Policy Perspective

Hydrogen Europe Research

Non-Conventional and Advanced Sustainable Manufacturing Technologies for Fuel and Electrolytic Cells

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Abstract

The integration of non-conventional and advanced sustainable manufacturing technologies into the production of fuel cells and electrolytic cells represents a paradigm shift towards enhanced efficiency, reduced costs, and greater environmental compatibility. This paper explores the current state of research, key challenges, and future directions in this rapidly evolving field, emphasizing the transformative potential of additive manufacturing and other innovative techniques. By examining the strategic, economic, environmental, and societal implications, this analysis aims to provide a comprehensive rationale for advancing research and development in this area, aligning with broader EU policy frameworks and sustainable energy goals.

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Introduction

This position paper evaluates novel manufacturing approaches to increase the efficiency and sustainability of fuel cells and electrolyzers. A primary goal is to identify advanced production methods that reduce costs while maintaining high component quality at large scale [1]. For example, high-throughput techniques (e.g., additive manufacturing and roll-to-roll fabrication) can improve process efficiency, yield, and cut material waste, thereby lowering manufacturing costs. These innovations are essential because conventional manufacturing may struggle to maintain quality as production volumes rise.

The scope of this paper includes both additive and non-additive non-conventional manufacturing technologies, examining their technical potential, economic and environmental benefits, and readiness for industrial deployment. The analysis also considers policy actions that can accelerate their adoption, especially in alignment with European energy and industrial strategies.

Moreover, the paper emphasizes the strategic importance of developing cutting-edge fuel cell and electrolyzer production capabilities within the EU [2]. By advancing domestic manufacturing, the EU can reduce dependence on foreign suppliers and create high-tech jobs, thereby supporting economic growth. This aligns with broader EU policies (such as the Net-Zero Industry Act) that aim to strengthen industrial competitiveness and energy resilience. In sum, advancing advanced manufacturing in the hydrogen sector will accelerate decarbonization and reinforce the EU's leadership in renewable energy technologies. Fuel cells and electrolysers are foundational technologies in the hydrogen economy. Table 1 and 2 summarise the main technologies used for the manufacture of fuel and electrolytic cells.

Table 1: Fuel Cell Technologies

(PEMFC proton exchange membrane fuel cell; AEMFC alkaline anion- exchange membrane fuel cell; SOFC solid oxide fuel cell; PCFC protonic ceramic fuel cell; PAFC phosphoric acid fuel cell; MCFC molten carbonate fuel cell)

Type	Temp. °C)	Ion	Fuel	Notes
PEMFC	60–80	H^+	H_2	Low-T, Pt-based, compact, mobile use
AEMFC	40–80	OH^-	H_2, NH_3	Low-cost, non-noble, early-stage
SOFC	600–900	O^{2-}	H_2, CO, CH_4	High-T, fuel-flexible, stationary/CHP
PCFC	400–600	H^+	H_2, NH_3	Mid-T, ceramic proton conductor
PAFC	150–220	H^+	H_2, reformate	Legacy tech, reliable but bulky
MCFC	600–700	CO_3^{2-}	H_2, CH_4, CO	Large-scale CHP, corrosive electrolyte

Table 2: Electrolyser Technologies

AEL alkaline electrolyzer; PEMEL proton exchange membrane electrolyzer; AEMEL alkaline anion- exchange membrane; SOEC solid oxide electrolyzer cell

Type	Temp. (°C)	Ion	Catalyst	Notes
AEL	60–90	OH^-	Ni, Co	Mature, low-cost, lower H_2 purity
PEMEL	50–80	H^+	Pt, Ir	High-purity H_2, compact, costly
AEMEL	40–70	OH^-	Ni, Co, Mn	Low-cost potential, emerging
SOEC	600–850	O^{2-}	Ni, LSM	Highest efficiency, uses heat, complex system


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Current state of research

A variety of traditional manufacturing techniques are currently employed in the production of fuel cell and electrolyzer components. These include spray coating, tape casting, screen printing, hot pressing, die coating, and slot die coating. These methods are widely adopted due to their maturity, relative simplicity, and availability of industrial equipment [1]. However, despite their established nature, they present significant challenges in terms of scalability, cost, material efficiency, and environmental impact, especially when applied to high-throughput and precision-demanding applications.

2.1 Challenges and Limitations

Traditional manufacturing processes often struggle with scaling to large production volumes, which can lead to increased costs and compromised efficiency. Many of these methods rely on subtractive or batch processes, resulting in substantial material waste—particularly critical when using high-cost or rare materials. Achieving uniformity and structural integrity is also difficult with multi-step processes, especially when assembling multilayered components such as MEAs (membrane electrode assemblies) or complete cells.

Catalyst Layers: are typically deposited by spraying catalyst ink onto a gas diffusion layer (GDL) or directly onto the membrane. This method faces multiple challenges: i) ***Cost***: The catalyst layer accounts for a major share of total fuel cell costs due to the use of noble metals like platinum; the MEA can contribute up to 60% of the total cost [1]; ii) ***Efficiency***: Spraying often results in inhomogeneous distribution and low catalyst utilization. Structure optimization, particularly of the catalyst layer, is essential to increase the utilization ratio of Pt [3]; iii) ***Environmental Impact***: Solvent-based inks and the energy-intensive nature of the process contribute to environmental concerns. **MEA:** critical components in PEMFCs, are usually fabricated through hot-pressing, using either a catalyst-coated membrane (CCM) or catalyst-coated substrate (CCS) configuration [1]. Key limitations include: i) ***Cost***: MEAs remain one of the most expensive components in stack [1]; ii) ***Process Sensitivity***: The hot-pressing process requires tight control over time, temperature, and pressure; iii) ***Non-homogeneity***: Non-continuous deposition can lead to layer delamination, inhomogeneity, and performance variability [4]. **Bipolar Plates:** essential for electrical conduction and gas separation, are often produced by machining graphite or corrosion-resistant metals. Limitations include: i) ***Machinability and Cost***: Graphite is fragile and hard to machine, while metals like Ti, Nb, and Au are durable but expensive; ii) ***Durability***: Even stainless steel may corrode under anode-side conditions, releasing contaminants that reduce system performance.

2.2 General Limitations of Traditional Methods

Traditional manufacturing has broader drawbacks: i) ***High Cost***: Expensive materials (platinum catalysts, specialized membranes) [1] and energy-intensive processes drive up costs; ii) ***Scalability***: Many conventional techniques are difficult to scale up for high-volume production; iii) ***Material Waste***: These processes often generate significant waste of costly materials [5]; iv) ***Environmental risks***: Hazardous chemicals (e.g. NiO in solide oxide cells (SOCs) or $Ni(OH)_2$ in AEM and high energy use contribute to environmental impact [5].


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Research challenges:

3.1 Background: Non-Conventional and Advanced Sustainable Manufacturing Technologies

While non-conventional manufacturing techniques have shown promising results in lab-scale applications, several technical and implementation challenges must be addressed to enable industrial adoption [1]. To address these limitations, several EU-funded initiatives have explored next-generation manufacturing processes for fuel cell and electrolyzer components. Projects such as ***MAMA-MEA***, ***VOLUMETRIQ***, ***GAIA***, have demonstrated successful scaling of digital fabrication techniques, novel material formulations, and automated MEA production with improved yield and reduced cost. For example, the MAMA-MEA project focused on scalable inkjet-based deposition for catalyst layers, while GAIA explored continuous-line production compatible with Clean Hydrogen JU targets. These emerging processes—especially additive manufacturing (AM), roll-to-roll coating, and digital slurry deposition—have demonstrated improved material efficiency and design flexibility. However, most techniques remain at Technology Readiness Level (TRL) 3–4, meaning they are currently validated in laboratory settings but require significant optimization and upscaling for full industrial deployment. Meeting Clean Hydrogen JU's 2030 Key Performance Indicators (KPIs)—including high throughput (100,000–500,000 $m^2\ yr^{-1}$), reproducibility above 95%, and scrap rates below 5%—will necessitate a coordinated effort to bring these methods to TRL 7–9 [6]. In this context, non-conventional manufacturing technologies are not only a promising alternative but also a strategic necessity for the hydrogen economy. Their development is key to lowering system costs, reducing environmental impact, and ensuring Europe's technological sovereignty.

3.2 Additive Manufacturing

Additive manufacturing enables the production of fuel cell and electrolyzer components with tailored geometries, improved catalyst utilization, and reduced material waste (see Table 2 [7]). Yet, open challenges include: i) ***Microstructural control***: especially in ceramics, achieving defect-free sintering and desired porosity remains difficult, ii) ***Standardization***: there is a lack of standardized inks, pastes, and process parameters for functional fuel cell layers, iii) ***Scale-up***: most AM techniques are limited in throughput and consistency; few are currently suited for roll-to-roll or automated high-volume lines.

Table 2: Summary of Additive Manufacturing Methods Employed for Fuel Cell Component Production

Technology	Description	Fuel Cell Type	Ref
Inkjet Printing	Droplet-based digital deposition	PEM, SOCs	[4]
Material Extrusion	Thermoplastic filament printing	PEM, SOCs	[8]
Vat Photopolymerization	Laser-curing of photopolymers	PEM, SOCs	[9]
Slurry-Based Printing	Layered ceramic/metal slurries	SOCs	[10]
Powder Bed Fusion	Laser melting/sintering of powders	AEM, PEM, SOCs	[11]
Binder Jetting	Liquid binder deposition + sintering	Full units	[12]

3.3 Other Non-Conventional Techniques

Beyond additive manufacturing, innovative non-additive techniques are gaining attention for their potential in fuel cell and electrolyser fabrication. Methods such as ultrasonic spray, electrospray, electrospinning, centrifugal casting, and electrodeposition offer unique capabilities for fabricating thin films, structured layers, and functional coatings. These approaches could be further explored for integration into roll-to-roll or continuous-line manufacturing systems, enabling scalable high-throughput production while maintaining material precision and performance.

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Timeline and Resources

The industrial adoption of non-conventional manufacturing technologies for fuel cells and electrolyzers requires a phased roadmap addressing TRL progression, process integration, supply chain, and regulatory alignment.

Short Term (1–3 years)

- Raise TRL from 3–4 to 5–6 via pilot-scale demonstrations;
- Optimize AM and hybrid processes (e.g., inkjet, binder jetting);
- Standardize printable materials and introduce initial in-line metrology;
- Launch industrial–academic consortia on key components.
  Estimated funding: €15–20M per topic, with public-private co-financing and early infrastructure investment.

Medium Term (3–5 years)

- Integrate non-conventional methods into continuous lines (e.g., roll-to-roll + AM);
- Validate under industrial conditions with automation and process control;
- Conduct LCA and recyclability studies;
- Strengthen EU supply chains for materials and precursors.
  Estimated funding: €30–50M per program, covering demo-scale lines, skills development, and digital monitoring.

Long Term (5–10 years)

- Deploy TRL 8–9 manufacturing platforms meeting Clean Hydrogen JU KPIs;
- Scale to commercial gigafactories for MEAs and SOCs;

Establish regional manufacturing hubs and align with global standards.
Estimated funding: >€100M (public + private), including CAPEX, regulatory support, and alignment with EU funding programs.

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Rationale for Advancing Research in This Area & Potential Applications

The shift toward non-conventional and advanced sustainable manufacturing technologies for fuel cells and electrolyzers is not only technically justified but strategically essential for achieving the EU's climate and industrial policy goals. Advancing research in this field addresses several intertwined imperatives: economic competitiveness, sustainability, energy security, and industrial leadership.

5.1 Strategic and Economic Rationale

The European Union's ambition to become a global leader in hydrogen technologies requires not only innovation in device design, but also scalable, cost-effective, and environmentally sustainable production processes. Traditional manufacturing methods are no longer sufficient to meet the projected deployment volumes, cost targets, and flexibility needs of emerging hydrogen markets.

Non-conventional approaches—such as additive manufacturing (AM), inkjet printing, roll-to-roll coating, and hybrid deposition—enable: i) *Reduced dependency on scarce materials*, such as platinum and iridium, through more efficient catalyst utilization and optimized layer architectures [5]; ii) *Lower production costs*, via automation, digital process control, and high-throughput fabrication [3]; iii) *Adaptability for different volumes and formats*, supporting diverse fuel cell and electrolyzer configurations; iv)

Enhanced European manufacturing sovereignty, through localized, modular, and digital production strategies aligned with the Net-Zero Industry Act and REPowerEU.

These innovations will support job creation (up to one million hydrogen-related jobs by 2030) and build competitive advantage in the clean tech manufacturing sector.

5.2 Environmental and Societal Impact

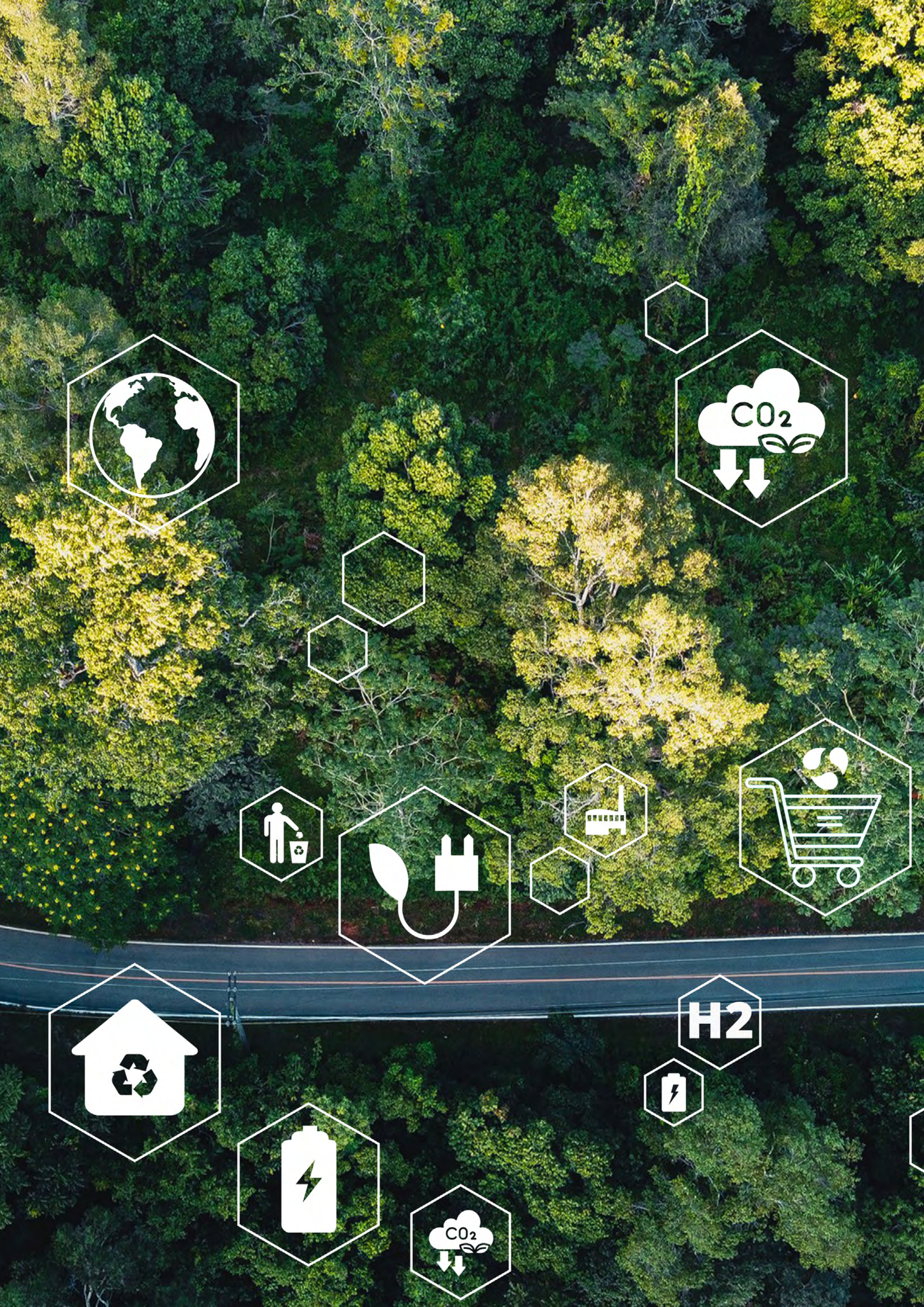
Non-conventional manufacturing techniques significantly improve the environmental performance of hydrogen technologies, making them more attractive for large-scale deployment and public procurement. Key benefits include: i) *Minimized material waste* via precise deposition (e.g., inkjet, slurry printing, binder jetting) and near-net-shape production [7]; ii) *Reduced energy consumption*, especially compared to legacy solvent-based or high-temperature processes; iii) *Smaller carbon footprint*, enabled by leaner manufacturing, fewer process steps, and potential integration with circular economy practices. These factors contribute to improved lifecycle performance and help meet EU decarbonization targets, especially when coupled with green hydrogen production.

5.3 Application Potential

Non-conventional manufacturing methods unlock design flexibility and production agility across a wide spectrum of applications, including: *Transport*: PEMFCs and AEMFCs for hydrogen-powered vehicles (cars, trucks, buses, trains); *Stationary power and heat*: SOFC-based combined heat and power (CHP) systems for residential, commercial, and industrial use; *Industrial decarbonization*: SOECs for high-efficiency hydrogen and e-fuel production from renewable heat; *Portable systems*: Compact PEM units for off-grid, military, or backup power; *Chemical and fertilizer production*: High-temperature electrolysis enabling green ammonia and synthetic fuels. The deployment of non-conventional techniques supports rapid prototyping, customized geometries, and high-durability components—tailored to specific sectoral needs.

5.4 Alignment with EU Policy Frameworks

The advancement of non-conventional manufacturing technologies directly supports the objectives of several key EU initiatives: i) *The Clean Hydrogen JU SRIA*, especially targets for manufacturability, recyclability, and TRL progression; ii) *The Green Deal and Fit for 55*, which require clean technology scale-up and emissions reductions across sectors; iii) *The Net-Zero Industry Act*, which prioritizes the establishment of European clean-tech manufacturing capacity; iv*) The Circular Economy Action Plan*, advocating for resource efficiency, waste minimization, and design for reuse/recycling. In conclusion, investment in this field is not only a technological necessity but a strategic imperative. Advancing non-conventional manufacturing will accelerate hydrogen deployment, enhance European industrial competitiveness, and deliver tangible societal and environmental benefits.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Conclusion and Recommendations

Non-conventional and advanced manufacturing technologies offer transformative potential for the production of fuel cells and electrolyzers by reducing costs, improving performance, and enhancing sustainability. However, their widespread adoption requires overcoming implementation challenges, such as supply chain risks, safety standards, and infrastructure gaps; through collaborative efforts among industry, academia, and policy-makers. To accelerate deployment, we recommend the following: i) ***Cost reduction:*** Minimize the use of critical raw materials (e.g., platinum, iridium) and scale advanced, efficient manufacturing methods; ii) ***Performance and durability:*** Target higher power density, improved efficiency, and long-term reliability [7] to ensure commercial viability; iii) ***Sustainability:*** Reduce waste, emissions, and energy use by adopting circular economy practices and recycling strategies; iv) ***Technological advancement:*** Support integration of additive manufacturing, automation, and high-throughput techniques such as inkjet printing and roll-to-roll coating [4], [7]; v) ***Infrastructure investment:*** Focus on developing durable, lightweight components for hydrogen storage and distribution**;** vi) ***Collaboration and funding:*** Promote public-private partnerships and transnational R&D projects, supported by targeted funding and subsidies; vii) ***International standards:*** Establish and align standards to ensure safety, interoperability, and regulatory clarity; viii) ***Regulatory clarity:*** Streamline legislation to boost investor confidence and enable predictable market conditions; ix) ***Demand-side policies:*** Introduce mandates (e.g., minimum green hydrogen shares) to foster long-term market stability and investment.

Through coordinated action along these strategic lines, a resilient, efficient, and clean hydrogen economy can be achieved.

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