

Hydrogen Fuel Cell Vehicles: A Review on Opportunities and Challenges in Future

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Abstract: This paper provides an in-depth review of the current state and future potential of hydrogen fuel cell vehicles (HFCVs). The urgency for more eco-friendly and efficient alternatives to fossil-fuel-powered vehicles underlines the necessity of HFCVs, which utilize hydrogen gas to power an onboard electric motor, producing only water vapor and heat. Despite their impressive energy efficiency ratio (EER), higher power-to-weight ratio, and substantial emissions reduction potential, the widespread implementation of HFCVs is presently hindered by several technical and infrastructural challenges. These include high manufacturing costs, the relatively low energy density of hydrogen, safety concerns, fuel cell durability issues, insufficient hydrogen refueling infrastructure, and the complexities of hydrogen storage and transportation. Nevertheless, technological advancements and potential policy interventions offer promising prospects for HFCVs, suggesting they could become a vital component of sustainable transportation in the future.

Keywords: HFCVs; zero-emission vehicles; technical challenges; market acceptance; future prospects

1. Introduction

Hydrogen energy is a versatile and clean energy source that has gained significant attention as a potential solution for addressing climate change and transitioning toward a sustainable energy future [1]. It has the potential to revolutionize various sectors, including transportation, power generation, and industrial processes. Hydrogen is the most abundant element in the universe but is primarily found in combination with other elements, such as oxygen in water (H₂O) or carbon in hydrocarbons [2]. To harness hydrogen as an energy source, it needs to be extracted and converted into a usable form. There are different methods for hydrogen production, including steam methane reforming, electrolysis, biomass gasification, and more [3]. Each method has its advantages and considerations in terms of efficiency, cost, and environmental impact.

One of the main advantages of hydrogen energy is its environmental benefits; when used as a fuel, hydrogen only produces water vapor as a byproduct, making it a zero-emission energy source [4]. This is particularly important in sectors such as transportation, where hydrogen fuel cells can be used to power electric vehicles, offering long driving ranges and fast refueling times. Furthermore, hydrogen energy has the potential to support renewable energy integration and energy storage [5]. Renewable energy sources such as solar and wind are intermittent, and their generation does not always align with energy demand. Hydrogen can be produced during times of excess renewable energy generation through electrolysis and stored for later use. It can be used for power generation when the renewable energy supply is low, thus

providing a reliable and dispatch able energy option.

Hydrogen energy has emerged as a global destination for multiple sectors due to its potential to address various energy challenges and contribute to a sustainable future. Figure 1 shows the global hydrogen production (2010–2022).

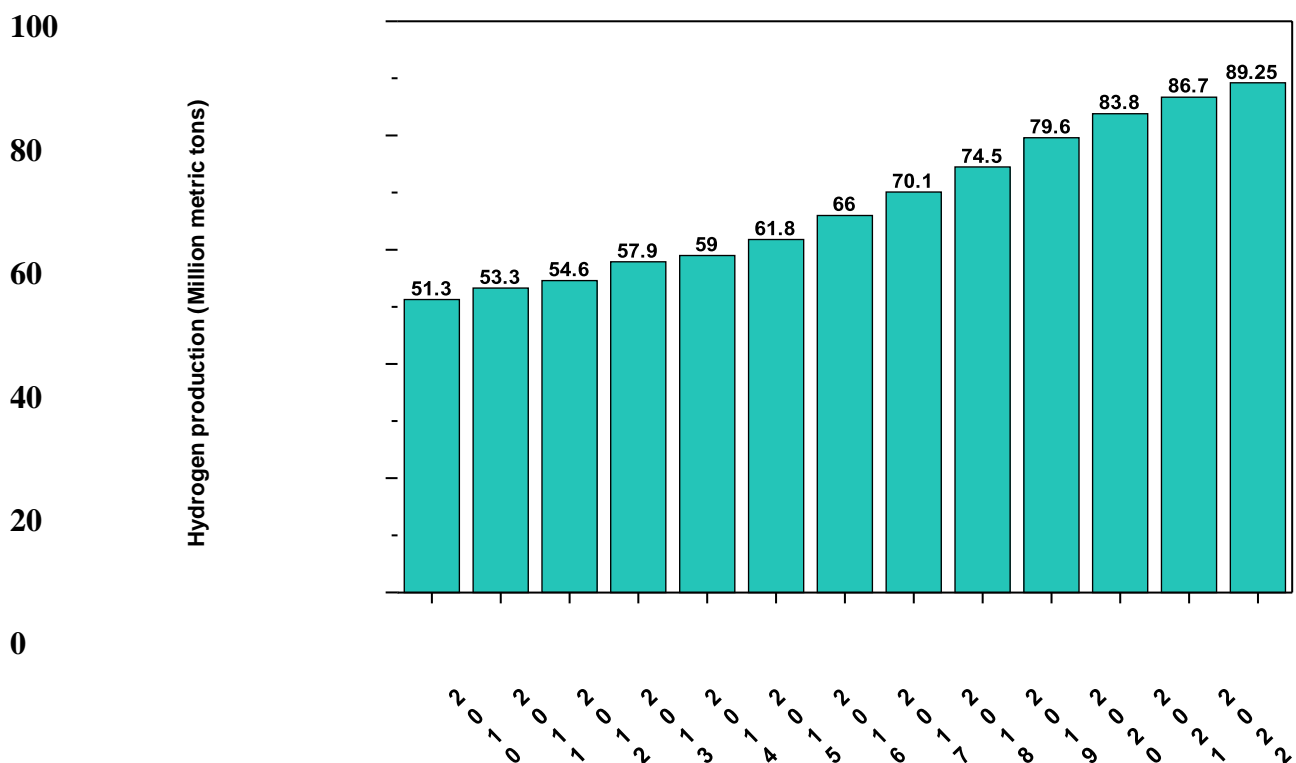


Figure 1. The global hydrogen production (2010–2022) [6,7].

The global destination for hydrogen energy is driven by its versatility, its potential for decarbonization, and its role in addressing various energy challenges. With increasing investments, supportive policies, and technological advancements, hydrogen energy is gaining momentum across multiple sectors globally, contributing to a sustainable and low-carbon future.

1.1. Hydrogen Types

Hydrogen energy can be categorized into different types based on its production methods and applications. Here are the main types of hydrogen energy:

Gray hydrogen refers to hydrogen produced from fossil fuels, such as natural gas or coal, through a process called steam methane reforming (SMR). It is the most common method of hydrogen production today [8,9]. However, gray hydrogen production generates carbon dioxide (CO₂) emissions, contributing to climate change.

Blue hydrogen is produced from fossil fuels, similar to gray hydrogen, but with an additional step called carbon capture and storage (CCS). The CCS involves capturing the CO₂ emitted during hydrogen production and storing it underground, preventing it from entering the atmosphere [10]. Blue hydrogen aims to reduce the carbon footprint of hydrogen production.

Green hydrogen is produced using renewable energy sources, such as solar or wind power, through a process called electrolysis. Electrolysis involves splitting water (H₂O) into hydrogen (H₂) and oxygen (O₂) using an electric current [11,12]. Since it relies on renewable energy, green hydrogen production has no direct carbon emissions and is considered a clean and sustainable option.

Turquoise hydrogen, also known as low-carbon or decarbonized hydrogen, is produced using natural gas but with carbon emissions offset by capturing and storing the CO₂, similar to blue hydrogen. The difference is that turquoise hydrogen production typically utilizes a different type of methane reforming process called methane pyrolysis, which can help in reducing the carbon intensity of hydrogen production [13].

Brown hydrogen is produced from coal using gasification or other processes. It is considered the most carbon-intensive method of hydrogen production as it involves extracting hydrogen from coal, which is a high-carbon fossil fuel [14,15]. Brown hydrogen production generates substantial CO₂ emissions and is not considered a clean or sustainable option.

Purple hydrogen is the hydrogen produced from nuclear energy sources, specifically through high-temperature electrolysis (HTE). This method utilizes heat generated by nuclear reactors to drive the electrolysis process, enabling the production of hydrogen without direct carbon emissions [16].

The green hydrogen only is considered the most environmentally friendly and sustainable option among these types as it relies on renewable energy sources. Blue and turquoise hydrogen, with the implementation of carbon capture and storage, can also help reduce the carbon footprint of hydrogen production. Figure 2 shows the global hydrogen production (2010–2022).

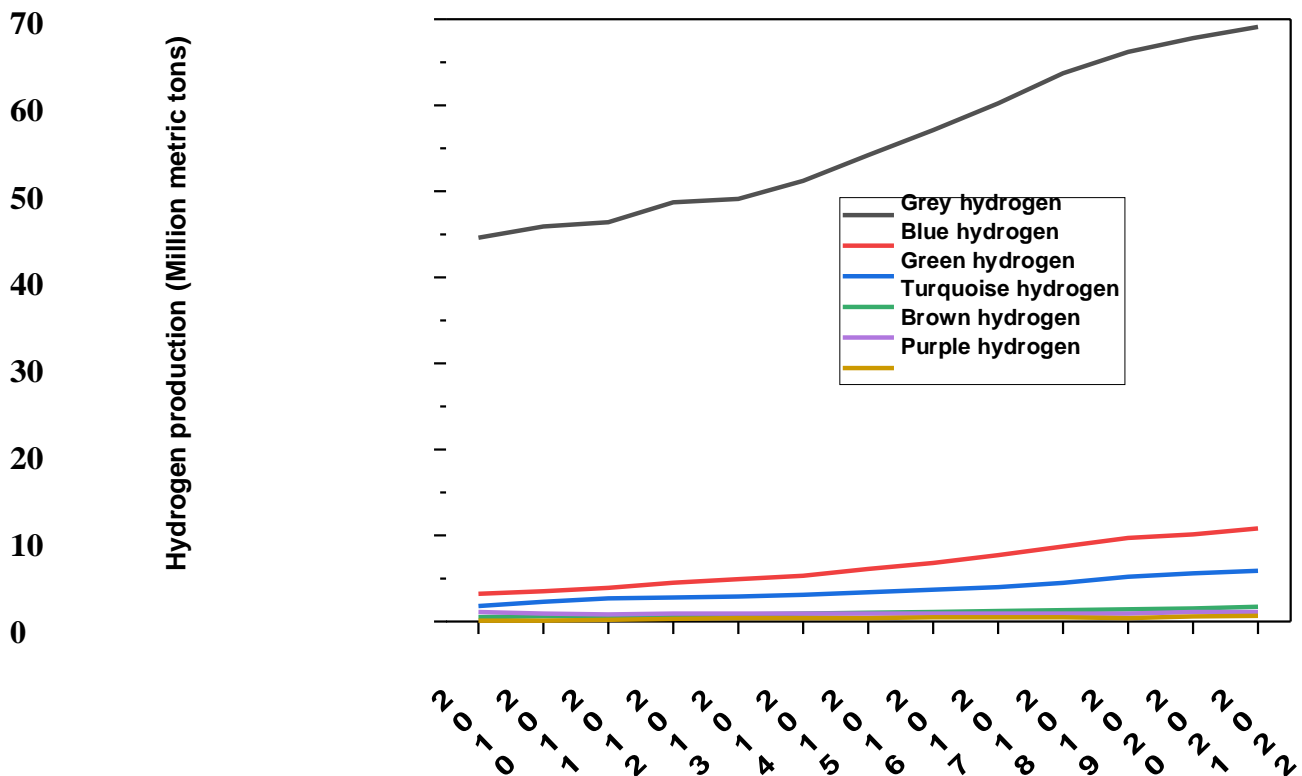


Figure 2. The global hydrogen production by type (2010–2022) [6,7].

However, gray, brown, and purple hydrogen are associated with higher carbon emissions or environmental concerns. The development and adoption of green hydrogen, along with advancements in electrolysis technology and renewable energy integration, are key to achieving a cleaner and more sustainable hydrogen economy.

2. Hydrogen Fuel Cell Vehicles

The HFCVs have emerged as a promising solution, offering a pathway to cleaner and more sustainable transportation. Harnessing the power of hydrogen, the most abundant element in the universe, HFCVs represent a paradigm shift in the automotive industry, providing zero-emission mobility without compromising on performance or range. The innovative technology behind these vehicles holds great potential to revolutionize the way to travel, addressing the detrimental impacts of traditional internal combustion engines

2.1. HFCV Overview

Hydrogen fuel cell technology represents a breakthrough in the quest for sustainable and environmentally friendly energy sources. This innovative technology leverages the energy stored in molecular hydrogen, converting it into electricity through a series of chemical reactions and producing only water and heat as byproducts. As such, it offers considerable promise, particularly in the field of transportation, as a clean and efficient alternative to conventional fossil-fuel-based internal combustion engines.

The central component of hydrogen fuel cell technology is the fuel cell stack. This consists of two electrodes—an anode and a cathode—separated by an electrolyte layer. The fuel cell operates through several interlinked chemical reactions

1. **Hydrogen supply:** Stored in high-pressure tanks within the vehicle, hydrogen gas is delivered to the anode of the fuel cell stack.
2. **Hydrogen ionization:** Once at the anode, a platinum catalyst assists in the ionization of hydrogen molecules, splitting each into two hydrogen ions (protons) and two electrons.
3. **Ion and electron separation:** The electrolyte, commonly a proton exchange membrane (PEM), permits only the positively charged hydrogen ions to move through to the cathode. This forces the electrons to travel via an external circuit to reach the cathode, thereby generating an electric current.
4. **Oxygen reduction and water formation:** At the cathode, oxygen from the ambient air is reduced and merges with the incoming hydrogen ions and electrons to generate water—the technology's sole exhaust product.
5. **Power generation:** The electric current produced by the flow of electrons powers the vehicle's electric motor and other auxiliary systems such as the headlights, heating, and air conditioning. Significantly, while the vehicle is operational, these reactions take place continuously, providing a consistent source of electricity for as long as hydrogen and oxygen remain available. This technology, although still developing, has notable benefits. Hydrogen fuel cells are more energy-efficient than traditional combustion engines, and the fuel—hydrogen—can be derived from a variety of sources, including renewables. Nevertheless, challenges persist, including safe and efficient hydrogen storage and the need for cost-effective, environmentally friendly hydrogen production. Despite these obstacles, hydrogen fuel cell technology holds substantial potential and could play a pivotal role in driving a sustainable future in transportation

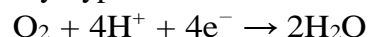
2.2. Working Principle of HFCVs

The HFCVs operate based on the electrochemical reactions occurring in a device called a fuel cell. This fuel cell combines hydrogen and oxygen to produce electricity, which is then used to power the vehicle electric motor as follows

1. **Hydrogen supply:** Hydrogen gas, stored in a high-pressure tank within the vehicle, is supplied to the anode side of the fuel cell.
2. **Hydrogen ionization:** At the anode, a catalyst, usually made of platinum, facilitates the ionization of hydrogen. Each hydrogen molecule (H_2) is split into two hydrogen ions (protons) and two electrons

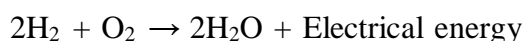


3. **Ion and electron separation:** The proton exchange membrane (PEM) in the middle of the fuel cell only allows protons to pass through it, while the electrons are forced to travel along an external circuit to reach the other side (the cathode). This movement of electrons creates an electric current.
4. **Oxygen reduction and water formation:** At the cathode side, oxygen from the air is reduced and combined with the incoming protons and the electrons that have traveled through the external circuit. This reaction forms water, which is expelled as the only byproduct



5. **Power generation:** the electricity generated (the flow of electrons) is harnessed to power the vehicle electric motor and other electrical systems

The overall reaction in the fuel cell, therefore, can be summed up as



The kinetics and thermodynamics of the reactions in a hydrogen fuel cell, which underpin the functioning of HFCVs, primarily involve two processes: the breaking of the H–H bond in hydrogen molecules and the formation of the O–H bond in water molecules. These processes happen in the two halves of the fuel cell: the anode (where hydrogen gas is supplied) and the cathode (where oxygen from the air is supplied).

The thermodynamics of these reactions whether they occur spontaneously depend on the Gibbs free energy change (ΔG). This quantity can be calculated from the equation

$$\Delta G = \Delta H - T\Delta S$$

where ΔH is the enthalpy change, T is the absolute temperature, and ΔS is the entropy change. In a hydrogen fuel cell, the enthalpy change is primarily due to the difference in energy between the breaking of H–H bonds and the formation of O–H bonds. The entropy change is usually negative as the reaction leads to a decrease in the number of gas molecules.

The Gibbs free energy change is also related to the electrochemical potential (E) of the fuel cell by $\Delta G = -nFE$

where n is the number of electrons transferred per molecule of hydrogen ($n = 2$), F is the Faraday constant, and E is the cell potential. The cell potential is what drives the electric current in the external circuit.

While the exact values of ΔG , ΔH , and ΔS depend on the specific design and operating conditions of the fuel cell, it is the favorable thermodynamics (negative ΔG) and fast kinetics (thanks to catalysts) of the hydrogen oxidation and oxygen reduction reactions that make HFCVs a promising technology for sustainable transportation.

3. Hydrogen Fuel Cell Vehicle Technology

The technology of HFCVs is an innovative approach to powering automobiles that utilizes hydrogen as its primary fuel. At the heart of this technology is a device called a fuel cell, which uses hydrogen to produce electricity within the vehicle, powering the electric motor and offering a clean alternative to traditional internal combustion engines

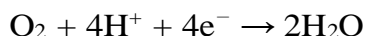
3.1. Fuel Cell Technology and Its Use in Vehicles

Fuel cell technology is the backbone of HFCVs, which involves the electrochemical conversion of hydrogen fuel into electrical energy, which can be used to power the vehicle's electric motor. The primary components of a fuel cell include an anode, a cathode, and an electrolyte.

When hydrogen (H_2) is supplied to the anode of the fuel cell, it undergoes a process called hydrogen oxidation. In this process, hydrogen molecules are split into protons (H^+) and electrons (e^-) through a reaction facilitated by a catalyst (usually platinum)



The protons migrate through the electrolyte, while the electrons travel through an external circuit, creating an electric current that can be utilized to power the vehicle motor. At the cathode, oxygen from the air combines with the protons and electrons to form water as the only byproduct



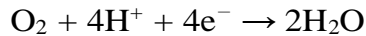
This electrochemical reaction produces a continuous flow of electricity, allowing for sustained vehicle operation. The fuel cell system can be designed in various configurations, such as proton exchange membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), and solid oxide fuel cells (SOFCs), with PEMFCs being the most commonly used in HFCVs.

3.2. The Chemistry behind Hydrogen Fuel Cells

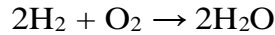
The chemical process behind hydrogen fuel cells revolves around the electrochemical reactions that occur within the fuel cell. These reactions are governed by principles of redox (reduction–oxidation) reactions and involve the movement of charged particles, protons, and electrons.

The anode of the fuel cell is where hydrogen oxidation takes place. The hydrogen molecules dissociate into protons and electrons due to the catalytic effect of the platinum catalyst. The protons (H^+) are small, positively charged particles that can easily pass through the electrolyte, typically a proton exchange membrane (PEM), while the electrons (e^-) flow through an external circuit to create an electric current

At the cathode, oxygen from the air combines with the protons and electrons to form water. This process is known as oxygen reduction:



The overall reaction in a hydrogen fuel cell can be represented as



This reaction demonstrates that the only byproduct of the fuel cell system is water, making it a clean and environmentally friendly energy conversion technology.

3.3. *The Design and Structure of a Hydrogen Fuel Cell Vehicle*

The HFCVs are designed to incorporate the fuel cell system, hydrogen storage, and electric drivetrain components. The key elements of the design and structure of an HFCV include the following:

Fuel cell stack: The heart of the HFCV is the fuel cell stack, which contains multiple individual fuel cells. Each fuel cell consists of an anode, a cathode, and an electrolyte. The fuel cell stack generates electrical energy from the chemical reaction between hydrogen and oxygen.

Hydrogen storage: HFCVs require a mechanism to store hydrogen fuel on board the Vehicle. Common methods of hydrogen storage include high-pressure compressed gas cylinders or cryogenic liquid hydrogen tanks. These storage systems ensure the safe and efficient containment of hydrogen fuel.

Electric motor: The electrical energy produced by the fuel cell stack powers an electric motor, which drives the wheels of the vehicle. The electric motor offers smooth acceleration and quiet operation, contributing to the overall performance and efficiency of the HFCVs.

Power control unit: The power control unit manages the flow of electrical energy from the fuel cell stack to the electric motor. It regulates the voltage and current to ensure optimal performance and efficiency.

Auxiliary systems: HFCVs also incorporate auxiliary systems, such as cooling systems to maintain the optimal operating temperature of the fuel cell stack, as well as air supply systems to provide oxygen for the fuel cell reaction.

Energy storage: Some HFCVs also include energy storage systems, such as lithium-ion batteries, to capture and store excess electrical energy produced by the fuel cell stack. These energy storage systems can be used to provide additional power during high-demand situations or for regenerative braking.

4. Opportunities for HFCVs

4.1. Opportunities Associated with HFCVs

The HFCVs offer several advantages and opportunities compared with conventional internal combustion engine vehicles. These advantages and opportunities stem from the unique characteristics of hydrogen as a fuel and the efficient and clean operation of fuel cell technology. This section highlights some of the advantages and opportunities associated with HFCVs:

Zero emissions: HFCVs produce zero tailpipe emissions as the only byproduct of the electrochemical reaction is water vapor. This makes HFCVs an environmentally friendly alternative to conventional vehicles, contributing to improved air quality and reduced greenhouse gas emissions.

Energy efficiency: Fuel cells can achieve higher energy conversion efficiencies compared with internal combustion engines. The direct conversion of chemical energy into electrical energy in fuel cells results in less wasted energy, leading to greater overall efficiency and reduced energy consumption.

Extended range and quick refueling: HFCVs typically offer longer driving ranges compared with battery electric vehicles. Hydrogen fueling stations can refill a fuel cell vehicle in a matter of minutes, similar to the refueling time for conventional vehicles. This addresses concerns about range anxiety and long recharging times associated with battery electric vehicles.

Scalability and flexibility: Hydrogen fuel cell technology can be scaled for various applications, from small portable devices to large-scale power generation. It offers flexibility in energy sources as hydrogen can be produced from diverse resources such as renewable energy (e.g., solar and wind) or by reforming fossil fuels. This scalability and flexibility enable the decarbonization of various sectors, including transportation, power generation, and industrial processes.

Energy storage and grid integration: Hydrogen can serve as an energy storage medium. Excess electricity generated from renewable sources can be used to produce hydrogen through electrolysis, which can be stored and later used in fuel cells to generate electricity. This integration of hydrogen fuel cells with renewable energy sources supports the development of a sustainable and resilient energy system, enabling the utilization of intermittent renewable energy and helping to balance the grid.

Fast refueling infrastructure deployment: Compared with the widespread deployment of electric vehicle charging infrastructure, establishing hydrogen refueling infrastructure is relatively quick. Existing natural gas pipelines can be repurposed for hydrogen transportation, and new hydrogen refueling stations can be built using modular and scalable designs. This provides an opportunity for accelerated infrastructure development, especially for long-haul transportation and heavy-duty applications. **Quiet operation and comfort:** Fuel cell vehicles produce significantly less noise compared with conventional vehicles with internal combustion engines. This leads to quieter and more comfortable driving experiences, reducing noise pollution in urban areas.

Economic development and job creation: The development and deployment of hydrogen fuel cell technologies and infrastructure offer opportunities for economic growth and job creation. The hydrogen sector encompasses research and development, manufacturing, the installation and maintenance of fuel cell systems, hydrogen production and distribution, and the operation of refueling stations.

The HFCVs offer advantages such as zero emissions, high energy efficiency, extended range, quick refueling, and scalability, flexibility in energy sources, energy storage capabilities, fast infrastructure deployment, quiet operation, and economic development opportunities. These advantages and opportunities position HFCVs as a promising and sustainable solution for the transportation sector and the broader transition to a low-carbon economy.

5. Conclusions

The HFCVs hold great promise for a sustainable and low-carbon future. They have distinct advantages such as zero tailpipe emissions, high energy efficiency, and the potential for fast refueling, making them a compelling solution for long-range and heavy-duty transport where battery electric vehicles may be less practical. Moreover, if produced from renewable sources, hydrogen can provide a truly green fuel option, further contributing to climate change mitigation efforts. However, the journey toward widespread adoption of HFCVs is fraught with challenges. Key among these are the high costs associated with vehicle production and hydrogen fuel cell technology, a lack of refueling infrastructure, and concerns about the efficiency and environmental footprint of hydrogen production. Despite these hurdles, advancements in technology, economies of scale, and significant R&D investments may likely help overcome these obstacles in the future.

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