Sustainable Hydrogen Energy: Opportunities, Challenges, And The Worldwide Shift To A Hydrogen-Based Economy

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ABSTRACT
For years, countries aiming for net-zero emissions have been pondering how to enhance hydrogen's role in their economies. At the beginning of the twenty-first century, the spearhead of the green movement was renewable technologies. Moving green moves from merely reducing greenhouse gas emissions to net-zero emissions. By the end of the century, hydrogen can assume a role similar to that of the target. This article reviews the growth of the hydrogen economy in the last decade and discusses prospects and difficulties for India. The study is conducted in three stages. The first two phases involve a review of the academic and grey literature on the subject.
The first two stages involve a review of the scholarly and grey literature on the topic. In the third stage, the argument for India is made on the basis of data obtained in the first two stages. Today, green hydrogen is relevant in the energy policy narrative because it can decarbonize "hard-to-abate" industries. Without a single country or group of countries controlling the technology, hydrogen could be a game changer in global energy geopolitics. International collaboration can help India overcome the challenges of high technical prices, undesirable sunk costs and low public awareness to tap the benefits of its large market potential, experience of cost reductions and solar PV-based low-cost electricity.

Keywords: Green hydrogen, hydrogen economy, energy transition, energy policy.

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INTRODUCTION

Greenhouse gas (GHG) emissions are calling into question the share of fossil fuels in overall energy use. Countries are incorporating green technology into their energy plans to reduce emissions. Renewable energy technologies are now an essential component of many national electricity systems. Governments are deploying alternative technologies to achieve a net-zero economy. It has emerged as a natural alternative as a net-zero fuel because it can be produced from renewable sources in an environmentally benign way [1]. Hydrogen is a colourless, odourless gas under normal conditions of temperature and pressure. It is the most abundant element in the atmosphere. Hydrogen in its molecular form is not found in the environment as a supplemental fuel [2]. Hydrogen is getting popular because of its multiple applications and compatibility with other energy sources. It can be used as an energy carrier, a fuel and feedstock. It's a good candidate for the clean energy transition because it doesn't emit carbon dioxide when it burns. It is considered the most promising technology next due to familiarity in handling since its industrial use in 1920 [3]. There are several ways to make hydrogen, each with a different greenhouse gas emissions profile. Processes such as coal gasification and steam methane reforming (SMR) produce significant emissions. Grey hydrogen is the hydrogen produced via these processes. Other than methane steam reforming, ethanol, methanol, glycerol, acetic acid and toluene can all be steam reformed [4]. It is hydrogen produced with little or no emissions, called green hydrogen. It is now technically feasible to produce large scale green hydrogen. Hydrogen's "net-zeroness" depends on how it is produced. Countries trying to reach net-zero emissions have been exploring how to bring green hydrogen to their economies for decades. Hydrogen's role in the transition phase has been unclear, but the "green hydrogen hope" of the stakeholders has been fuelled by the falling cost of renewable electricity.

METHOD

This analysis aims to assess the development of the hydrogen economy over the last decade and provide practical frameworks for energy transition strategy. The aim is to understand its feasibility and challenges for India. There are three phases in this investigation. To understand the basics of the hydrogen economy, the first step is to look at the academic literature. The second phase focuses on policy-level changes and the current situation of hydrogen-based technology through studies, fact sheets, briefings, databases, and videos from government, intergovernmental and independent think tanks and organisations. In the third stage, we build the case for India on the basis of data collected in the first two stages. The book choosing and reviewing process is shown in Fig. 1. Articles that review developments related to the hydrogen economy as a whole are within the scope. Two sets of keywords were selected to include papers from peer-reviewed literature. The first set examines the "clean hydrogen economy", "green hydrogen economy" and "low carbon hydrogen economy". The second set comprises articles with the theme "India" and the keywords of the first batch. A focused literature search on Scopus and Web of Science using the above-mentioned keywords resulted in 1026 and 305 results, respectively. Two hundred and eight duplicate entries are removed. The resulting papers are then collected and passed through two selection criteria to focus the literature search. The first pass method [5] was employed. The main selection criteria were articles that discuss a hydrogen economy extensively and are not based on specific technical laboratory tests aimed at specific research objectives.

Secondary selection criteria are designed to focus on recent and cutting-edge literature, and exclude articles published after 2010. The International Energy Agency (IEA) database [6] shows that about 75% of the hydrogen projects are in Germany, the Netherlands, France, Denmark, the USA, Australia, the UK, Spain, China, Norway, Japan and Canada. This section includes articles examining the development of hydrogen technology in these twelve countries and India. To ensure the review is comprehensive, grey literature known to the writers or obtainable by backward referencing is included. The following sections present analyses and syntheses of the literature gathered.

Development of the Hydrogen Economy

The current hydrogen economy is dominated by grey hydrogen and driven by specific industrial applications in refineries, steel and chemicals. Hydrogen has been under study in contemporary science for the last few hundred years. It was initially described in 1520 [7]. In 1800, the electrolysis method was found, and a fuel cell, 1838. 122 years of development, and in 1960, the fuel cell was first used in space [8]. The term "hydrogen economy" was introduced for the first time in 1970, and since then it has been widely studied in the literature for production, storage, transportation, and utilisation aspects. The development of hydrogen-based technology can be discussed in terms of the three waves of enthusiasm [9]. After the oil embargo of the 1970s, hydrogen was the buzzword in all energy discussions. But the wave was dampened by the discovery of oil reserves. It was seen as a solution to climate change in the 1990s and the 2000s. But the low oil prices, the financial and economic crisis and the popularity of alternative renewable technologies such as wind and solar PV have impacted the long-term financial support needed for its development.

Research and development is an important part of the hydrogen economy. Figure 2 illustrates the trend of public RD&D budget in Japan, the USA, Germany, France, South Korea, and the UK over the last 15 years. On average, fuel cells and hydrogen still account for only 4.8% of the total yearly budget for all energy technologies in the six nations. Other areas of budget use are renewable technologies, energy efficiency, fossil fuels, nuclear, cross-cutting technologies and power and storage technologies. The USA gradually reduced the budget from 10% in 2006 to 1.49% in 2019 [10]. Following 2008, the financial crisis resulted in a decrease in budget allocations. As seen in Figure 2, since 2018, the expenditure has been steadily increasing, and all six countries have shown a resurgence in interest of the technology. The enthusiasm and positive outlook on hydrogen has brought it to the forefront of the ongoing energy transition conversation despite the occasional hurdles.

Hydrogen is given different colour codes to reflect its carbon impact. Their chemical properties are the same, no matter what their colour designation. Table 1 lists nine varieties of hydrogen, classified by the way they are produced. Hanley, E. S. et al. predicted that technologies will be ripe by 2050 and hydrogen will enter the mainstream energy grid after 2030 [14]. In many countries, large-scale renewable sources of electricity are not feasible, and blue hydrogen may be considered as an interim solution in the energy transition [9]. Using the Sankey diagram method, Bakenne A et al. conclude that cheap and plentiful fossil fuels can contribute to the development of a robust hydrogen economy. The reason is that low costs can increase the viability of hydrogen projects (not necessarily green H2 projects), hence generating a market for them [15]. Distributed hydrogen generation, trade and use could be fostered by business structures that support such activities [16].

Sectoral Developments (October 2023)

The five categories of hydrogen generation technologies are thermochemical, electrolysis, renewable liquid reforming (based on bio-methanol and bio-ethanol), photobiological, and nuclear energybased production [17]. SMR is the most economically attractive option, while electrolysis is the most environmentally friendly method [18]. A study by Lee D. H. Fuel cells, fuel cell-driven cars, and H2 production methods such as biomass, wastewater, and sludge are subject to technological breakthroughs [19]. The hydrogen production market is expected to increase from USD 115 billion in 2017 to USD 155 billion in 2022 [20]. Strong research activities are needed to fill the gap between strategy and technology [21]. After its production hydrogen can be dealt with in three ways. It can be eaten locally, initially. Second, it can be stored for future use in insulated tanks, pressure vessels, salt caves or as ammonia. Third, it is transportable to other sites for remote storage and/or use by trucks, ships, special pipes, or by blending it with already existing natural gas pipelines. It is under active development and testing and being commercially introduced in the transportation and electric power sectors. It is also used to produce derivatives such as ammonia, methanol and synthetic fuel. Pure hydrogen demand grew continuously from 18.17 Mt in 1975 to 73.88 Mt in 2018 [22]. If the total emissions of hydrogen are above 0.19 kg of CO2/kWh, it is called grey hydrogen [12]. 96.8% of grey hydrogen is made from coal and methane. Renewable energy-based electrolysis accounts for only 0.3% of the total production. However, similar technologies coupled with Carbon Capture and Storage (CCS) facilities produce 1.1% of blue hydrogen [23]. Grey hydrogen from coal in electricity systems might increase emissions of nitrous oxide and volatile organic compounds [24].

Solid oxide electrolyser, alkaline water electrolyser and polymer-electrolyte membrane (PEM) electrolyser have been widely discussed in the literature [2,25]. Important factors are the durability (load factor), efficiency, and capital and operational costs of the electrolyser [26]. There are commercial alkaline electrolysers available in the market. Small- and medium-scale (50 kW to 4 MW) production is increasingly being supplied by PEM electrolysers, with more than 500 units in operation. They can work at low temperatures (up to 100o C) and are suitable for intermittent loads. The cost of the electrolyser is now about USD 840/kW. The International Renewable Energy Agency (IRENA) foresees a 50% reduction in costs by 2040-2050 [27]. Green hydrogen electricity landing cost is in the order of $50/MWh [28]. The levelized cost of hydrogen from a PEM electrolyser is higher (USD 6 to 7.4 per kg) compared to an alkaline electrolyser (USD 4.7 to 5.8 per kg) [29]. An alkaline electrolyser with an efficiency of 73% and an energy consumption of USD 53.4 kWh/kg can produce 380 tonnes of hydrogen at costs as low as USD 3.2/kg [30].

Electrolysers need about 40% less water than current fossil fuel refineries. In green hydrogen production, around 8.92 liters/kg of demineralised water is used. Seawater or wastewater desalination plants can utilise electrolysis. In areas with limited water resources, these desalination plants can also provide freshwater to the local populace [31]. In addition to the above, current thermochemical processes based on biomass are being commercialised. They could be a strong competitor to electrolysers. Demirbas A. warns of possible land use conflicts in the production of hydrogen from biofuels [32]. The author continues to say that food utilisation protocols can avoid the food versus fuel conundrum. Salt caves are preferred amongst all current storage systems due to their proven use, limited loss (around 1%) and low risk of contamination [25]. Europe has a storage capacity of 2500 Mt or 82.8 PWh [12]. In 2016, natural gas pipes were about 3 million kilometres long [33]. However, only 16000 km of dedicated hydrogen pipelines (or 0.53% of all gas pipelines) have been built worldwide during the last 50 years [3]. Most of the pipelines are in Belgium, France, the Netherlands, Germany, and the United States. Germany's pipelines will be converted to hydrogen: 5900 km, which is 15% of the total. Pipeline transport of hydrogen still costs $5 to $6 per kilogram over distances of 3500 kilometres. Afterwards, ammonia pipelines will become an economically feasible option [13]. Existing natural gas pipelines can be reused to deliver hydrogen to places where there is more potential for use of hydrogen. A small investment is needed to make existing equipment compatible with the blend. The integration of up to 10% hydrogen into the existing infrastructure can enhance asset value and create new economic opportunities for companies working in natural gas pipelines [34]. In Europe, approximately 20% of the blending maximum has been reached [35].

Some national gas grids have tested blending ratios from 0.5% to 25% by volume. In the Netherlands, it is 12%, in Germany 5%, and in the UK 2-3% of volume. A 10% mixing has been tested in the US state of Hawaii [25]. The most practical solution today, in the opinion of Nazir H et al. [36], is the transportation of compressed hydrogen by road. The main hazard with hydrogen handling is leakage. In view of previous events such as the Hindenburg accident in New Jersey in 1937, the hydrogen leak in Houston in 1989 during maintenance and the pressurised hydrogen tank burst in Frankfurt in 1991 [37, 38], hazard-proof methods are needed to enhance the confidence of the stakeholders. Current studies show that the power needed for the production of green hydrogen using renewable energy is only a few GWh [40]. This underscores the significance of regulating the deployment of fuel cell vehicles across sectors and coupling excess electricity with the production of hydrogen, which can also be an effective way to cut greenhouse gas emissions [41]. A study in Japan with the MARKet Allocation (MARKAL) model [42] revealed that the Japanese electric power sector must reduce carbon dioxide emissions to achieve the 80% CO_2 emission reduction target by 2050 from 2013 levels. [43] argues for a cyclical process of converting energy from electricity to hydrogen with an electrolyser and from hydrogen to electricity with a fuel cell to accomplish this goal. The industrial sector accounts for approximately 25% of CO_2 emissions linked to energy. Around 75% of industrial carbon emissions are generated by the iron and steel, chemical and petrochemical, cement and lime and aluminium industries [12]. The industrial sector contributes about 25% of energy-related CO_2 emissions. Iron and steel, chemical and petrochemical, cement and lime, and aluminium industries account for approximately 75% of the carbon emissions in the industrial sector [12].

Sometimes referred to as “hard-to-abate” sectors, they require a larger investment in green technology than the current carbon-based technologies. High costs and lack of investor confidence and enabling legislation are hindering the uptake of green hydrogen in carbon-intensive industries. Rissman J et al suggest policy solutions to achieve net-zero emission targets in industries from the supply-side and demand-side [44]. According to Arens, M. et al., the current carbon-intensive steel industry will make it difficult to reach netzero by 2050 [45].

The biggest obstacle to Hydrogen Fuel Cell Powered Vehicles (HFCV) is the capital expenditure as opposed to battery-operated electric vehicles. But cost parity for HFCVs is expected to be achieved between 2025 and 2030 as the production of HFCVs increases [46, 47]. A typical modern commercial vehicle will do 400 km on 24 kg of petrol. An internal combustion engine can require eight kilograms of Hydrogen for the same range, but a fuel cell-powered vehicle will only require four kilograms [48]. Production tax credits and incentives for the generation of energy for electrolysis are 24 times more effective than capital subsidies, carbon taxes or a ban on the production of grey hydrogen. People familiar with hydrogen technology and with experience in battery-powered electric vehicles are more likely to adopt HFCVs faster than other people [50].

The majority of Hydrogen Refuelling Stations (HRS) are located in Japan (114), Germany (87), and California (48). The policy push for HFCV [51] is resulting in new stations being built in different parts of the world. Research shows that battery electric vehicles are preferred over hydrogen fuel cell vehicles across passenger segments. They are not enough on their own to enable decarbonisation in the personal mobility subsector [3]. A well-to-wheel study in China found that the grid electricity emits 431 g CO_2 equivalent per kilometre, while HFCVs powered by renewable electricity for electrolysis emit only 31 g [52]. Comparing and studying the large-scale energy economy models to China, the USA and the world, the transport sector is more difficult to decarbonise than other sectors [53]. Therefore, it is necessary to prioritise sectors to avoid unintended sunk costs that could affect the deployment trajectory in the future.

A major obstacle to large-scale penetration of existing electric grids is the intermittency of renewable energy. In cases of intermittent behaviour, the stability of power systems is critical. Smart investments in electric and gas infrastructures can partially solve the problems caused by the increasing penetration of renewable energy sources [54]. The power system performance in areas with high solar and wind penetration could be improved by modern electrolysers, which are faster at ramping up and down (measured in seconds and minutes). Batteries and supercapacitors are useful for short-term energy storage but the excess electricity can be converted to hydrogen, which is useful for long-term energy storage [55]. Chapman A et al. [56] wrote that the main barriers to the transition to a hydrogen economy in four case studies are the high costs of infrastructure and technological development. Hydrogen will be a practical option for transportation and industry only if investment costs decrease [57].

Policy Developments

Governments around the world have put in place several policies to encourage the development of hydrogen and related technologies. Staffell I et al. [46] stated that the successful development of the hydrogen economy is also dependent on continuous government policy support. The authors also argue that stop-go policies will undermine confidence among long-term investors and stall the development of a lowcarbon energy sector. Some organisations have put forward policy recommendations to support the energy transition and eventually establish a sustainable hydrogen economy. IRENA's handbook recommends an integrated policy strategy for green hydrogen policymaking. It recommends building a policy plan on four pillars: enabling policies, guarantees of origin, national strategy, and policy priority. It promotes the evolution of green hydrogen as a complementary rather than substitute approach. It is important to give priority to high-value applications and to follow the principle of additionality. The principle of additionality implies that green hydrogen should not be produced from electricity that could be used for other highyielding purposes. In short, green hydrogen should only be produced with additional renewable electricity, or it may be restricted. This strategy can be useful in the early stages of market formation. It preserves the current state of the use of hydrogen [12].

New borough and Cooley suggested two carrier strategies to generate demand and establish hydrogen as a key commodity. It argues that the world's future energy needs cannot be satisfied by one carrier, like electricity in terms of electrons. Hydrogen can be considered as a complementary carrier. Three groups of proposed policy actions are identified: power-to-gas, hydrogen mobility, and industrial processes. It suggests the implementation of multi-sectoral strategies for the construction of a hydrogen market [58].

The premise of IEA's targeted value chain strategy is that the 2020s are a critical decade to put in place the fundamental infrastructure for future hydrogen supply chains. It supports gas infrastructure, fleets, goods, corridors and coastal industrial clusters. It also highlights hydrogen shipping routes, as late market entrants are likely to prefer them. It recommends setting global standards, promoting R&D and knowledge sharing, setting long-term policy goals, and supporting demand creation to increase investor confidence [13]. Bloomberg New Energy Finance has promoted seven signposts to safeguard investors' interests against uncertain regulatory regimes. The signposts are: establishing a market for low-emission products; offering incentives and decarbonisation measures for industries; mainstreaming of H2-compatible technology; harmonising standards; setting targets; enforcing stringent emission limits; and setting net-zero climate targets [59].

The hydrogen valley platform of the Fuel Cells and Hydrogen Joint Undertaking offers hydrogenbased companies the opportunity to establish facilities in geographically constrained areas, thereby reducing barriers to deployment. The concept of a hydrogen valley is based on regional economic growth and locally connected ecosystems. Currently, EUR 36 billion has been invested in 36 projects of hydrogen valleys in 19 countries [60]. Hydrogen Europe's Hydrogen Act provides a holistic framework to address all hydrogenrelated challenges in one policy document to avoid fragmented policymaking. It has two components, infrastructure (supply side) and market (demand side). The law distinguishes three stages of development: market expansion, ramp-up, and kick-start [61].

The Indian Scene

Current global policy is aimed at infrastructure development, commercialisation, and demand creation. Commercialising, scaling up and promoting HFCV is difficult for countries due to the high costs, lack of understanding, and inadequate global supply chain [62]. French S. Nevertheless, argues that many areas have the potential for hydrogen to be incorporated into energy systems and the deployment of advanced technology should commence immediately [63]. According to Sazali N., Asia's expanding domestic economy will create a huge demand [64]. India's involvement in hydrogen technologies started in 1976 when the Department of Science and Technology began to fund hydrogen activities in academic institutions and technical institutes [4]. In 2003, the Indian government established the National Hydrogen Energy Board (NHEB) to fill the hydrogen technology gap. India's national strategy for hydrogen energy, aimed at the transport and power sectors, was released by NHEB in 2006. The targets included having one million HFCVs on the road by 2020, developing hydrogen-based power aircraft with a capacity of up to 1 GW, and achieving hydrogen transport costs of up to INR 60–70 per kg. India is planning to launch the National Hydrogen Mission 16 years after the roadmap was developed to make India a global hub for fuel cell and hydrogen production. The mission contains a 10-year long-term strategy and a 4-year short-term strategy [65].

Current status

India spends over USD 160 billion annually on energy imports. Over 75% of this cost is due to the import of crude oil and natural gas [66]. The last decade has completely changed the story of green energy in the country with solar and wind power. But electricity accounts for only 18% of the country's total energy consumption. In other words, more work needs to be done to cut emissions from the other 82% of the energy we use. Deep decarburisation initiatives in "hard-to-abate" industrial sectors are required to achieve a net-zero energy economy [66]. India produces some 6.7Mt of hydrogen a year. The country uses 2.5 Mt of hydrogen to produce approximately 14.5 Mt of ammonia. The Energy and Resource Institute (TERI) has estimated the total hydrogen demand to be about 23 Mt in 2050 [67]. The major users of hydrogen in the country are the steel, fertiliser, and refinery industries [68]. Hydrogen is currently priced between INR 340 and INR 400 per kilogram (USD 4.5 and USD 5.3 per kilogram). Cost parity is expected to be achieved at INR 150 per kg (USD 2 per kg) for green hydrogen production [69].

Enhanced use of renewable energy sources could lead to duck curve phenomena, as was first observed in California, USA [66]. The phenomenon of the duck curve is the displacement of the daily load curve of peak demand and renewable power output with hours. This problem can be solved by the combination of grid-scale battery storage and green hydrogen. In a merit factor study by Vezirp lu A and Macüge R, India is at 138th position out of 141 countries for earlier conversion to hydrogen-fueled transportation [70]. The study shows that countries with high per capita income and smaller geographic areas are more suitable for short-term investments in hydrogen-powered vehicles. Based on research of Dhar S. et al., under normal circumstances, the energy consumption of India's transport sector may increase to about 4.5 times by 2050 [71]. But as the need for hydrogen mobility increases, the age-old chicken-andegg question still stands. Policymakers need to consider the issue of whether infrastructure for cars or refuelling comes first [25]. High cost of oil imports and dependence on oil-based fuels threaten the energy security of India [72]. India has a huge potential market for hydrogen [73] due to its large supply-demand gap and rapid economic growth. India can become a reality in green hydrogen as an energy sector by fully exploiting the indigenous resources of solar and water [74].

Challenges and Opportunities

India has, in its pursuit of a hydrogen economy, based on a literature review. These are inputs for
future discussions on the hydrogen narrative of India." Solar PV power in India is being procured at a price as low as INR 1.99/kWh, but most projects are being built at INR 2-3.5/kWh. India can make green hydrogen cheaply by producing renewable power cheaply. It could export hydrogen to the world market, taking advantage of its ability to implement cheap green hydrogen. India's large and young population and strong economy also position it as a promising market for hydrogen. Demand-oriented policy initiatives are needed to support an early integration of hydrogen in the country's energy system. The country can lower the cost of producing hydrogen faster than expected by drawing on its experience with reverse bidding in solar PV and wind. The best results are obtained by coordinating hydrogen and renewable energy missions [69].

There are numerous reports that the biggest barrier to broader application of this technology is the large price gap between green and other hydrogen sources. In addition to RD&D, a mix of supply-side policy tools, such as grants, loan guarantees, and accelerated depreciation, must be adopted. Today's cutting-edge technology systems may become obsolete in the future due to technological advances. This can lead to hidden costs, reduce investor confidence, and affect future investment. Therefore, current systems need to be designed so they can be retrofitted in the future. The country has almost no capacity to produce hydrogen storage systems, fuel cells, and electrolysers. Most hydrogen subsectors, such as transportation, storage, and mobility, act as an inertia for players because of a lack of specialized infrastructure. Governments need to demonstrate early "will and way" and sustained, strong policies until the most basic infrastructure is in place. Public awareness and trust are always issues with new technologies. Hydrogen policies may include workshops and public awareness campaigns to prevent separate intervention in later adoption stages. A public knowledge site with fact sheets, infographics, and information booklets can be created. For example, the US Department of Energy has established an information resources website [75]. This source is a tool that can be used by people from all walks of life to support their claims and make well-informed decisions.

Summary

Renewable energy has been a flagship of the green movement since the dawn of the twenty-first century. By the end of the century, hydrogen could play a similar role as the push to go green evolves from simply reducing greenhouse gas emissions to achieving net-zero emissions. On this path, hydrogen should not be viewed as a substitute for other green technologies or as the ultimate solution for all present energy problems. The biggest advantages of switching to hydrogen technology have been the diversity of production routes and the absence of technological dominance by one or more countries.

One possible interim solution could be to generate and consume hydrogen at the same location until a dependable storage and transport infrastructure is widely available. International cooperation is necessary for safe large-scale deployment and early commercialisation of existing technologies. Global harmonisation of financial, technical, and safety standards is essential.

Hydrogen can change the global energy geopolitics altogether. For the revitalised government programmes to be successful, the right mix of intra-sectoral and inter-sectoral policies must be implemented. The ongoing excitement and optimism around hydrogen will set the scene for the role of hydrogen in the energy transition, with the recent policy initiatives from the government. The government will have to ensure an accelerated and seamless transition to the green hydrogen ecosystem with steady, long-term policies and not stop-go policies.

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