

Fuel Cells in Healthcare Systems: Enhancing Administration, Laboratory Operations, Community Services, Anaesthesia, and Nutrition Efficiency

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Abstract

Fuel cells have emerged as a promising technology to enhance energy efficiency and sustainability in healthcare systems. This review explores the applications of fuel cells in various healthcare domains, including administration, laboratory operations, community services, anesthesia, and nutrition management. Fuel cells generate energy through an electrochemical process, providing higher efficiency and lower emissions compared to traditional energy systems. They are modular, scalable, and suitable for meeting the simultaneous electrical and thermal energy needs of healthcare facilities. Key applications discussed include their role in powering healthcare administrative functions, ensuring reliable energy for sensitive laboratory equipment, supporting remote healthcare services, advancing anesthesia delivery systems, and improving nutrition management. The review also highlights global and local trends, techno-economic analyses, and the sustainability perspective of fuel cell integration in healthcare systems. By adopting fuel cell technology, healthcare organizations can reduce greenhouse gas emissions, lower operational costs, and promote innovation in energy management.

(Keywords): Fuel Cells, Healthcare Systems, Energy Efficiency, Sustainability, Healthcare Administration, Laboratory Operations, Community Services, Anesthesia, Nutrition Management.

1. Introduction to Fuel Cells in Healthcare

Fuel cells are increasingly being explored and deployed in healthcare systems. Fuel cells provide on-site energy generation through an electrochemical process, in which a fuel (such as hydrogen or natural gas) is converted to electricity and heat. Compared with traditional energy supply methods such as steam, boilers, and chillers, fuel cells have unique features. They provide energy using an electrochemical process instead of combustion, resulting in much higher efficiency, 90 % or more when heat recovery is considered. They can use different fuels, primarily natural gas or biogas, and can achieve near-zero emissions when external reformers are used (K. Niakolas et al., 2016). Furthermore, being modular power generation systems, fuel cells can be easily scaled up and down to accommodate different heating and cooling loads. Healthcare systems often possess heavy and simultaneous thermal and electrical energy needs, making them highly suitable for fuel cell applications. This will examine how fuel cells can enhance efficiency in healthcare systems, focusing on combined heat and power (CHP) and combined cooling heat and power (CCHP) applications. First, it will introduce fuel cell technology and its potential applications in healthcare systems. Then, recent global and local trends in fuel cells will be discussed, followed by the techno-economic analysis of fuel cell applications in healthcare systems. Finally, it will address the sustainability perspective of fuel cell applications in healthcare systems (Elmer et al., 2015).

1.1. Overview of Fuel Cell Technology

This overview describes the fuel cell technology and its general working principles. It includes different types of fuel cells, their components, and working principles. The advantages of fuel cells in terms of efficiency, high and low emissions, and energy sustainability are briefly pointed out. Fuel cells convert the chemical energy of the fuel directly into electrical energy

through an electrochemical reaction. This technology makes fuel cells an attractive option for stationary, portable, and automotive applications (K. Niakolas et al., 2016). Current fuel cell technology development and research are also addressed. For the station application of fuel cell systems, the healthcare systems are focused on. Various implications of fuel cell technology for the healthcare systems are discussed, such as improving energy sustainability. Additionally, the critical issues regarding the implementation of fuel cell systems in healthcare centers are pointed out.

A fuel cell is an electrochemical energy conversion device that continuously converts the chemical energy of the fuel into electrical energy. Fuel cells consist of anode, cathode, electrolyte, and fuel processor. In addition to these basic components, the fuel cell system also includes balance of plant (BOP) components like the compressor, blower, heater, humidifier, and control system. At the anode side, hydrogen fuel is electrochemically oxidized to protons and electrons. Protons pass through the electrolyte to the cathode side. On the other hand, electrons flow through the external circuit, creating an electric current. At the cathode side, oxygen is reduced and combines with protons to form water. As a result of these electrochemical reactions, water, heat, and electricity are produced (Elmer et al., 2015). There are various types of fuel cells based on electrolytes, such as polymer electrolyte membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), and alkaline fuel cells (AFCs). Among them, proton exchange membrane fuel cells (PEMFCs) are widely used, especially in transportation applications. PEMFCs operate at a low temperature of about 80 °C and require pure hydrogen fuel.

2. Fuel Cells in Administration

Integration of fuel cells in the administrative functions of healthcare organizations can promote operational efficiency and energy cost reduction, and contribute to improving the healthcare industry's sustainability. Despite the early stages of deployment, innovative energy management strategies based on fuel cells can provide healthcare organizations with a competitive advantage. Nowadays, energy efficiency has become a vital concern for healthcare organizations worldwide. Fuel cells offer numerous benefits as energy management alternatives, such as low maintenance requirements and the reliable supply of energy, which are crucial in essential services like healthcare. Healthcare organizations also perform many administrative tasks such as accounting, human resources, and purchasing that can utilize fuel cell applications (Elmer et al., 2015). From billing systems using fuel cell-powered IT servers to printing and general office activities, there are various applications of fuel cells in the administrative functions of healthcare organizations. In addition to healthcare organizations, fuel cell applications in public administration and other services are also presented.

Several examples and case studies are discussed to illustrate the successful implementation and improvement of outcomes by applying fuel cells in the administrative functions of healthcare organizations. Even though the use of fuel cells in the health sector is still limited compared to other sectors, possible applications and innovative solutions can improve administrative efficiency. This approach also reflects a general trend in the healthcare industry towards adopting new and innovative solutions in management and administration. By promoting innovation in healthcare organization administration, the integration of fuel cells can streamline operations that have remained largely unchanged for decades, leading to better resource allocation, planning, control, and overall service delivery (K. Niakolas et al., 2016). The healthcare sector is essential for every society and nation and is regularly shaped and controlled by the government. Therefore, although basically independent, healthcare organizations are often subject to various regulations and rules. In recent years, however, several countries have gradually relaxed regulations in the healthcare sector and started a reform process towards integrated or market-driven healthcare systems. This shift in approach has resulted in increased competition between healthcare organizations to attract and retain patients. In such circumstances, the internal efficiency of healthcare organizations is increasingly emphasized and addressed.

2.1. Benefits and Applications

Healthcare systems require a significant amount of energy for their operation and maintenance. Healthcare systems consumed 7% of the world's energy in 2018, with this figure expected to rise as health budgets increase globally. As a result, this sector's contribution to greenhouse gas emissions is projected to increase. Therefore, implementing energy-efficient systems is considered critical in tackling climate change, while also resulting in cost savings for the health budget that can be redirected elsewhere. Fuel cell technology can have specific benefits and applications in the administrative role of healthcare systems.

Fuel cells can generate energy from natural gas with more than 50% efficiency. Compared to normal fuel generators, this is a more than 20% increase in efficiency. Taking this into consideration, a fuel cell system that fits the needs of healthcare facilities would pay back in a little over six years of continuous operation. Since most facilities operate 24/7, it would be

reasonable to consider fuel cells a viable solution that generates cost savings over time. Additionally, fuel cells generate very little CO₂. Coupled with the plan of most countries to phase out natural gas in favor of hydrogen, future development could lead to healthcare facilities operating without any CO₂ emissions. This is particularly useful in light of the Paris Agreement, where developed countries must significantly reduce their CO₂ emissions. Because healthcare systems are often seen as pillars of society, many would expect them to lead the way on such matters (Elmer et al., 2015).

Fuel cells are already a feasible solution for powering standalone administrative buildings, as they generate electricity and heat on-site. Such installations are already in use in several European countries. Watering holes in hospitals could be fitted with water-resistant fuel cells that would power electronic systems such as health monitoring devices and tablets that are often used by medical staff to track patient history. Patients receiving treatment in highly-controlled environments often have monitoring devices that track their state (K. Niakolas et al., 2016). Currently, these devices are powered using wired systems, as having them powered by batteries would result in either the device overheating or having to constantly waste energy on cooling the device to maintain lower temperatures. Adapting fuel cells to power such monitoring devices would limit the use of wires, thus making it easier to move patients if necessary while maintaining monitoring. Additionally, devices powered via wires tend to become entangled, resulting in potential harm to the patient. Fuel cells would enable more flexibility in how monitoring devices are set up, as they would no longer be tied down to a specific location. And, as with the previous case, fuel cells would ensure that devices would always have sufficient power, as it would be possible to have several backup systems. (Cigolotti et al., 2021)

One significant challenge is finding a fuel cell system that can be installed without a facility overhaul. In healthcare systems, there could be specific rooms for engineers to maintain the cogeneration system, but that is not the case everywhere. However, the solutions considered in the previous sections could be systems that do not require significant intervention from auxiliary systems. Fuel cells would be an appropriate solution in this respect since they can be installed alone, and staff only need to refill the fuel supply. On-site treatment plants are a good example of having to install a system without significant overhauls and staff training. Fuel cell solutions powering energy systems in healthcare facilities would still need to be researched in terms of system scalability. Also, alternatives to natural gas, which may not be available everywhere, have not been considered. However, if on-site treatment plants are in use, this could be a viable solution as well. Fuel cells would need to be adapted to fit the needs of the facility, but this is a feasible approach that has only rarely been considered. Finally, the solutions considered would work in a healthcare facility in one specific environment. However, energy production is often coupled with having a requirement for the treatment of wastewater. In such a case, fuel cell systems would have to undergo more significant changes to function effectively.

Overall, the points outlined would highlight the growing importance of innovative energy solutions for healthcare system management. This discussion may seem somewhat narrow, as the focus is on one specific technology of energy management. However, energy management in general is something that is not often actively researched with respect to the healthcare system, and this discussion should illustrate that beyond being providers of energy, fuel cells could also play an important role in enhancing the overall efficiency of the healthcare system.

3. Fuel Cells in Laboratory Operations

Laboratories, as one of the keystones of healthcare systems, demand high reliability and efficiency of power supply (Elmer et al., 2015). Many laboratory equipment can be expensive, sensitive to current and voltage variations, and critical to be powered-on uninterruptedly. As a consequence, Laboratories usually implement UPS systems to mitigate any power outages from the main grid. UPS systems internationally commonly use lead-acid batteries, which are sensitive to ambient temperature and require preventive maintenance. In contrast to such systems, several technological alternatives have emerged. Of particular interest are fuel cells, which have shown high reliability and efficiency in stationary applications.

Laboratory case studies have been selected that integrate PEM fuel cell technology, together with its prospective advantages, obstacles, and unique solutions designed and implemented in order to enhance operational workflows and potentially reduce laboratory costs. Additionally, the environmental benefits of adopting such technology are discussed and analyzed, in concordance with the growing sustainability objectives within many institutions. Finally, the implications of wider fuel cell adoption in laboratories for research and innovation practices are considered, as institutions at the vanguard of technology implementation can become forward-looking fountains of innovation around best practices to be emulated elsewhere. Fuel cells have the potential to fundamentally change how power is generated, transmitted, and used across multiple sectors,

including healthcare systems. Implementing on-site fuel cell systems can transform laboratory operations, inescapably enhancing reliability, efficiency, and environmental performance whilst paving the way for competitive research and innovation practices. (İnci et al.2021)

3.1. Advantages and Case Studies

Laboratories are in need of efficient energy sources to power sensitive instruments that perform micro-scale analyses on liquid samples and carry out time-critical standard chemical reactions. Fuel cells can serve this role (Elmer et al., 2015). The energy needs of laboratory instruments and processes could be oscillating, but most battery technologies cannot support this. Therefore, more and more laboratories are switching to fuel cells, which can supply a consistent and steady energy source. Several fuel cell case studies within laboratories are presented to show how efficiency was enhanced or operational interruptions were decreased.

In clinical laboratories and laboratories on research vessels, fuel cells have been used to enhance efficiency in scientific measurements. Proton exchange membrane (PEM) fuel cells using hydrogen gas and in some cases reformat methanol have been successfully employed in clinical, biochemistry, environmental monitoring, and research laboratories in diverse settings from pipe-integrated to portable and handheld stages (K. Niakolas et al., 2016). With these case studies, the compelling arguments and strongest evidence are presented as laboratory-focused advantages of using fuel cells, on top of the obvious general power generation advantages of zero to very low emissions, lower fossil fuel reliance, and upgradable to wider energy sources. Fuel cells are also thought to be adaptable to emerging laboratory setups or future technological developments. Since most case studies are published recently or in the last ten years, this could be a timely focus for labs that have yet to consider power generation options outside the grid or batteries. Fuel cell experiments have been carried out using laboratory-generated hydrogen gas from electrochemical water splitting and also from sodium hydroxide and aluminum foil. These experiments proved the concept of using laboratory-generated hydrogen for fuel cells to power laboratory instruments. Nevertheless, to increase result yield and comprehensively understand laboratory-generated hydrogen gas stabilization with real-time measurement, much effort is still needed.

4. Fuel Cells in Community Services

Though initially conceived for stationary high-demand applications, fuel cells can effectively be adapted to and deployed in service functions related to health, and thus ensure community access to the health system. Fuel cells can act as a reliable energy source for the health-related community services that currently exist — or will be established — even in under-served, remote areas, where the energy landscape may otherwise not enable the presence, or effective operation, of such facilities. Health assessment and delivery services can be provisioned for healthy, yet remote, communities who otherwise would have no access to essential health services, or only reactive, after-the-fact access to health services, (K. Niakolas et al., 2016) through periodic on-site health “checks” by visiting mobile health units. Similarly, and most ideally, community health resilience may be enhanced by on-site newly-established healthcare facilities that run entirely off- or stand-alone energy systems, yet are supported by robust and potentially mobile fuel cell installations, coupled with either flux energy resource converters or transporting energy resources. On the other hand, such fuel cell installations can augment the otherwise limited stand-alone energy provision of remote, health-service-offering community facilities, while offering parallel energy service(s) with fuel cells-based stands to such mobile health units and enhancing their operational effectiveness (Elmer et al., 2015). As a valid, yet forward-looking example, the focus is placed on the health-related community service function of mobile units, exploring the benefits from and addressing the challenges in the implementation of fuel cell technologies within such a service. Several validation and proof-of-concept scientific studies and corresponding publicly funded projects are summarised, while the overall community service function of fuel cell technology in health delivery is outlined.

4.1. Impact on Remote and Rural Areas

Each community has the right to achieve health equity and access to services, regardless of how remote or rural it is. However, accessibility and availability of healthcare have been persistent challenges for remote and rural areas generally focused on community and primary healthcare. These communities are often disadvantaged in terms of infrastructure facilities and the services that rely on them. Due to the critical nature of healthcare services, a conventional lift of infrastructure is expected; however, it is protracted due to various reasons, including the financial viability of investment and continuous operation. Therefore, these communities often rely on portable and mobile healthcare services, which are sensitive to the environmental conditions and power needs. Essential services, particularly healthcare, need a reliable power source; however, across the globe, thousands of villages are still un-electrified or have an unreliable power source. For the ones who are electrified, most

services run on conventional diesel-based generators, which are not only costly to operate but are also one of the largest greenhouse gas emitters. To tackle local healthcare accessibility issues, permanent or portable community health facilities powered by fuel cells, preferably using green hydrogen, can be a viable solution. Different configurations can ensure healthcare services at any power demand, with community level catering up to 50 kW power need. It has been demonstrated that the health facilities fuelled by fuel cells have been a tremendous success and improved health service delivery, with notable implementations in countries like (K. Niakolas et al., 2016). The use of fuel cells in healthcare systems is not only to empower the community but also critically required for time-sensitive healthcare services such as maternal, neonate, and emergency care. Moreover, to ensure life-critical services in any circumstance, the health facility should be hydraulic based and run entirely on fuel cells. The portable healthcare services can be towed to the desired location and deployed in less than an hour, as has been demonstrated during the time of the natural disaster when the entire conventional services fail. Time-sensitive healthcare services can thus be ensured, and the framework can be replicated in any part of the globe. During the COVID-19 pandemic, the importance of community-level health facilities caught attention as the world struggled to contain the spread. Most parts of the undeveloped and developing world are still heavily dependent on a few central hospitals. It is envisioned that a decentralized and community-level approach can greatly complement primary healthcare systems. To promote technology adoption, the environmental benefit of implementing this technology in rural healthcare is that around 65 tonnes of carbon dioxide generation can be avoided per health facility per year. With a bigger picture approach, this technology can, directly and indirectly, ensure a better and healthier environment for the community, which is paramount for the natural growth of the children. (Sapuan et al.2022)(Gür, 2022)

5. Fuel Cells in Anaesthesia

Anaesthesia is a crucial aspect of healthcare, especially during surgical procedures. It is essential to ensure that the doses of anaesthesia provided to the patient remain constant and consistent to avoid complications. Anaesthesia machines are primarily used to mechanism the supply of anaesthesia to patients. The technology used in delivery systems, such as anaesthesia machines, has not significantly advanced since their invention. The current advanced anaesthesia machines are electronic devices consisting of many valves and rotameters that need power to operate and to deliver anaesthesia mechanically to patients. In the case of power failure, these machines fail to operate, resulting in severe outcomes for patients owing to a lack supply of anaesthesia (K. Niakolas et al., 2016). Fuel cells can be used as an alternative reliable power source to assist mechanical anaesthesia machines in advancing the delivery system of anaesthesia machines. Fuel cells can be designed to implement mechanisms for the delivery supply of anaesthesia to the patient mechanically; hence, these machines will not depend on power supply and will continue to operate anaesthesia regardless of the scenarios. These systems will enhance safety standards and reduce operational costs associated with energy consumption. Several innovations in technology in anaesthesia have been developed that implement fuel cell mechanism systems. These new fuel cell devices implanted in anaesthesia machines could transform the anaesthesia landscape and improve patient outcomes with better efficacy and less downtime. It is emphasised that energy is a fundamental requirement in healthcare systems. Most importantly, energy is required in anaesthesia machines for the high precision and high standard mechanism of care for patients during surgical procedures. Anaesthesia machines deliver several different anaesthetic types; hence, it is crucial to maintain high standards of care for patients. This care depends on reliable energy, and therefore, it is vital to discuss the energy aspects within anaesthesia systems.

5.1. Improving Anesthesia Delivery Systems

Anaesthesia delivery systems can be significantly improved with the integration of fuel cell technology. Ecologically sustainable designs can be developed, enabled by low-power consumption and innovative designs. For example, a micro fuel cell integrated with a vapouriser can provide a portable source of energy for anaesthetics. Multi-dose anaesthesia devices can also be powered, using fuel cells to provide a more portable alternative to current hefty compressed gas systems. New functionalities can be built into designs made possible by a fuel cell-powered system. An example is a temperature stabiliser for a vapouriser, ensuring the accuracy of anaesthetic dosing over a wider temperature range and preventing inaeesthetic overdosing due to vapouriser run-dry (K. Niakolas et al., 2016). Enhancements to the safety profile of an anaesthesia delivery system can also be achieved with fuel cells. The most significant risk associated with anaesthesia is the unintended, uncontrollable cessation of delivery. This hazard can be enhanced with a fuel cell system, providing an uninterrupted power supply throughout a procedure.

Innovative designs in anaesthesia delivery systems can be made possible with fuel cell technology. A portable anaesthesia delivery device that would fit in an equipment bag for emergency use is one example. Compact energy sources can be used to

power devices normally dependent on mains electricity due to high-power consumption. Devices with new energy storage technologies, such as supercapacitors and ultracapacitors, provide extra features. For instance, a device can sense when a practitioner is using it, automatically turning on when picked up and going to standby when placed down. An advantage of the significance and ubiquity of anaesthesia monitoring equipment is that the potential cost savings seen by reducing energy-related interruptions can be realised. During anaesthesia, the delivery and monitoring systems for vital signs run continuously. Therefore, the patient would continue to receive monitoring despite delivery system failure, although the period would be critical loss of anaesthesia (Talbot, 2013). It is also imperative that high-quality care is maintained, not just in operating theatres but also in diverse environments. Portable anaesthesia delivery systems are required for use with patient transfer and cryogenic care in MRI scanners. Remote settings such as helicopters and field hospitals are becoming more common for necessitating anaesthesia. A fuel cell system is a step forward in developing portable anaesthesia devices, progress in which would be a boon to the discipline of anaesthesia.

6. Fuel Cells in Nutrition Efficiency

Healthcare systems rely on numerous infrastructures to maintain the health of their patients, one aspect of such infrastructures being their nutrition management systems. Nutrition management encompasses everything from food procurement to preparation, storage, serving, and waste disposal. Out of these processes, food procurement, storage, and transportation can be deemed supply chain processes traditionally handled by external institutions, most notably catering companies, due to the energy-intensive nature of food processing facilities. Nevertheless, to be fully compliant with food-related health outcomes, healthcare institutions ought to handle food supply chains in-house. This necessitates the implementation of improved efficiency and waste reduction across food supply chain operations, ideally whilst minimizing the overall carbon footprint. Such a footprint mitigation is achievable by using fuel cell technology to supply the energy needs of food processing, storage, and transportation systems. New energy-related technologies ought to comply with the already existent energy-efficient frameworks of industrial health systems. Therefore, the fuel cell-focused hierarchy prioritizes energy efficiency enhancements in energy-intensive operations, followed by the energy supply system changes in the currently non-energy-intensive processes and finally the exploration of fuel cell potential in novel technologies (K. Niakolas et al., 2016). Food supply chains involve healthcare-related processes, which, alongside the exemplary focus on healthcare facilities, make the discussion on fuel cells pertinent to food's health-related outcomes.

Food chain processes are energy-intensive and thus often require optimization of energy efficiency and waste reduction. Process energy efficiency is typically increased by investing in new technologies. Although applied energy-saving technologies are often at the forefront, feasible improvements can still be found in the designs of food chain systems. Such energy-intensive processes can involve novel fuel cell technologies resulting in the overall goal of an improved carbon footprint of food supply chains. For instance, fuel cells offer high efficiency power generation, currently commercially viable for a wide range of applications. Open applications of food chain processes, especially of large-scale food processing, could benefit from the installation of fuel cells as energy supply units. Furthermore, facilities currently utilizing on-site energy production can shift towards fuel cell utilization because of the currently greater net efficiency (Elmer et al., 2015). For already implemented units, the change to fuel cells implies enhanced energy efficiency in food chain processes. Nonetheless, the typical food processing technologies and their compliance with fuel cell operating conditions limit direct implementation. This limitation can be overcome by utilizing common facilities such as steam supply or currently unused energy streams that can be turned into power in a fuel cell. Fuel cells can also support technologies essential for maintaining food safety and quality during the supply chain, especially during the presently limiting condition of food temperature abuse. (Grossmann et al.2022)(Kuleshova et al.2022)

6.1. Enhancing Food Processing and Storage

Food Processing and Storage Enhancement Fuel cell technology promotes food processing and storage energy efficiency, helping reduce spoilage and waste. Lowering energy costs enhances food production viability, especially in remote areas. Reductions in food supply chain energy consumption can help maintain food quality, crucial for public health. Food supply chains often struggle with maintaining quality for perishable products. Sustainable energy systems can assist in food supply chains, enhancing health and safety (Elmer et al., 2015). Energy-efficient food processing reduces energy use per produced food unit, optimizing food storage and transport lifetime and improving processing technology robustness. Globally, food waste is a critical economic and environmental concern. In-store waste prevention relies on close monitoring of food storage conditions, processed food quality checks, and purchasing rule consideration. Maintaining desired temperature and humidity during food storage is crucial for food quality preservation. Currently, most food storage technologies utilize standby

refrigerators or humidifiers, which are insufficient in some cases. Technologies integrating fuel cells enable portable food storage with the desired temperature and humidity, preserving food quality and extending shelf life. Within a healthcare context, enhanced food processing relates to patient care and wellness improvements. Healthy nutrition management is vital for preventing chronic diseases common to aging populations. Fuel cell technology can ease the difficulty in maintaining high-quality food supply for the elderly. Efficacy and benefits derived from fuel cells technology in food processing and storage are demonstrated through successful implementation examples. A food supply chain case study shows how fuel cell-based energy systems can considerably reduce the energy cost of an applied food processing technology. Multifunction food containers designed for rural areas combine fuel cell-generated power with maintaining food thermal energy, humidity, and quality, extending food storage lifetime. With over 30% of the worldwide population predicted to exceed 60 years of age by 2050, elderly care becomes increasingly burdensome and costly for society. Efforts are made to develop technology solutions that promote independent living and healthy aging of the elderly, alleviating the need for constant professional supervision. Compact, easily transported, and simple-to-use devices supporting daily activities perfectly suit the elderly. A novel portable food storage device combining robust food cooking/processing and temperature/humidity-controlled food storage technologies is presented. As food safety is one of the critical public health concerns in the food supply chain, this innovative device is particularly beneficial for chain edge food processing and storage.

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