campaigns on the benefits of renewable energy and sustainable energy practices can help garner support for clean energy initiatives and encourage behavioral changes towards more environmentally friendly energy consumption patterns.

3.1.2. Germany

Germany's commitment to reshaping its energy landscape is evident in its ambitious policies outlined in the German Coal-fired Power Generation Termination Act (KVBG) and the revised German Renewable Energy Sources Act (EEG 2021) [60,61]. These policies signify a transformative shift, including the anticipated cessation of nuclear power generation and a partial coal exit by 2030 [47].

The introduction of the Renewable Energy Act in 2000 was aimed at diversifying investors and professionalizing the sector [62]. However, responding to EU guidelines, the German government transitioned to an auction-based system in 2014, raising concerns about potential compromises to the diverse actors in the German RE system. Despite implementing measures to support community energy projects, questions persist regarding their effectiveness in addressing challenges associated with standard project finance approaches [62].

Germany's commitment to the aggressive deployment of RES technologies surpasses EU targets. As part of its Energiewende initiative, Germany aims to increase the share of RES in gross electricity consumption to 50% by 2030 and an ambitious 80% by 2050, contributing significantly to the overarching goal of an 80–95% reduction in GHG emissions by 2050 [50].

The German Climate Action Plan 2050 outlines a bold initiative to provide electricity entirely from renewable sources by 2050 [63]. The German Federal Government has set expansion goals for RE shares in total electricity generation, targeting 40–45% by 2025 and 55–60% by 2035 [64].

Legislation, including the Grid Feed-In Act in 2000, has played a pivotal role in shaping Germany's energy transition [65]. The Renewable Energy Sources Act 2017 (EEG) defines self-supply and introduces the concept of an energy community, translating as 'Citizen Community' (EEG). Efforts are underway to increase the renewable energy share in total energy production, aligning with Germany's climate goals for 2050, e.g., [66].

The Energiewende, or energy transition, represents a strategic shift towards a renewable energy-dominated portfolio. Germany aspires to achieve as close to a 100% substitution of non-renewable energy sources as possible, with specific sub-goals for greenhouse gas reduction, renewable energy share, increased electricity efficiency, and associated research and development efforts [66]. The ongoing transition has already yielded a substantial increase in renewable energy production, particularly in wind energy [67].

Germany's energy transition journey dates back to the introduction of the Grid Feed-In Law in 1990, which proposed a feed-in tariff [68,69]. The subsequent Renewable Energy Sources Act (EEG 2000) marked a significant shift, differentiating between various renewable energy sources and setting a target to increase the share of electricity generated from renewable sources from 5% to 10% by 2010 [68].

Modifications to the EEG in subsequent years reflected evolving political landscapes and responses to challenges, including the Fukushima disaster in 2011 [68,70–72]. The Energy Security of Supply Act empowers regulatory acts to ensure individual responsibility for backup solutions, aligning with Germany's focus on increasing energy efficiency and achieving 2030 energy and climate goals [73].

These policies strategically promote sustainable energy practices and contribute to global efforts to achieve emission reduction targets [74]. As wind and solar energy gain prominence in Germany's electricity sector, the country's energy policy shifts toward integrating electricity generation from these renewable sources [75]. Germany's recognized success in promoting renewable energy is evident in its consistent global ranking and strategic initiatives, such as the Energiewende [76,77].

Furthermore, Germany's comprehensive and evolving energy policies reflect its commitment to decarbonization, sustainability, and renewable energy. The legislative landscape, encompassing acts such as the EEG and the KVBG, shapes the nation's energy transition, setting ambitious targets and fostering innovation in the renewable energy sector. The Energiewende is a testament to Germany's leadership in transitioning to a sustainable energy system, providing valuable insights for global efforts to combat climate change [66,76]. The ongoing commitment to increasing the share of electricity from renewable sources and addressing challenges in the energy transition reinforces Germany's role as a pioneer in sustainable energy practices [78].

In conclusion, despite efforts to promote community energy projects, questions persist regarding their effectiveness in addressing challenges associated with standard project finance approaches, indicating a need for more tailored and inclusive policy measures. Germany's commitment to the aggressive deployment of renewable energy technologies aims to surpass EU targets and significantly reduce greenhouse gas emissions by 2050. However, achieving these goals requires overcoming challenges such as grid integration, energy storage, and ensuring affordability and social acceptance. The ongoing transition to renewable energy sources, particularly wind and solar, underscores Germany's leadership in sustainable energy practices. Nevertheless, continued policy innovation and adaptation are essential to address evolving challenges and ensure the effectiveness of Germany's energy transition efforts, reinforcing its position as a global pioneer in sustainable energy practices.

3.2. South American Landscape

Decarbonization policies in South America showcase significant diversity, varying according to the individual characteristics of each country. Brazil, for instance, stands out for its commitment to biofuels, notably sugarcane ethanol, while Chile leads in adopting solar and wind energy. Each South American nation is somehow working to diversify its energy matrices and reduce carbon emissions. In addition to regional approaches, many South American countries align with global decarbonization policies. International commitments, such as the Paris Agreement, influence regional strategies, prompting the transition to cleaner energy sources and emissions reduction. Global goals, driven by initiatives such as the shift to RE and the enhancement of energy efficiency, have tangible impacts on decarbonization efforts across South America.

Brazil

Brazil is a notable example in the global landscape of energy matrices, showcasing a distinctive profile compared to the rest of the world. Despite the predominance of non-renewable energy sources in national consumption, Brazil relies more on renewables (e.g., hydropower and sugarcane derivatives). Approximately 44.8% of Brazil's energy matrix is constituted by renewable sources, illustrating a significant commitment to sustainable energy practices [13].

The country has emerged as a role model, particularly for developing nations, in the establishment and expansion of onshore wind farms at a large scale [79]. Brazil's venture into photovoltaic (PV) energy began in 2011, marked by the National Electric Energy Agency's Call for R&D. This initiative aimed to propose technical and commercial arrangements for electricity generation through PV energy, fostering infrastructure and technology development [80]. In anticipation of a tripled energy demand by 2030, Brazil strategically aligns its energy decennial plans, emphasizing sustainability, reduced energy costs, and diversification of the energy system, all of which are fulfilled by PV energy [80].

Brazil has implemented various policy instruments to promote renewable energy, such as the Alternative Sources Incentive Program (PROINFA). The program, initiated in 2002, utilized Feed-in Tariffs (FITs) to generate 3300 MW from renewable energy sources such as wind, biomass, and hydro plants [81]. The government's adoption of auction regimes, loan systems, and guaranteed purchase contracts significantly contributed to the growth of wind power installations to 5300 MW in 2013 [82]. The legal framework for solar PV energy systems was established in 2012, incorporating net metering, FIT, and cash incentives [83].

Strategically outlined plans, such as the 2010–2019 Plan for Energy Expansion, demonstrate Brazil's commitment to reducing fossil fuel power plant construction and expanding hydro and wind grid-connected power sectors [83]. Moreover, Brazil's Nationally Determined Contribution aims to reduce greenhouse gas (GHG) emissions by 37% and 47% below 2005 levels by 2025 and 2030, respectively. This ambitious goal requires substantial investments in renewable energy within the country's energy mix [84].

Brazil's leadership extends to biofuels, where recent resolutions highlight the pivotal role of biofuels in the country's energy mix and emphasize the need for further investments in the sector [85]. The Brazilian power sector's regulatory framework has undergone significant structural changes, creating a model that promotes economic efficiency through competitiveness [86]. The auction program, initiated in 2007 and continued with special auctions for renewables, has been instrumental in procuring renewable energy capacity [86].

Governmental bodies such as the National Energy Policy Council (CNPE) and the Ministry of Mines and Energy (MME) play crucial roles in policy formulation and enforcement [87]. The Normative Resolution No. 482/2012 allowed consumers to generate their electricity from renewable sources, contributing to the development of market arrangements [88]. The National Biofuels Policy (RenovaBio), launched in 2017, has further stimulated biofuel production and introduced a cap-and-trade decarbonization credits program (CBIOs) [89].

Brazil's NDC aims to substantially reduce greenhouse gas emissions, driven by intensive investments in renewable energy [84]. Long-term and medium-term sectoral expansion plans through the Energy National Plan (ENP) and the Decadal Plan for Energy Expansion (PDE) outline the nation's commitment to sustainable pathways [90]. Environmental governance, executed by institutions such as IBAMA and SEPA, emphasizes the licensing of projects in alignment with federal, state, and local environmental regulations [90].

Brazil relies significantly on renewable energy sources, including hydropower and sugarcane derivatives, which make up nearly half of its energy matrix. The country has become a role model for developing nations, particularly in expanding wind energy and venturing into solar power. Policy instruments such as the PROINFA program have facilitated renewable energy growth, aligning with Brazil's ambitious goals to reduce greenhouse gas emissions. However, challenges persist in implementing and enforcing policies and addressing environmental concerns.

To mitigate these challenges, Brazil could focus on enhancing policy implementation and enforcement mechanisms to ensure that renewable energy projects are effectively developed and managed. Strengthening regulatory frameworks and the institutions responsible for overseeing energy projects can help improve compliance with environmental standards and address concerns related to land use, biodiversity conservation, and community engagement. Additionally, investing in research and development initiatives to advance renewable energy technologies and infrastructure can enhance the efficiency and reliability of renewable energy systems, making them more competitive with conventional energy sources.

3.3. Comparative Analysis of Decarbonization Energy Policies: Challenges, Implications, and Future Directions

In the landscape of global energy policies, hydrogen production has garnered significant attention due to its potential to reduce emissions, despite facing challenges associated with high costs [91]. The transition towards cleaner energy sources is evident in the ambitious goals set by European countries, such as Germany, as part of their energy transition plans [92]. In Europe, biomethane has been recognized as a promising alternative to natural gas, with substantial environmental benefits [39]. Financial support for bioenergy consumption in the European Union is contingent on sustainability criteria [44].

Austria, a European country committed to decarbonization, is exploring using biomethane to reduce carbon emissions in residential heating and cooling [93]. Integrating green gas into existing heating technologies presents a viable option for sustainable energy consumption. The availability of renewable gas contributes to Austria's efforts to decarbonize residential building heating [93]. The International Energy Agency (IEA) projects a significant increase in biomethane consumption globally, emphasizing the influence of energy policies on market developments.

In Germany, a key player in renewable energy adoption, the transition to cleaner sources is underscored by the Renewable Energy Act, shaping a regulatory framework to promote innovation and technological expansion [94]. The German biogas industry is undergoing a transition, emphasizing electricity production and the declining sale of biomethane as a fuel [95]. Recent years have witnessed a substantial cost reduction in wind and solar energy, aligning with Germany's commitment to renewable energy [96]. The country's shift towards a tendering system and economic competitiveness in renewable energy contribute to its mainstream adoption [97,98].

Brazil, with its vast territory and high solar irradiance, holds substantial potential for increasing power generation using PV energy [80]. Studies indicate that Brazil's capacity for using solar PV surpasses that of some European countries [99]. Moreover, the growth of wind power in Brazil has been remarkable, making it the second-largest source of energy in the country [100].

4. Sustainable Pathways for the Hydrogen Sector (America/Europe)

In the present scenario, Brazil aligns with the global trend of hydrogen production through natural gas reforming, primarily targeting the refining and fertilizer sectors, which typically employ processes with high carbon dioxide emissions. Most hydrogen production plants are situated in coastal regions near Brazil's gas pipeline network [101]. Natural gas constitutes the largest share of hydrogen production at approximately 48%, followed by petroleum (30%), coal (18%), and water (4%) [102]. Consequently, only 4% of the current global hydrogen production is considered green.

Concerning the decarbonization of energy sources, Germany strives to reduce its reliance on fossil fuels, including oil, and increase its share of renewable energy sources. As outlined in Germany's National Hydrogen Strategy [103], the German Government anticipates a demand for 90 to 110 TWh of green hydrogen by 2030 to meet decarbonization goals. Studies such as Liebich et al. [104] discuss additional environmental impact categories for electrolytic hydrogen production in 2050. The study's relevance lies in its comprehensive coverage of Germany, evaluated variants, impact categories, and timeliness. The study found, in a retrospective consideration of 2015, significantly higher contributions of electricity generation to potential global warming results [105].

On average, existing studies indicate that Austria's total energy production can be entirely covered by renewable energy if technical potential is fully explored and final energy technologies are adapted [106]. The country aims to achieve climate neutrality by 2040, requiring decarbonization across all sectors. Therefore, renewable hydrogen production is deemed essential, as stipulated in the national hydrogen strategy in alignment with the European Commission [107]. The Austrian Government's current objective is to attain climate neutrality by 2040, a decade ahead of the European Union's set target [108]. A report commissioned by the Austrian Government forecasts a minimum hydrogen demand of 16 TWh per year in Austria by 2040, emphasizing the need for future domestic hydrogen production [109].

In response to the energy scarcity scenario following the Fukushima disaster, Germany initiated the closure of its nuclear power plants, with the last three shutting down in April 2023. However, challenges to energy security compelled the country to reassess its nuclear policy [110]. Meanwhile, Brazil, known for its abundant natural resources such as hydropower and biofuels, grapples with challenges such as population growth, economic development, and infrastructure expansion, impacting the energy supply–demand balance. Conversely, through investments in renewable energies such as hydropower, wind, solar, and biomass, Austria aims to reduce its dependence on fossil fuels and promote energy sustainability.

4.1. Comparative Analysis: Challenges and Opportunities in Hydrogen Production between Brazil and Europe

In the global landscape, hydrogen is recognized for its low emissions but faces the challenge of high production costs [91]. Germany, a pioneer in ambitious energy transitions, is undergoing a significant shift away from fossil fuels and nuclear power by 2022 [92]. Embracing hydrogen as an alternative fuel, Germany is strategically expanding its infrastructure, with hydrogen fuel stations playing a crucial role in fueling vehicles, especially those powered by fuel cells [111].

The notable "H2-Bus Rhein-Main" project exemplifies Germany's commitment to large-scale deployment and commercialization of fuel cell buses, contributing to a regional green hydrogen value chain. Aligned with Germany's National Energy and Climate Plan, this initiative focuses on integrating hydrogen technologies into public transport systems [112]. The participation of diverse stakeholders, such as governmental entities, research institutions, industry collaborators, and local communities, has played a pivotal role in shaping and propelling the project forward. Through synergistic collaboration and meticulously coordinated planning, these stakeholders have assumed crucial responsibilities in conceptualizing, financing, and implementing the project. This underscores the significance of multi-sectoral cooperation in realizing ambitious objectives related to energy and climate initiatives.

In Brazil, hydrogen production methods include fossil fuel-based processes, biomass utilization, and water electrolysis [113]. Currently, hydrogen is predominantly produced in oil refineries through methane-reforming processes, particularly steam reforming [113]. Petrobras data reveals that over 70% of Brazilian refineries, notably Paulínea and Mataripe, contribute significantly to hydrogen production, primarily for internal processes within the oil refining industry.

Brazil follows the global trend of hydrogen production from natural gas, emphasizing the refining and fertilizer sectors, often associated with high carbon dioxide emissions [114]. Recognizing the potential of hydrogen in renewable energy scenarios, Brazil views hydrogen technologies as vital for improving the efficiency of the oil industry and reducing greenhouse gas emissions.

The Ten-Year Energy Expansion Plan by Empresa de Pesquisa Energética forecasts substantial growth in wind energy, positioning it as a primary source of expansion in Brazil [115]. Brazil's extensive hydroelectric potential, concentrated in the northern region, contributes significantly to the energy mix, with 44% already in operation [13]. Despite a higher consumption of non-renewable sources, Brazil utilizes more renewables compared to the global average [13]. Moreover, reports from the International Renewable Energy Agency highlight significant growth in Brazilian hydroelectric capacity, coupled with a substantial increase in solar and wind energy evolution in 2022 [116]. The realization of this plan involves substantial investments in wind energy infrastructure, including the development of wind farms and associated transmission systems. These investments are backed by both public and private sector funding, with a significant portion allocated from government budgets and supplemented by investments from energy companies and financial institutions.

Brazilian governmental entities such as the Ministry of Mines and Energy, in conjunction with regulatory agencies such as the National Agency of Electricity (ANEEL), have assumed pivotal roles in formulating and supervising the implementation of the plan. Energy companies, comprising both state-owned enterprises and private entities, have assumed responsibility for the establishment and management of wind farms, while research institutions have actively contributed to technological enhancements and innovations within the sector.

The challenges encountered in transitioning towards hydrogen-based energy systems are multifaceted, encompassing technological, economic, and infrastructural obstacles. These hurdles originate from the imperative to expand hydrogen production while concurrently driving down costs and ensuring environmental sustainability. Moreover, integrating hydrogen into existing energy frameworks necessitates substantial investments in infrastructure, notably the establishment of hydrogen storage and distribution networks.

Potential solutions to these challenges are rooted in sustained research and development endeavors aimed at enhancing the efficiency and cost-effectiveness of hydrogen production technologies. Progress in electrolysis methods, such as proton exchange membrane electrolysis and solid oxide electrolysis, offers prospects for reducing the energy input required for hydrogen generation. Furthermore, harnessing renewable energy sources such as wind and solar power for hydrogen production can alleviate the environmental concerns linked with fossil fuel-dependent processes.

Effective policy interventions, comprising financial incentives and regulatory frameworks supporting hydrogen infrastructure expansion, are pivotal in fostering the widespread adoption of hydrogen-based energy systems. Collaborative initiatives and knowledge-sharing platforms at the international level can expedite advancements in surmounting technological and economic barriers to hydrogen deployment.

4.2. Hydrogen Storage: An Essential Component in the Transition to Sustainable Energy

Hydrogen, as a clean and versatile energy carrier, holds immense potential for addressing global energy challenges. However, effective storage solutions are essential to enable its widespread utilization in various applications. Hydrogen storage technologies can be broadly categorized into two main groups: physical-based and material-based [117]. Each technique possesses unique characteristics, including energy density, kinetics, and efficiency, making it challenging to identify a universal solution for all storage needs [118]. Stationary storage methods are primarily used for on-site storage and stationary power generation, while mobile applications involve transporting hydrogen to storage or usage points, including vehicle applications [117].

As researchers and engineers around the world increasingly focus on hydrogen storage and conversion into different forms of energy [119], collaborative efforts and interdisciplinary approaches are crucial for overcoming existing challenges and driving innovation in hydrogen storage technology. By addressing key technical barriers and leveraging advancements in electrocatalysis, chemical hydrides, and storage infrastructure, the realization of efficient, safe, and scalable hydrogen storage solutions becomes attainable, paving the way for the widespread adoption of hydrogen as a clean energy source in the transition towards a sustainable future.

One critical aspect in advancing hydrogen storage technology is the development of highly effective electrocatalysts capable of facilitating both the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) during water electrolysis [120]. These electrocatalysts play a crucial role in enhancing the efficiency and stability of electrochemical water splitting processes, which are integral to hydrogen production at scale [121].

Ammonia borane (AB) methanolysis emerges as a promising integrated technology for both hydrogen storage and production, offering high efficiency and safety [122]. However, despite significant progress, the efficient and safe storage and transportation of hydrogen remain major challenges, hindering large-scale applications [122]. Among the potential solutions, the storage and transportation of hydrogen in the form of chemical hydrides holds promise due to their efficiency and safety characteristics [122].

The generation of hydrogen from AB has garnered increasing research interest due to its intrinsic characteristics of high portability in hydrogen production [123]. This highlights the importance of exploring alternative storage methods to overcome existing limitations and propel hydrogen storage technology forward.

5. Conclusions and Policy Recommendations

The ongoing energy transition towards a cleaner, lower-carbon system underscores the pivotal role of hydrogen as a crucial energy vector for decarbonizing energy sources. The analysis of keywords within the scientific discourse reflects a multidisciplinary approach, emphasizing a commitment to advancing sustainable and environmentally responsible energy solutions. This analysis was particularly useful in determining both the global trend and the specific trends within the countries under review. Globally, there is a growing emphasis on the use of hydrogen as an energy carrier, aligning with the broader goal of transitioning towards cleaner energy sources. Similarly, the examination of keywords provided insights into the unique approaches taken by Austria, Germany, and Brazil in addressing their energy challenges and integrating hydrogen into their respective energy frameworks. Furthermore, the analysis reveals gaps in the scientific discourse regarding hydrogen production and energy policy, particularly within the specified geographic contexts.

Austria, classified as a developed country, demonstrates dedication to decarbonization, particularly through the exploration of biomethane for residential heating and cooling. This aligns with its advanced social system, which prioritizes sustainability and environmental responsibility. The decision to ban nuclear power in 1978, followed by subsequent legislative measures such as the Green Electricity Act of 2002, underscores Austria's commitment to renewable energy development. The synergy between Austria's Mission 2030 and initiatives such as the Climate and Energy Fund highlights its holistic approach towards sustainable energy development.

In contrast, Germany, also classified as a developed country, serves as a pioneer in renewable energy adoption. It showcases a regulatory framework that promotes innovation and technological expansion, reflecting its highly developed social system and commitment to transitioning away from fossil fuels. The legislative landscape, encompassing acts such as the EEG and the KVBG, shapes the nation's energy transition, setting ambitious targets and fostering innovation in the renewable energy sector.

Brazil, classified as a developing country, exhibits vast renewable energy potential, particularly in the wind and solar energy sectors, positioning itself for substantial growth in the coming years. This reflects the country's transition towards embracing renewable energy sources as a key component of its energy mix. The country has emerged as a role model, particularly for developing nations, in the establishment and expansion of onshore wind farms at a large scale. Brazil relies significantly on renewable energy sources, including hydropower and sugarcane derivatives, which make up nearly half of its energy matrix. These examples underscore how the distinct approaches of each country are shaped by their developmental stages and social systems.

Specifically identifying areas such as production efficiency, storage technologies, infrastructure development, and integration into various sectors would provide clarity on the necessary advancements needed to propel renewable energy technology forward effectively. This entails a comprehensive approach to research and development, encompassing innovations in renewable energy generation methods, energy storage solutions, grid integration technologies, and sustainable infrastructure development. Additionally, focusing on enhancing the efficiency and scalability of renewable energy systems, optimizing resource utilization, and reducing environmental impacts are critical aspects that warrant attention. By addressing these broader areas of technological advancement, we can foster the widespread adoption of renewable energy sources and accelerate the transition towards a sustainable and low-carbon energy future.

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