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Envisioning Zero-Emission Urban Mobility by 2050: Exploring Hydrogen Vehicles, Alternative Fuels, and Future-Oriented Planning through Advanced Design

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Abstract

The future of personal transportation presents opportunities for innovation and transformation, despite uncertainties. The ongoing digitalization of the automotive sector marks a profound shift in its 140-year history, driven by technological advancements, declining costs, urbanization, and rising demand for efficient mobility solutions. Consumers increasingly favor digital services such as online sales, car-sharing, and peer-to-peer lending, reflecting a shift toward convenience and personalization. However, transportation remains a major contributor to air pollution.
The automotive industry is undergoing significant transformation, requiring investment and new business models. Vehicles are evolving into "network nodes on wheels", while environmental concerns and regulations push OEMs toward sustainable propulsion technologies. This aligns with consumer expectations for cleaner mobility. This study focuses on hydrogen as a key fuel for decarbonizing transportation. Hydrogen fuel cells offer a compelling solution where Battery Electric Vehicles (BEV) face limitations. Together, BEVs and hydrogen fuel cells reduce fossil fuel dependence and mitigate vehicular emissions. The urgency of these developments is underscored by global health statistics. Ambient and household air pollution accounts for nearly 7 million annual casualties, particularly developing countries. Alarmingly, 99% of the population is exposed to unhealthy particulate matter levels, highlighting air pollution as a leading risk factor for noncommunicable diseases. Addressing this challenge remains a critical public health priority.

Keywords
Clean energy, Safety, Future mobility, Innovation, Design

1. Introduction
Since 1880, global average temperatures have risen by approximately 1.17 °C (2.11 °F) over the past century, highlighting the severe impact of climate change on the planet (NASA, 2024). Climate change is arguably the most pressing environmental issue humanity has ever encountered (Midilli et al., 2005). This research aims to innovate mobility systems and accelerate the transition to renewable energy sources for vehicle propulsion. The journey toward decarbonization is arduous but urgently necessary, as scientific evidence indicates that we are nearing a point of no return (Aengenheyster et al., 2018) . Excessive resource consumption driven by human activity, such as water, fossil fuels, and forests, currently exceeds natural replenishment rates (Wang & Azam, 2024).

Personal vehicles contribute significantly to the emission of harmful substances, posing a threat to ecosystems (Godish, 2014; Hua et al., 2022). This has prompted legislators to promote alternatives to petroleum-based fuels and to restrict access to urban centres for vehicles whose byproducts are not environmentally friendly. A system of carrots and sticks (Mitchell et al., 2010) like the one in Singapore would be optimal to achieve the public consent in public acceptance towards a shift to more sustainable mobility. Manufacturers and governments are increasingly investing in alternative fuels. For instance, in 2019, the Chinese government shifted its focus from battery technology to hydrogen production, a priority also recognized by the European Commission, which has identified clean hydrogen as essential for the energy transition. France and Germany have each pledged €9 billion toward fuel cell technology. Although hydrogen is currently considered costly and complex by the automotive sector, Germany's mechanical engineering industry underscores its expertise in hydrogen storage and electrolysis and advocates for increased government support. While hydrogen remains less competitive for passenger vehicles, it holds significant potential for trucks, buses, and industrial applications, with costs projected to decrease as production scales (Simonazzi et al., 2020).

Motorization is synonymous with progress (Barakati et al., 2024). As a result, governments implement policies to increase vehicle accessibility, leading to rising vehicle ownership trends in developing nations and regions experiencing population growth and economic prosperity (Tao et al., 2021; Yang, 2019). In this context, a report by McKinsey & Company (2016) predicts that regulatory pressure on vehicle emissions will intensify and that adoption rates for alternative fuel vehicles will be highest in densely populated cities with stringent emission standards and consumer incentives for sustainable mobility options.

1.1 Objectives

Achieving desirable future scenarios requires adopting a systemic perspective on the transportation sector and urban mobility (Patten et al., 2002). In this context, the four interrelated dimensions discussed by Gössling in Desirable Transport Futures (2018) must be considered when addressing mobility, as they play a crucial role in shaping sustainable and effective transportation strategies.

The design and implementation of a hydrogen-powered sports vehicle aim to introduce hydrogen technology compellingly, leveraging its performance and desirability to build public trust and interest in this alternative fuel. This initial step plays a crucial role in showcasing the reliability and safety of hydrogen fuel, while also addressing concerns about refueling convenience. The project simultaneously involves the development of a compact hydrogen-powered city car, translating the appeal and innovations of the concept sports car into a more practical format for urban use. By focusing on a compact design similar to Internal Combustion Engine (ICE) vehicles, the city car caters to environmental impact, efficiency, traffic congestion, and parking issues in densely populated areas. As suggested by Mitchell et al. (2010) in the book *reinventing the automobile*, the first steps would be "the development of imaginative, carefully conceived pilot projects". This project has the goal to discover innovative solutions through creativity and possible arrangements of existing technology and how it is expected to evolve.

The dual approach addresses critical issues such as pollution and emissions, and technical problems such as performance and storage capacity, aiming to foster public appreciation of hydrogen through a desirable and accessible vehicle. The vehicles employ advanced hydrogen storage solutions, including advanced fuel cells and metal hydrides systems, ensuring safety and efficiency. The initiative also supports the early stages of the hydrogen economy by promoting hydrogen production hubs and demonstrating hydrogen as a safe fuel for the environment, human health, and the economy.

Brands like Tesla and BMW exemplify this shift by emphasizing luxury and advanced technology to attract buyers (Loureiro, 2016). Furthermore, societal changes, including the rise of single-person households and shifting consumer behaviours, are reshaping automotive design and marketing strategies to adapt to these new lifestyles (Oh et al., 2016). Hydrogen offers a sustainable, scalable solution for future transportation and energy systems (Ball & Wietschel, 2009), demonstrating that innovation in mobility can align with the urgent demands of environmental sustainability. This project leverages hydrogen's potential to transform perceptions and establish it as a cornerstone of the green revolution. Drawing inspiration from Hypercar, Inc.'s design philosophy, the project adopts a "clean sheet" approach, setting clear and ambitious product requirements while emphasizing whole-system thinking. This methodology prioritizes lightweight and efficiency, leveraging the 'beneficial mass spiral', where a lighter body reduces the need for heavier components, creating a cascading effect that minimizes overall vehicle mass and enhances performance (Lovins & Cramer, 2004).

Rejecting incrementalism, which risks stagnation, the project is shaped by bold goal statements that distinguish between essential needs and secondary features, ensuring a focused development process (Lovins & Cramer, 2004).

By addressing technical challenges, the design maintains a balance between technical feasibility and aspirational innovation. Aligned with the vision that nanotechnologies, robotics, and digital logic will define the future, the project sets out to create a vehicle that is not only functional but also compelling, capturing public imagination while paving the way for broader acceptance of cutting-edge technologies (Koster, 2023). This integrated and ambitious approach ensures the project transcends traditional barriers, reshaping the automotive landscape for a sustainable and efficient future.

2. Literature Review

To understand the potential of Hydrogen, a literature review was conducted on 6 main topics: mobility scenario, hydrogen production, comparison of BEVs and FCEVs, fuel cell technology, safety of hydrogen as a fuel, hydrogen storage. Hydrogen and BEVs are poised to collaboratively drive the decarbonization of the private transportation sector. Hydrogen's role as a zero-emission fuel source offers dual functionality: it could power fuel cell electric vehicles (FCEVs) directly and serve as an energy carrier for generating electricity for BEVs. Presently, however, the production of BEV batteries and of hydrogen is offsetting some environmental benefits by generating emissions (Albatayneh et al., 2023; Sharma & Ghoshal, 2015). Battery production depends on finite metals, and BEV value declines with battery aging despite efficiency gains. However, costs may drop by 52% by 2030, improving their economic viability (Colthorpe, 2021). Simultaneously, fuel cells present a solution to range anxiety (Fischer et al., 2024), offering drivers longer travel distances on a single charge and a refuelling process that is faster than recharging batteries (Albatayneh et al., 2023). As the learning curve for BEVs continues to advance alongside expanding infrastructure, electric vehicles are becoming more accessible and affordable. This trend is expected to extend to hydrogen fuel cells (Albatayneh et al., 2023). Together, hydrogen and electric vehicle technologies hold the potential to replace traditional-fuel-powered vehicles, significantly reducing harmful emissions within the transportation sector. Hydrogen fuel represents a promising alternative to carbon-based fuels, particularly within the private transport sector, where it can address pressing environmental and energy challenges (Edwards et al., 2008). The global demand for energy is projected to continue its upward trajectory, primarily driven by rapid economic development in China, India, and other developing nations. Moreover, oil and gas reserves are distributed unevenly across the globe, with a significant concentration in politically unstable regions, particularly in the Middle East and certain Arab countries. This geographic concentration of energy resources is expected to persist as a source of political tension and may even lead to conflicts over remaining reserves (Barbir, 2009). Traffic congestion exacerbates energy consumption and environmental degradation, with an important toll on consumers (Federal Highway Administration, 2017; Schrank et al., 2011; Tao et al., 2021).

Hydrogen is considered a promising solution to current energy challenges. It is inherently non-toxic, and its combustion produces no pollution or greenhouse gases (GHG) sources has zero emissions and enables renewable energy integration into transport sector, enhances energy security, supports local economies, and promotes distributed energy generation infrastructure (Edwards et al., 2008). Its high energy density and zero-emission profile make it a viable alternative to traditional fossil fuels in transportation. FCEVs exemplify this potential by using hydrogen to generate electricity in fuel cells, emitting only water vapor as a byproduct. This positions hydrogen as a competitive option for applications requiring long ranges and heavy loads, such as freight trucks, trains, and ships (Sharma & Ghoshal, 2015).

Hydrogen may supply up to 18% of global energy consumption by 2050 and help cut yearly carbon emissions by six gigatons (Albatayneh et al., 2023).

Hydrogen offers a sustainable alternative to fossil fuels in transport, enhancing energy security, cutting emissions, and improving air quality. Its adoption requires strategic investment, regulation, and public awareness.

Hydrogen is emerging as a key energy carrier for sustainable transport amid the shift to greener technologies. Microbial hydrogen production offers a renewable, decentralized solution, supporting local supply in areas lacking large-scale infrastructure and aiding FCEV adoption. (Bhatia et al., 2022; Xiang et al., 2020).

Hydrogen production from fossil fuels, particularly natural gas via Steam Methane Reforming (SMR), remains the most common method, accounting for approximately 80% of global hydrogen production (Sharma & Ghoshal, 2015). While economically viable, SMR contributes to significant carbon emissions, limiting its sustainability. Blue hydrogen, derived from SMR coupled with carbon capture and storage (CCS), presents a cleaner but transitional solution (Albatayneh et al., 2023).

Electrolysis of water, powered by renewable energy sources such as wind, solar, and hydropower, is considered the cleanest and most sustainable method for hydrogen production (Sharma & Ghoshal, 2015). Green hydrogen, produced entirely through electrolysis using renewable energy, eliminates GHG emissions, offering a pathway to zero-carbon energy systems. Although cost-prohibitive today, declining renewable energy costs are expected to make electrolysis more competitive, with future green hydrogen costs projected to range between $3–$4/kg (Edwards et al., 2008). Nuclear energy also offers potential for large-scale hydrogen production via thermal conversion or high-temperature electrolysis, though concerns about radioactive waste and safety persist (Edwards et al., 2008).

A literature review was conducted to highlight key differences between BEVs and FCEVs. Unlike batteries, hydrogen fuel cells operate continuously with a hydrogen supply, offering an efficient and sustainable energy alternative without the need for recharging (Albatayneh et al., 2023). A key advantage of BEVs is the widespread availability of charging through standard electrical outlets. In contrast, FCEVs depend on the development of new hydrogen refueling infrastructure, posing a major challenge to their large-scale adoption. (Albatayneh et al., 2023). FCEVs generate electricity from hydrogen via fuel cells, emitting only water and using smaller batteries, which lowers weight and boosts efficiency. Their high energy density and quick refueling make them ideal for long-distance travel. In contrast, BEVs use large lithium-ion batteries, but advancements now allow ranges over 400 km and rapid charging of 200 km in about 15 minutes with 800V systems (Albatayneh et al., 2023). BEVs are favored for their efficiency, low emissions, and reduced operating costs but face issues like limited range, long charging times, and heavy, costly batteries. FCEVs, while promising, are constrained by the high costs and limited availability of hydrogen production and refueling infrastructure. (Barbir, 2009). Both BEVs and FCEVs are supported by global regulations targeting GHG reduction and cleaner transport. Incentives like tax credits and subsidies have boosted their adoption, with growing recognition of hydrogen's role in decarbonizing mobility and cutting fossil fuel-related pollution. (Albatayneh et al., 2023; Barbir, 2009).

Hydrogen and electricity are poised to play complementary roles in the future of sustainable transportation. BEVs are currently more accessible due to existing infrastructure and technological maturity, whereas FCEVs offer unique advantages for long-distance and heavy-duty applications. Strategic investments in hydrogen infrastructure and continued innovation in both technologies are essential to achieving a decarbonized transportation sector.

Fuel cells are a key component of sustainable energy systems, offering high efficiency and adaptability across various applications, from electric vehicles to combined heat and power systems. Hydrogen fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, producing only water vapor and heat as byproducts. Their basic structure—comprising an anode, cathode, and electrolyte membrane—enables hydrogen to split into electrons and protons, with the electrons creating an external current and the protons reacting with oxygen at the cathode to form water and release heat (Albatayneh et al., 2023; Edwards et al., 2008). Proton Exchange Membrane (PEM) fuel cells are particularly suited for automotive applications. These systems operate at temperatures of 80–85°C, allowing for efficient electricity generation. However, the limited dispersion of waste heat necessitates larger radiators, increasing cost, weight, and aerodynamic drag (Lovins & Cramer, 2004). Fuel cells can achieve efficiencies of up to 65%, significantly surpassing the 25% efficiency of ICEs (Edwards et al., 2008). Moreover, fuel cells are not constrained by the limitations of the Carnot cycle (Edwards et al., 2008). Unlike fossil fuels, hydrogen combustion or use in fuel cells produces no carbon emissions, making it a critical technology for addressing climate change and improving air quality (Hordeski, 2008). Fuel cells offer rapid refueling and increased energy density, making them ideal for long-distance travel and heavy-duty applications (Albatayneh et al., 2023). Fuel cells also alleviate grid pressures associated with simultaneous vehicle charging during peak times, a growing concern as BEV adoption increases (Chen et al., 2016). Additionally, the reliance on rare and expensive materials, such as platinum catalysts, contributes to the high production costs of fuel cells. Fuel cells represent a transformative technology in sustainable energy, delivering superior efficiency and environmental advantages.

Hydrogen is a promising fossil fuel alternative with strong potential to reduce GHG emissions, though safety concerns have hindered its widespread adoption. Unlike heavier fuels, hydrogen's low density (6.9% of air) and high diffusivity allow it to disperse quickly in case of a leak, significantly lowering fire and explosion risks(Sharma & Ghoshal, 2015; Veziroğlu & Şahin, 2008). Unlike fossil fuels, hydrogen leaks do not threaten soil or water quality, and its combustion produces only water vapor, making it one of the cleanest energy sources available (Hordeski, 2008; Sharma & Ghoshal, 2015).

Hydrogen's fire and explosion risks are mitigated by its rapid dispersion properties, with studies showing that hydrogen has a safety factor of 1 (Edwards et al., 2008), which is safer than methane (0.8) and gasoline (0.53). While hydrogen's flammability range is wider than that of traditional fuels, advancements in storage and transport technologies, including leak-proof containment systems and advanced sensors, have effectively mitigated these risks (Edwards et al., 2008; Hordeski, 2008). Hydrogen's rapid dispersion upon leakage minimizes the likelihood of prolonged fires, further enhancing its safety profile (Hordeski, 2008).

Hydrogen can be transported safely through pipelines and stored in pressurized tanks or cryogenic systems, with advances in material sciences enhancing the durability and reliability of storage systems to reduce leakage risks during transport (Edwards et al., 2008; Sharma & Ghoshal, 2015). In confined spaces, hydrogen-driven vehicles pose a lower risk compared to gasoline-powered vehicles. Gasoline leaks typically result in extensive flammable vapor clouds, while hydrogen's rapid dispersal, combined with its lack of toxic emissions, makes it a safer choice for urban and industrial applications (Sharma & Ghoshal, 2015; Veziroğlu & Şahin, 2008).

The integration of hydrogen into the energy economy is guided by stringent international standards and regulations. These protocols cover hydrogen refueling stations, vehicle storage systems, and transportation networks, ensuring safety across all aspects of hydrogen utilization (Edwards et al., 2008; National Research Council, 2008). Hydrogen's unique properties, such as its rapid diffusivity, non-toxic nature, and clean combustion, position it as a superior alternative to conventional fuels in terms of safety and environmental impact. By addressing misconceptions about hydrogen safety and continuing to innovate in storage and transport technologies, hydrogen can play a pivotal role in the global transition to sustainable energy. Its ability to provide a safer, cleaner, and more efficient energy solution underscores its potential as a cornerstone of the future energy landscape.

As highlighted by Albatayneh et al. (2023), significant global investments are driving the advancement of hydrogen and fuel cell technologies. In the United States, the Department of Energy has allocated up to $100 million for hydrogen and fuel cell R&D between 2022 and 2026. Likewise, the Hydrogen Fuel Technology Organization is supporting numerous initiatives focusing on FCEVs, hydrogen production, storage, and infrastructure development.
In Europe, the European Union has committed $430 billion to 70 green hydrogen projects by 2030, in line with the European Green Deal. Furthermore, McKinsey & Company (2024) forecasts that by 2050, hydrogen could meet up to 18% of global energy demand, generating billions in annual revenue. These developments highlight hydrogen's growing importance in the automotive industry, reshaping energy consumption patterns and enabling the widespread adoption of zero-emission mobility solutions.

From an economical perspective, in regions like India, for example, a hydrogen-based energy economy could reduce reliance on Middle Eastern oil imports, enhance energy security, and create lasting scientific and industrial employment opportunities (Jain, 2009**.** Zhang and Wu (2017) highlight hydrogen as "a potential energy source to effectively address the future energy crisis," emphasizing its role as a safe, clean, and renewable alternative.

In conclusion, regarding this energy source it is possible to state that: Hydrogen possesses the highest gravimetric energy density among all energy carriers, with a lower heating value (LHV) of 120 $MJ \cdot kg^{-1}$ at 298 K, compared to 44 $MJ \cdot kg^{-1}$ for gasoline (Allendorf et al., 2022). The higher efficiency allows reducing tanks volume (Edwards et al., 2008)

For instance, over a driving distance of 100 km, a conventional vehicle with an internal combustion engine (ICE) typically consumes around 6 kg of gasoline, while a hydrogen-powered ICE requires only 2 kg of hydrogen. This efficiency is further enhanced in FCEVs, which need just 1 kg of hydrogen to cover the same distance (Schlapbach & Züttel, 2001).

In addressing hydrogen storage challenges, trade-offs between hydrogen release thermodynamics and reversible capacity are critical considerations, particularly when evaluating metal hydrides for transportation applications. At the 700-bar pressure utilized in commercially available FCEVs, hydrogen's energy is lost during compression. Minimizing both storage system volume and weight remains a paramount objective in achieving practical and efficient hydrogen-powered mobility solutions.

Metal hydrides excel here; their volumetric capacity is at least double 700-bar pressurized gas. Hydrogen stored in metal hydrides is safer, and weight is not a concern. Zhang and Wu (2017) identify metal hydrides as the most practical solution for hydrogen storage in stationary power, portable power, and transportation. Among various hydride systems, Li-Mg-N-H compounds stand out due to their high hydrogen storage capacity exceeding 5 wt%. The application of nanotechnology further enhances these systems, improving both storage capacity and operational properties. The authors highlight Li-Mg-N-H systems as particularly promising for light-duty vehicles, thanks to their high hydrogen capacity and moderate theoretical operating temperatures.

Nanotechnology can enhance the surface properties of hydrogen storage tanks through the incorporation of ultra-high surface area nanoporous materials into metal hydrides. These advancements improve the mechanical stability, rigidity, and load-bearing capacity of the hydride, significantly increasing the efficiency of hydrogen storage within these systems. The use of nanostructured materials, particularly ultra-high surface area nanoporous materials, enables greater absorption and storage efficiency of hydrogen (Saeed et al., 2024).

For hydrogen-fueled vehicles to become viable in the consumer market, a robust, accessible refueling infrastructure must be developed, similar to the advancements achieved in battery electric vehicles. In summary, the successful integration of hydrogen into the global energy system could significantly enhance energy security, reduce environmental impact, and provide socioeconomic benefits. Nevertheless, realizing a hydrogen-based economy will depend on coordinated investments in technology, infrastructure, and policy.

3. Methods

The starting point that leads the research process is "how might we decrease emissions, deriving from energy production plants and the transportation sector, in order to mitigate the negative effects on the ecosystem?".
In the effort to give an answer to the question, this paper applies Advanced Design (Celaschi, 2015) methodologies. The project is meant to be considered as a Fuzzy Front End (Koen et al., 2002) project (Table 1). The resulting concept is visionary design and technical act (Deserti, 2015), a vision of the future (Figure 1). Advanced Design methodologies represent a forward-looking approach to product and process development, integrating creativity, technological innovation, and strategic foresight. Rooted in sectors like automotive and expanded across diverse industries, these methodologies focus on the early phases of innovation—often referred to as the Front End of Innovation—where the potential for radical transformation is highest.

Table 1. Fuzzy Front End project definition (Koen et al., 2002)

	Fuzzy Front End (FFE)	**New Product Development (NPD)**
Nature of work	Experimental, often chaotic, 'Eureka' moments. Can schedule work—but not invention	Disciplined and goal-oriented with a project plan
Commercialization date	Unpredictable or uncertain	High degree of certainty
Funding	Variable—in the beginning phases many projects may be 'bootlegged,' while others will need funding to proceed	Budgeted
Revenue expectations	Often uncertain, with a great deal of speculation	Predictable, with increasing certainty, analysis, and documentation as the product release date gets closer
Activity	Individuals and team conducting research to minimize risk and optimize potential	Multifunction product and/or process development team
Measures of progress	Strengthened concepts	Milestone achievement

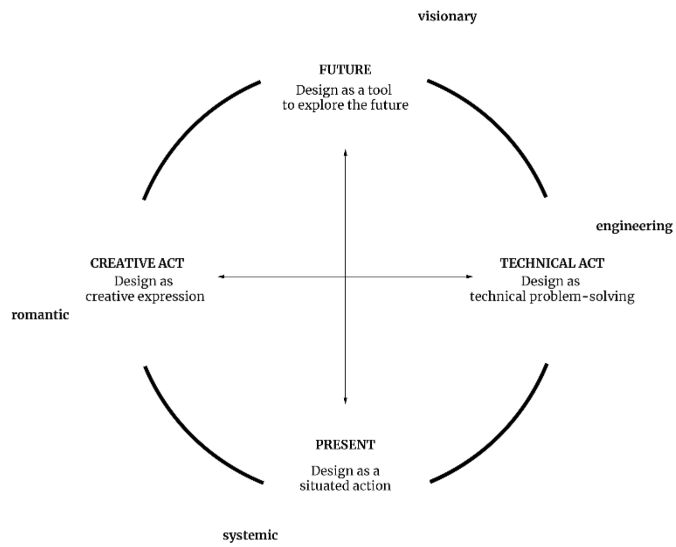

Figure 1. Advanced Design Categories (Deserti, 2015)

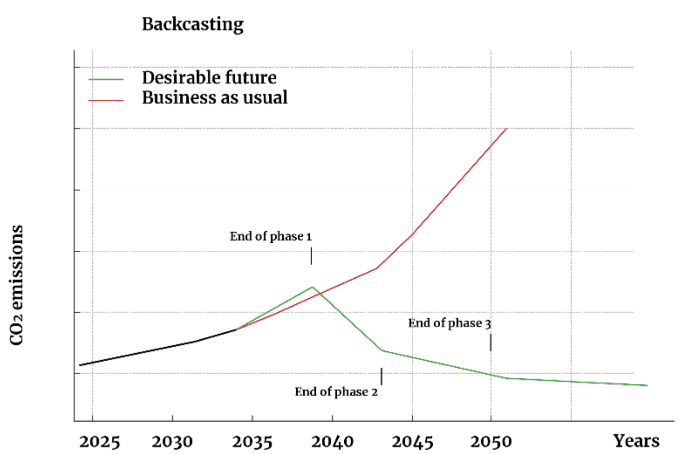

Figure 2. Backcasting to a sustainable future example based on the desired future envisioned in this paper

Central to Advanced Design is the practice of envisioning: imagining, visualizing, and shaping future scenarios to guide design action. This approach combines visual knowledge with technical expertise, enabling the creation of products and processes that address emerging social, economic, and environmental challenges.

Advanced Design methodologies operate across two complementary dimensions: a tangible one, concerned with materials, technologies, and production systems; and an intangible one, aimed at interpreting and encoding cultural, emotional, and societal needs. Through this dual perspective, design becomes both a driver of technological progress and a catalyst for new meanings and experiences.

By integrating user involvement, speculative scenarios, and interdisciplinary tools, Advanced Design methodologies provide a framework for exploring unexplored innovation routes and generating solutions that are both visionary and feasible. (Celi, 2015)

4. Results and Discussion

In order to achieve the global zero-emissions target by 2050, both behavioral shifts and technological advancements are essential, particularly in transportation and energy production. The adoption of BEVs and hydrogen-powered vehicles—via fuel cells or internal combustion engines—represents a critical step toward sustainable mobility, reducing the environmental and health impacts associated with fossil-fuel emissions.

While the transition to zero-emission vehicles offers substantial benefits, it is hindered by key barriers such as public perception, high costs, and insufficient infrastructure and industrial capacity. BEVs continue to face challenges in competing with conventional vehicles, and there is growing concern that the withdrawal of public subsidies could impede progress in the broader shift toward electric and alternative fuel mobility. Nonetheless, BEVs have shown considerable promise in specific sectors, especially micro mobility, where they have proven to be more economically viable and user-friendly.

Modern mobility poses critical but often overlooked problems with serious consequences. Key challenges include harmful emissions, noise pollution, traffic congestion, and inefficient use of urban space for roads and parking. These issues are entrenched in societal habits and past urban planning, which have fostered a car-dependent urban structure that perpetuates reliance on private vehicles (Tao et al., 2021).

To foster safer, quieter, and more efficient cities, a comprehensive approach to sustainable urban development is required—one that prioritizes behavioral change over purely technological fixes. As highlighted by Camilleri et al. (2022), shifts in travel habits and lifestyle choices are central to reducing dependence on private vehicles and enhancing urban livability.

Equally important is the integration of non-polluting transportation technologies, coupled with improved public transit systems and the expansion of micromobility options. These interventions respond to the growing need for diverse and flexible transport modes, increasingly embedded in modern mobility patterns (Kelkar et al., 2024).

In this context, hydrogen and electric technologies should be regarded as complementary rather than competing solutions. As Chapman (2007) notes, "any renewable pathway to electricity is a renewable pathway to hydrogen," underscoring their interconnected roles in achieving a zero-emissions future.

Hydrogen technology holds strong and competitive potential, yet its widespread adoption in small and mid-sized vehicles will require a phased approach over the coming decades. Initial deployment should prioritize sectors suited for long-haul, heavy-duty transport and stationary energy systems, supported by targeted policies and public incentives to ensure a sustainable and economically viable transition.

In this moment and in the early stages of a hydrogen-based economy, production largely depends on SMR, resulting in emissions comparable to conventional fossil fuels. Infrastructure and distribution costs sre substantial, posing a barrier to its implementation. However, the growing adoption of BEVs might catalyze the expansion of renewable energy infrastructure, paving the way for low-emission hydrogen production from renewable sources and further decarbonizing the energy sector.

My project proposal starts with Robinson (1990) backcasting methodology. This study outlines a vision about a future where human society is powered by unharmful sources of energy, with the goal of generating a substantial reduction in CO_2 emissions when graphically represented (Figure 2). This approach focuses on identifying the necessary actions to achieve a predetermined goal by working backward from the desired future state. The optimistic choice of words and phrasing aims for exceptionally high goals, with the understanding that even partial achievement would constitute a significant and valuable outcome. Numerous underlying assumptions take place such as as technological progress and policy enforcement level. Although, uncertainties remain in demand growth, technological progress and public or private funding, hydrogen could play an important role in decarbonizing multiple industrial sectors.

As hydrogen propulsion technology evolves—alongside advances in production, distribution, and storage—the costs of both blue hydrogen (via SMR with CCS) and green hydrogen (from zero-emission methods like photosplitting) are expected to decrease. Innovations such as solid-state storage with metal hydrides and the integration of fuel cells into private vehicles might further enhance the feasibility of hydrogen-powered mobility.

Hydrogen offers strategic advantages beyond transportation. It can strengthen energy security and enable decentralized energy production, especially in regions lacking conventional resources. For example, a hydrogen facility in a remote village could generate electricity for basic needs and, over time, produce surplus energy for sale, stimulating local economies (Sharma & Ghoshal, 2015). What follows is a visionary scenario that goes backwards from 2050 to present day, based on corporations' projections and scientists' analysis:

By 2050, with global net-zero CO_2 emissions target, energy systems could become cleaner and renewable, with energy being produced mostly by non-polluting sources. Bern Heid (McKinsey, 2024) states clean hydrogen could account for 73 to 100 percent of total demand by 2050. Urban regulations will be demanding non-polluting fuels, accelerating technology adoption. Mobility-as-a-Service (MaaS), supported by autonomous vehicles, is expected to replace private car ownership, reducing traffic and transforming urban spaces into safer, more liveable environments.

By 2050, green hydrogen is projected to become the predominant source in the global hydrogen supply mix, driven by significant cost reductions in renewable energy and electrolyzer technologies that enhance the economic viability of this production pathway. Projections show blue hydrogen production to be concentrated in regions such as the Middle East and North America.

Regions endowed with cost-competitive natural gas reserves and access to CCS technologies—such as the Middle East, Norway, and the United States—are anticipated to exhibit the highest cost competitiveness, potentially contributing up to a third of global hydrogen exports at production costs below $1.5/kg by 2050. Regions likely to require hydrogen imports to meet domestic demand include Europe and Asia, while areas such as North and South America, along with the Nordic countries, are expected to act as net exporters due to their capacity to produce hydrogen in excess of local consumption.

Air pollution in megacities could be substantially reduced—and potentially nearly eliminated—through the adoption of emerging technologies in both transportation and energy production, particularly via the widespread deployment of clean fuels in mobility and the built environment. Realizing this vision will necessitate coordinated, cross-sectoral efforts encompassing energy, transportation, urban planning, and policy to facilitate the development of integrated, zero-emission mobility systems. MaaS fleets, using autonomous and shared vehicles, will operate on-demand, returning to refueling hubs at city outskirts for recharging, maintenance, and storage. This model will optimize traffic flow and reduce vehicle numbers on urban roads. The shift from private vehicle ownership to MaaS models presents opportunities to eliminate costs associated with insurance and maintenance, while dynamic pricing mechanisms can further enhance system efficiency and resource optimization.

Commuting, in a future where autonomous cars are widespread, could become more productive and comfortable, as passengers reclaim travel time for work, leisure, or social interaction. Mobility will be accessible and tailored to diverse lifestyles, as companies shift from selling cars to offering flexible transportation services.

If Hydrogen-powered vehicles become fully competitive in cost, performance, and convenience, countries could move toward energy independence through domestic hydrogen production and extensive fuel cell use across mobile and stationary applications, reducing dependency on regions where oil is spilled, also reducing geopolitical tensions. Portable hydrogen solutions—such as those developed by Toyota—are set to further expand utility, powering both transport and everyday activities.

Autonomous vehicles have the potential to also improve safety in social contexts, reduce accidents, and operate quietly, allowing access to natural, protected environments without pollution by the year 2050. Future mobility prioritizes sustainability, zero emissions, and enhanced quality of life, redefining how people interact with cities and nature.

In the second phase of hydrogen adoption—projected to occur 10 to 15 years from now—the deployment of critical technologies such as fuel cells, hydrogen production systems, and renewable energy integration will represent key milestones in the years preceding this phase. These advancements are essential for enabling the large-scale generation and utilization of green hydrogen. As observed in the early market dynamics of Tesla and battery-electric vehicles, adoption is led by early adopters and further accelerated by advanced vehicle design, performance, and branding that would associate hydrogen-powered vehicles with innovation and social status prestige.

Key technological advancements, particularly in hydrogen storage, will play a pivotal role according to the literature. The development of lithium-magnesium-nitrogen-hydrogen (Li-Mg-N-H) systems within metal hydride tanks, supported by nanotechnology, could significantly reduce system mass and volume. These innovations, such as battery efficiency, fuel cell performance and fuel tank volume reduction could work together to enable lighter, more efficient vehicle architectures, enhancing hydrogen's competitiveness as a mainstream energy carrier.

Additionally, purpose-built vehicles optimized for urban, shared, on-demand service models will redefine personal mobility. These models could be the key players to eliminate traditional ownership hurdles—such as depreciation, insurance, and maintenance—thereby improving affordability and resource efficiency, while supporting broader decarbonization and urban sustainability goals.

In the initial phase, hydrogen is expected to be primarily deployed in heavy-duty transport, long-haul logistics, and stationary energy systems. During this stage, infrastructure development has to begin with dedicated pipeline networks and the gradual establishment of refueling stations. However, hydrogen production is considered to be largely dependent on carbon-intensive methods such as SMR during this phase.

Concurrently, if regulatory frameworks are introduced to restrict access to urban centers—particularly densely populated zones—to zero-emission vehicles and public transport only decarbonization of urban mobility could be accelerated. Hydrogen in the initial phase should be feasible and be marketed primarily for freight fleets and stationary applications, with polluting production methods initially tolerated during infrastructure rollout. Hydrogen-powered public transportation systems would also be deployed to support cleaner urban mobility.

To address anticipated public resistance to these regulatory shifts, comprehensive awareness campaigns are needed to be implemented to highlight the long-term public health and environmental benefits. These initiatives will target behavioral change and promote acceptance of alternative mobility solutions.

The transition needs to be supported by the expansion of reliable, efficient public transportation networks and shared vehicle services. These systems will offer viable alternatives to private car use, facilitating public acceptance and promoting more sustainable urban travel behaviors. Shared, lightweight vehicles could eventually and increasingly replace fossil-fuel powered cars, offering high energy efficiency and user-centric design as well as a safer environment. Initial resistance to restricted urban access is expected to decline as micromobility becomes more accessible and cost-effective.

Over time, car dependency is preferrable to diminish as sustainable transportation modes gain traction. Central to this transition will be strategies that elevate the appeal of alternative mobility, supported by public education, outreach, and incentives. Positioning hydrogen and other zero-emission technologies as both practical and aspirational will be key to achieving widespread acceptance and advancing toward a zero-emission transport future.

After these considerations expressed as a visionary scenario, the project proposal identifies that value could be generated starting with the creation of a hydrogen production center modeled after Toyota's Hydrogen Headquarters (Toyota Newsroom, 2024). A facility alike that one produces and distributes energy from renewable sources, integrates advanced hydrogen production methods.

Additionally, the production center could eventually turn into a base for an autonomous, hydrogen-powered vehicle fleet. This initiative might accelerate the adoption of hydrogen mobility solutions and promote public engagement by demonstrating the safety, efficiency, and potential of hydrogen as a key fuel for sustainable urban transport.

This scenario is more likely to be achieved through the development of a desirable, high-performance vehicle designed to introduce hydrogen technology, as emphasized by Koster (2023). The aim is to surpass the performance of traditional combustion-engine vehicles and generate excitement around hydrogen mobility.
A concept car will be available for test drives on a dedicated track at the hydrogen research center, offering users an interactive experience while supporting R&D funding. Hydrogen's higher energy yield and compact storage enable longer driving ranges compared to gasoline, with zero emissions.

The vehicle will demonstrate key innovations, including reduced tank size with the same range of regular tanks, improved efficiency, and modular design, contributing to scalable hydrogen vehicle architectures (Figure 3 - Figure 6). Inspired by GM's 2002 AUTOnomy project and its hydrogen skateboard chassis, this initiative will showcase hydrogen's potential and accelerate the transition toward sustainable, advanced mobility solutions.

Another key element of this project is the development of an urban vehicle. This vehicle would integrate the aesthetics and technologies of the concept car with current challenges in automotive design and manufacturing. The result is a compact, lightweight, zero-emission vehicle with autonomous driving capabilities, designed within a MaaS framework to enhance urban transport efficiency. Its core value will reside in advanced software systems that enhance safety, efficiency, and user experience.

The vehicle will seat two passengers, reflecting actual usage patterns, as the average car trip involves approximately 1.6 occupants. Emphasizing efficiency and sustainability, it will be significantly lighter and have a smaller footprint compared to conventional cars. Lower urban driving speeds can also reduce the energy demand and safety risks associated with collisions. To optimize performance and minimize weight, the vehicle's range will be limited to under 100 miles, meeting daily urban commuting needs (Mitchell et al., 2010).

Externally, the vehicle will feature a friendly, approachable design (Figure 7) to foster user familiarity, while the interior will offer a secure, comfortable, and private space tailored to the evolving demands of urban mobility.

The resulting vehicle is designed to showcase the potential of recently discovered technologies by combining them into innovative configurations that address the evolving mobility needs of users. It is a compact, hydrogen-powered solution that offers an alternative to current options on the market.

Built on a skateboard platform that integrates a hydrogen tank, a fuel cell, and a battery, the vehicle demonstrates how hydrogen propulsion can effectively power small, non-polluting vehicles—just BEVs. This project not only positions hydrogen vehicles as a viable alternative to BEVs, but also highlights how the development of new technologies and architectures can lead to unprecedented results in sustainable mobility with hydrogen as a potential alternative fuel in the upcoming years to replace polluting technologies.

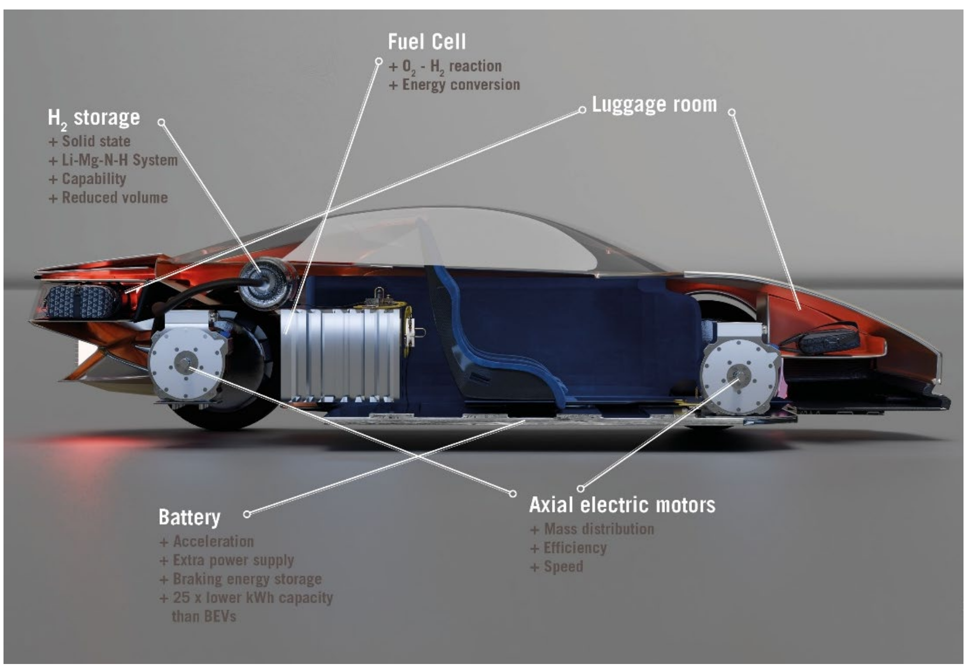

Figure 3. Product architecture of the racing car – technical features

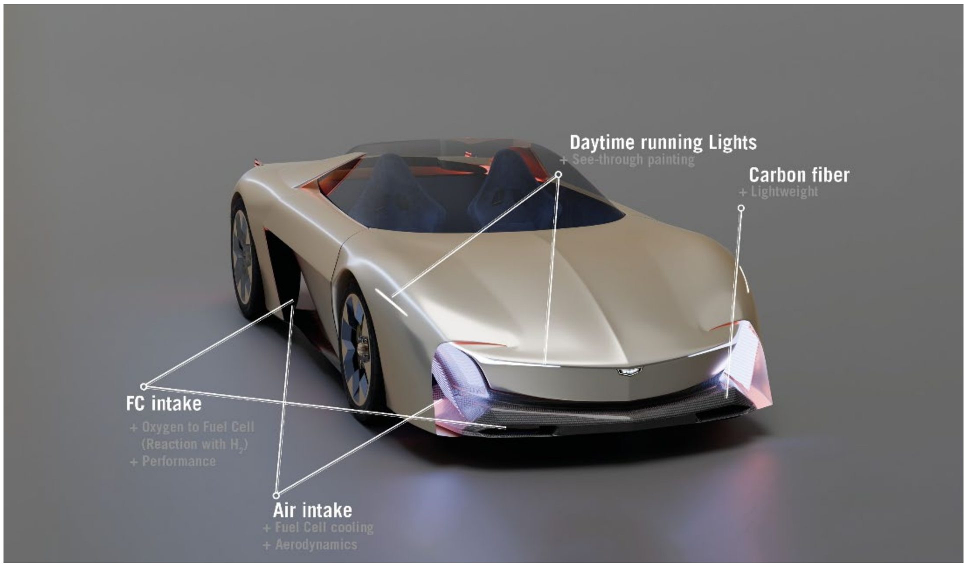

Figure 4. Product architecture of the racing car – exterior cooling and performance features

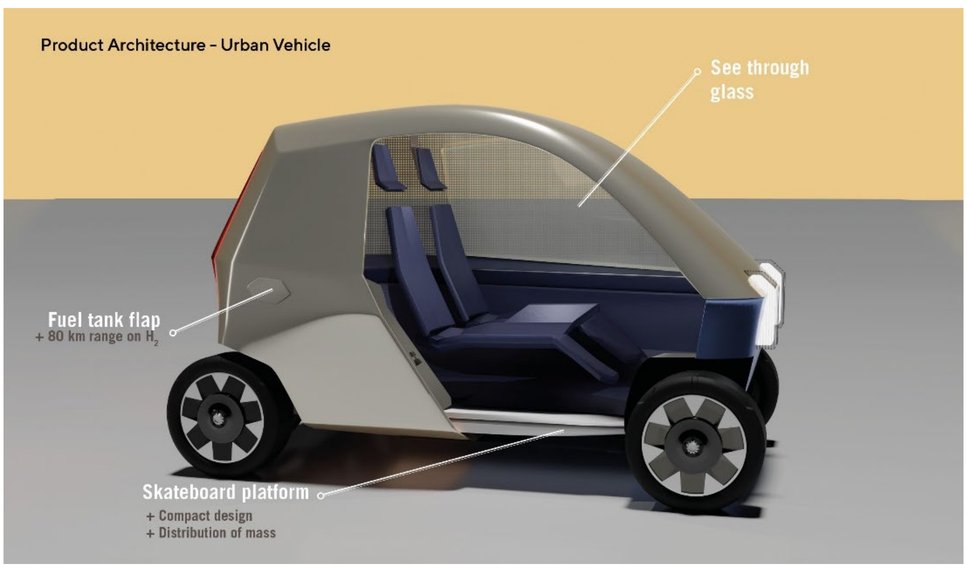

Figure 5. Technical features of the urban vehicle with interiors

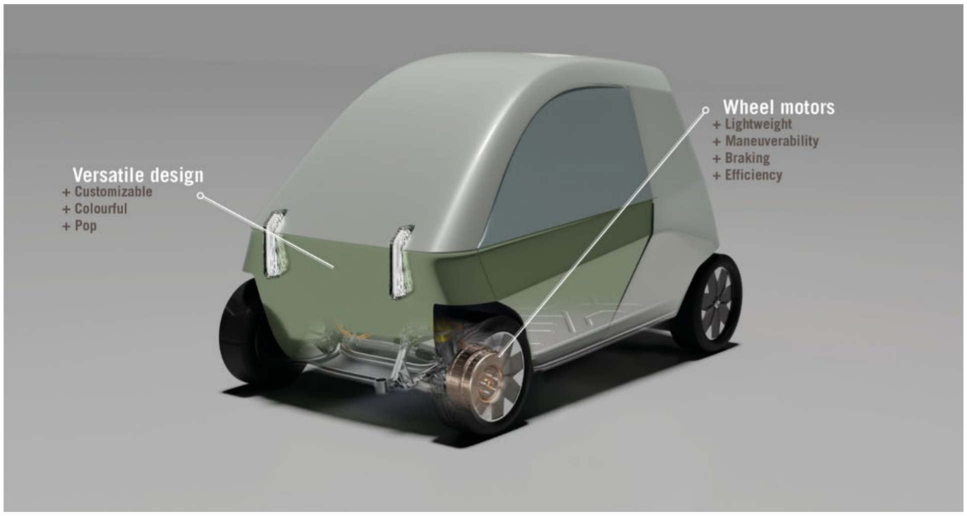

Figure 6. Exterior design of the urban vehicle and technical features

Figure 7. Rendering of the urban vehicle in a realistic setting

5. Conclusion

This paper examines the global transition toward sustainable mobility, emphasizing the pivotal roles of hydrogen FCEVs and BEVs in achieving net-zero emissions by 2050. This shift is motivated by the urgent need to reduce the environmental and public health consequences of fossil-fuel-based transportation systems. While BEVs have made significant progress—especially in micromobility and short-range applications—their widespread adoption is still challenged by high upfront costs, limited charging infrastructure, and consumer skepticism.

Hydrogen technology emerges in this context as a complementary pathway, especially in applications where BEVs face limitations, such as heavy-duty transport, long-haul logistics, and backup power systems. Advocates highlight hydrogen's fast refueling times, longer ranges, and ability to decarbonize sectors that are otherwise difficult to electrify. However, alongside this optimism, there are critical safety and economic concerns that must be acknowledged.

Hydrogen is a highly flammable gas that requires stringent safety measures throughout its lifecycle—from production and storage to transport and use. Accidents involving leaks or improper handling could pose serious hazards, particularly in densely populated urban areas. Moreover, the infrastructure required to support hydrogen mobility—including refueling stations, pipelines, and storage systems—is costly and underdeveloped in most regions, raising questions about economic feasibility and scalability. The production of "green hydrogen" using renewable electricity remains energy-intensive and expensive, with costs currently far exceeding those of fossil-based fuels or even battery electric alternatives. Although hydrogen is often perceived as dangerous, it can be considered safer than gasoline when evaluated based on key safety parameters such as flame temperature, explosion energy, and flame emissivity. These factors suggest that hydrogen poses a comparatively lower risk under certain conditions.

This work also explores innovative configurations of hydrogen-based technologies, such as a compact urban vehicle featuring a hydrogen-powered "skateboard" chassis. In this design, the Li-Mg-N-H metal hydride system is proposed as a safer and more compact hydrogen solid state storage solution. Urban-specific performance requiremetns enable the use of downsized fuel cells and batteries, minimizing vehicle mass and improving energy efficiency (Figure 6). Additional features, like in-wheel motors, offer further benefits in terms of weight distribution, space utilization, and maneuverability, as can be seen in Figure 5 and 6. The reduced performance requirements associated with urban driving scenarios allow for downsized fuel cells and batteries, further decreasing vehicle mass and component footprint leading towards less consumptions on a same trip.

Despite these technical advancements, hydrogen's future as a mainstream mobility solution remains contingent on resolving key challenges. These include reducing the cost of clean hydrogen production, building reliable supply infrastructure, addressing safety standards, creating viable business models, and getting stakeholders such as country governments onboard through subsidies and policies to favour alternative fuels adoption. When deployed strategically alongside BEVs, hydrogen vehicles—particularly in specialized roles—may contribute meaningfully to transport decarbonization. However, their widespread adoption will depend not only on technological readiness but also on policy support, market incentives, and societal acceptance.

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Biographies

Leonardo Frizziero is a Senior Assistant Professor of the Department of Industrial Engineering, at Alma Mater Studiorum University of Bologna. He promotes the scientific issues related to the Mechanical Design and Industrial Design Methods (CAD 2D, 3D, Advanced Design, QFD, TRIZ, DFSS, DFD, DFA, ecc.). In 2005, he was recruited by Ferrari Spa, as project manager of new Ferrari cars projects. In 2009 he came back to University, obtained the Ph.D. degree and started collaborating with the Design and Methods Research Group of Industrial Engineering becoming Junior Assistant Professor in February 2013 at DIN of AMS University of Bologna. He teaches and follows researches in the design fields, participating at various competitive regional, national and international research projects. Since 2018 he has been a Senior Assistant Professor. Since 2017 he is qualified Associate Professor of Design and Methods of Industrial Engineering (ING-IND/15). Prior to the role of university professor, he held relevant positions for some industrial companies.

Davide Cardi is currently pursuing a Master's degree in Advanced Design at the University of Bologna (UniBo), having completed my Bachelor's degree in Industrial Product Design at the University of Ferrara (UniFe) in 2019. Recently, he moved from Italy to Lawrence Technological University to conduct research in the industry, focusing on how design can shape the future of transportation and foster sustainable mobility solutions. His passion for design is driven by a desire to innovate and improve systems, particularly through process and material optimization. Davide is deeply interested in social innovation and transportation design, with a specific focus on developing new modes of transport for smart mobility and future scenarios. His primary interest lies in hydrogen fuel cell vehicles within the broader context of a future hydrogen economy. Davide aims to contribute to the decarbonization of the automotive industry, improving air quality and the overall quality of life in urban environments.

Curzio Pagliari is a Ph.D. Student and academic tutor of the Department of Industrial Engineering, at Alma Mater Studiorum University of Bologna. Curzio is focused on studying Product and Automotive Engineering and Design.

Giulio Galiè is a PhD candidate in Automotive Engineering for Intelligent Mobility at the University of Bologna. As an industrial designer, his research primarily focuses on innovative technologies for design, with a particular emphasis on virtual reality and additive manufacturing. He has served as a Teaching Assistant in Mechanical Engineering Drawing and collaborated with industry-leading companies such as Pininfarina and Modelleria Modenese. He also completed a research period at Lawrence Technological University in Southfield, MI, gaining insights into the American automotive industry in Detroit. He holds a Master's degree in Advanced Design and is passionate about product design, viewing its multifaceted challenges as opportunities for innovation.