



Transforming Automotive Emissions: The Impact of Ammonia Engines and Nano-Electro Fuel Technologies on Environmental Sustainability

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Abstract

Title: Transforming Automotive Emissions: The Impact of Ammonia Engines and Nano-Electro Fuel Technologies on Environmental Sustainability

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The automotive industry is at a standpoint, faced with the critical challenge of reducing its environmental footprint. This dissertation examines the transformative potential of ammonia engines and nano-electro fuels as potential solutions to achieving a carbon-free future. Ammonia engines provide a revolutionary path, cutting CO₂ emissions with minimal change to current infrastructure. In parallel, NEFs are an innovative approach to tackle battery technology, leveraging on renewable electricity and offering improvements in power delivery, battery life, and overall efficiency.

The research integrates qualitative insights from industry experts with quantitative data from a survey of automotive professionals to assess the adoption potential, benefits, and barriers of both of these technologies. The findings suggest that while ammonia engine and NEFs have great potential for improving environmental sustainability, their widespread adoption is currently impeded by high costs, technical challenges, and the industry's focus on electric vehicles. Regulatory pressure and the industry's ability to adapt to new technologies is essential for overcoming these barriers. This study highlights the crucial need for investments and collaborative efforts to integrate these technologies into the automotive world, driving the industry towards a greener future.

Keywords: Ammonia engines; Nano-electro fuels; Dynamic capabilities; Renewable energy; Greenhouse gas emissions

Abstrato

Título: Transformando as Emissões Automotivas: O Impacto dos Motores a Amônia e das Tecnologias de Combustíveis Nano-Eletro na Sustentabilidade Ambiental

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A indústria automotiva encontra-se em um ponto crucial, enfrentando o desafio crítico de reduzir sua pegada ambiental. Esta dissertação examina o potencial transformador dos motores a amônia e dos combustíveis nanoeletro como soluções potenciais para alcançar um futuro sem carbono. Os motores a amônia oferecem um caminho revolucionário, reduzindo as emissões de CO₂ com mudanças mínimas na infraestrutura existente. Paralelamente, os NEFs representam uma abordagem inovadora para aprimorar a tecnologia de baterias, aproveitando a eletricidade renovável e proporcionando melhorias na entrega de energia, na vida útil das baterias e na eficiência geral.

A pesquisa integra insights qualitativos de especialistas da indústria com dados quantitativos de uma pesquisa com profissionais do setor automotivo para avaliar o potencial de adoção, os benefícios e os obstáculos de ambas as tecnologias. Os resultados sugerem que, embora os motores a amônia e os NEFs tenham grande potencial para melhorar a sustentabilidade ambiental, sua adoção em larga escala atualmente é impedida por altos custos, desafios técnicos e o foco da indústria em veículos elétricos. A pressão regulatória e a capacidade da indústria de se adaptar a novas tecnologias são essenciais para superar esses obstáculos. Este estudo destaca a necessidade crucial de investimentos e esforços colaborativos para integrar essas tecnologias no mundo automotivo, impulsionando a indústria em direção a um futuro mais verde.

Palavras-chave: Motores a amônia; Combustíveis nano-eletro; Capacidades dinâmicas; Energia renovável; Emissões de gases de efeito estufa

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1. Introduction

The automotive industry find itself at a significant turning point, facing pressure to reduce their environmental footprint. As one of the major contributors of greenhouse gas globally, the automotive sector accounted for nearly one-fourth of global energy related CO₂ emissions in 2020 (International Energy Agency, 2023). The urgent need for sustainable transformation within the automotive world calls for a shift away from traditional fossil fuel engines, toward innovative and environmentally friendly technologies (US. Department of Energy, 2021). Among the promising fossil fuel alternatives that have emerged, ammonia engines and nano-electro fuels (NEF) represent breakthroughs in sustainable automotive technology, offering a path to a greener future for the automotive industry.

Ammonia has the potential to be used as a sustainable fuel source (i.e., carbon-free fuel) in engines. This new technology is appealing because it can reduce CO and CO₂ emissions, making sustainable transportation possible (Kurien, C & Mittal, M., 2022). Nevertheless, the implementation of ammonia as an alternative to combustion engines also presents challenges. Managing NO_x emissions is crucial to the widespread adoption of this technology. Overcoming these hurdles requires advanced combustion strategies, such as low temperature combustion, to ensure the operational efficiency and environmental compliance of the engines (Qi, Y et al., 2023).

NEF presents a new approach to expand the efficiency and environmental compatibility of different fuel production processes. These new technologies involve the utilization of renewable electricity and nano-catalysts to transform different feedstocks, such as biomass and water, into sustainable combustion fuels. These innovations are a promising step towards sustainability in the transportation sector, especially for new fuel sources (Kircher, M. et al., 2015).

However, integrating these pioneering technologies into the automotive landscape raises questions about the potential impact of existing technologies, especially concerning battery technology. In this study, we aim to explore how the adoption of ammonia engines and NEFs can reshape the automotive sector, focusing on their environmental impacts, integration challenges, and technological synergies.

Research Question: How will adoption of ammonia engines and nano-electro fuel technologies impact the sustainability and technological landscape of the automotive industry?

Hypotheses:

H1: The adoption of ammonia engines will significantly reduce CO₂ and NO_x emissions in the automotive industry.

H2: Regulatory pressures and environmental policies are significant drivers in the adoption of ammonia engines and NEFs in the automotive industry.

H3: Initial high costs and technical challenges are the primary barriers to the widespread adoption of new technologies like ammonia engines and NEFs.

H4: The ability of professionals to dynamically adapt to technological advancements like ammonia engines and NEFs is crucial to the successful integration and scalability of the related technologies.

Although the direct impact of NEFs on battery performance was not the primary focus in this study, its broader role in the battery technology ecosystem remains critical. Having a green and sustainable electricity grid, supported by NEFs, could substantially reduce the environmental impact of electric vehicles (Ulaganathan, M., 2015). Such grids have become increasingly important because the adoption rate of electric vehicles has been accelerating (McCormick et al., 2022). Furthermore, NEFs could be utilized in the development of novel materials or manufacturing processes. These innovations could improve the performance and lifespan of the batteries used in both hybrid and electric vehicles. Research on silicon (SI-based anode materials) has shown that it can increase battery energy density, and that NEFs could be key in developing a sustainable and scalable production method for these materials (Tzeng, Y. et al., 2020).

As we embark on this journey toward a sustainable automotive future, it is paramount to have a thorough understanding of how ammonia, NEFs, and battery technologies can be developed and implemented. This study aims to shed light on these intricate dynamics, examining the potential challenges and opportunities for the developments. By doing so, a more sustainable and integrated automotive landscape could be reached.

2. Literature Review

The following chapter details the environmental impact of the automotive industry and its transition toward sustainability. It contains an outline of the theoretical foundations and links these concepts with the shift from fossil fuel dependency to innovative, sustainable solutions.

2.1 Sustainable Innovation

The automotive industry is undergoing transformation toward sustainability. This shift is driven by stringent regulatory pressures and evolving consumer preferences. Sustainable innovation has become an essential concept for the industry, pushing for the development of green technologies and their implementation in the value chain (PWC, 2023).

However, achieving sustainable innovation in the automotive sector requires more than the introduction of new technologies, such as electric vehicles, ammonia, or NEFs. It requires firms to adopt a dynamic approach, ensuring that these technologies are scalable and adaptable. In this context, Barreto's interpretation of dynamic capabilities provides a framework for understanding how firms can sustain their competitive advantage while transitioning to sustainable technologies (Barreto, 2010).

Firms that lead in sustainable innovation are capable to sense emerging trends, seize opportunities, and reconfigure to implement these innovations (Teece, Pisano, and Shuen, 1997).

2.1.1 Dynamic Capabilities

The concept of Dynamic Capabilities (DC) has become crucial in understanding how firms maintain and enhance their competitive advantage in rapidly changing environments. The foundation of this theory by Teece, Pisano, and Shuen (1997), later expanded upon by Barreto (2010), introduced the DC as the firm's ability to integrate, build, and reconfigure internal and external competences to adapt rapidly changing environments. This firm-level theory is relevant to the automotive sector, where the constant push for innovation requires firms to be adaptive and proactive in their decision making.

Barreto's framework expands the original theory by highlighting the multidimensional nature of dynamic capabilities (Barreto, 2010). For automotive firms, DC presents itself in their ability

to sense changes in the external environment (i.e., emissions regulations, advancements in technologies), seize opportunities for innovation (i.e., R&D, acquisitions), and transform their internal processes (i.e., supply chain). These allow firms to comply with requirements and shape market dynamics through successful implementation of sustainable innovations.

This DC framework is essential for understanding the interaction between sustainability and competitiveness in the automotive sector. By applying this approach, firms can manage challenges of transitioning to new sustainable technologies and create a foundation for long-term flexibility. This approach is emphasized by the volatility of the global automotive market, where firms have to balance short-term operational efficiency with long-term investments in sustainability (Bari, N et al., 2022).

In this study, DC is examined through ammonia and NEFs. The successful integration and scaling of these technologies depends on their technical viability and on a firm's ability to dynamically adapt their resources and processes. Therefore, the DC framework offers a way to understand how sustainable innovation can succeed in the automotive world.

2.2 Automotive Industry's Environmental Impact

The automotive sector is at a standpoint. Although it is a driving force for global economic development, modern transportation, and innovation, its current reliance on fossil fuels negatively reflects on environmental sustainability. This section of the paper examines the current environmental impact of the automotive industry, putting forth the urgency of implementing new and green technologies, because they provide a basis for the development of new solutions like ammonia and NEF.

The automotive industry is one of the largest sources of greenhouse gas (GHG) emissions worldwide, heavily contributing to climate change. According to the International Energy Agency (IEA, 2023), the automotive sector accounted for 28% of global energy-related CO₂ emissions in 2021. The Union of Concerned Scientists emphasized the severity of this issue, highlighting that the automotive industry is the largest source of GHG emissions in the United States (UCSUSA, 2023). Today, the burning of fossil fuels in both conventional diesel and gasoline engines are the main culprits behind the GHG emissions. The two main gases being emitted are carbon dioxide (CO₂), which traps heat in the atmosphere, and nitrogen oxide (NO_x), which causes smog and acid rain (Environmental Protection Agency, 2023).

The automotive industry's dependence on fossil fuels has led to an increase in environmental concerns, necessitating the adoption of environmentally friendly practices. This urgency for this shift, put forth by the Intergovernmental Panel on Climate Change (IPCC), highlights the need for drastic GHG emission reduction to reduce the effects of climate change, including extreme weather events, rising sea levels, and disruption of ecosystems (IPCC, 2022). The automotive sector has taken a two-fold approach to sustainable practices: reducing greenhouse gas emissions and increasing energy efficiency. A study undertaken by McKinsey and Company outlines different ways to accomplish these goals, including the development of cleaner fuels, the electrification of vehicles, and making improvements to vehicle manufacturing processes and designs to increase their fuel efficiency (McKinsey & Company, 2020).

It has become clear that transitioning toward a green, sustainable automotive industry requires a definitive move away from the use of diesel and gasoline as it stands. Unfortunately, the automotive industry continued over-dependence on fossil fuels contributes to increasing GHG emissions and poses a threat to global oil reserves worldwide (BP Statistical Review of World Energy, 2023). Research by the U.S. Department of Energy emphasizes the necessity of developing and fostering clean energy technologies to reduce our dependence on fossil fuels (U.S Department of Energy, 2021). Fuel sources like hydrogen, ammonia, and biofuels should be explored to give the automotive industry a green and promising future.

2.2.1 Green Solutions

The automotive industry must focus on creating and implementing clean technologies to combat the environmental issues discussed above. This study investigates the potential of two such innovative technologies, ammonia engines, and NEFs, in the future of the automotive industry, specifically their impact on the evolution and integration of battery technology. Ammonia engines produce less GHG emissions than conventional combustion engines. However, difficulties are still faced with their NO_x emissions (Langella, G., et al., 2022). NEF are produced using an innovative approach to fuel production using nano-catalysts and renewable electricity, creating sustainable fuel sources (Rashid, U et al., 2023). It will therefore be essential to understand the interplay between both technologies and existing battery technology to increase sustainability in the automotive landscape.

Although transitioning to those sustainable fuel sources can lead to great environmental benefits, understanding and acknowledging the challenges associated with such a change is crucial. For instance, the related challenges may include how to fund research and development for alternative fuel sources, how to ensure their economic viability, and understanding the potential limitations of certain alternative fuel sources (BP Statistical Review of World Energy, 2023). That said, ammonia and NEFs, can be used to address some of these issues and pave the way to an environmentally friendly future, which is further explored in subsequent sections.

2.3 Current Automotive Technologies

Given that the automotive industry contributed around 28% of all CO₂ emissions in 2021, its path toward environmental sustainability is critical (IEA, 2023). Recognizing this, this part of the study aims to look at the environmental footprints of the three most common powertrains in the automotive industry: internal combustion engines (ICEs), electric vehicles (EVs), and hybrid electric vehicles (HEVs).

2.3.1 Internal Combustion Engines

ICEs are large contributors to CO₂ emissions and other greenhouse gases resulting from the combustion of fossil fuels. In the United States, gasoline-powered vehicles are responsible for around 4.6 metric tons of CO₂ throughout their operational lifetime (ICCT, 2021). Going further than greenhouse gases, ICEs emit a variety of pollutants, including particulate matter, hydrocarbons, and nitrogen oxides, which are the cause of acid rain, smog, and respiratory diseases (WHO, 2021). The World Health Organization has linked 7 million premature deaths annually to air pollution on a global scale. Although many technological advancements intended to improve fuel efficiency and reduce emissions have emerged, ICEs continue to pose a significant environmental challenge, requiring stringent regulatory measures and the exploration of sustainable alternatives (ICCT, 2021).

2.3.2 Electric Vehicles

Due to their complete lack of tailpipe emissions, EVs stand out as a pivotal solution in reducing the automotive sector's environmental impact (ANL, 2020). However, the overall environmental footprint of EVs is contingent upon the electricity generation mix used for charging purposes. According to a study by Argonne National Laboratory in 2020, EVs exhibit lower greenhouse gas emissions in their lifecycle compared to conventional gasoline vehicles, especially in "greener" areas. EVs are a key solution to improving urban air quality by

eliminating particulate matter, hydrocarbons, and nitrogen oxide (UCS, 2020). However, EVs face challenges such as a shorter life cycle and environmental impact of battery production (Franzo, S., 2021).

2.3.3 Hybrid Electric Vehicles

HEVs represent a mix of technological advancements. They have both an electric motor with an internal combustion engine to increase fuel efficiency and reduce emissions (EPA, 2023). However, they still partially depend on gasoline, and their environmental impact varies depending on the extent to which the utilization of the electric motor (EPA, 2023).

2.3.4 Towards a Greener Future

The path toward a sustainable automotive world is not without challenges. The transition is made difficult by many technological and infrastructural barriers that necessitate research and innovation beyond the current automotive landscape. The push to improve the future is emphasized by the emergence of ammonia engines and NEF technology, both showing promise in overcoming the current limitations of existing engines and battery technologies (Negro, V., 2023; Rashid et al., 2023).

Having examined current automotive technologies, their current environmental footprints, and discussed the transition challenges, accentuates a crucial need for a shift. It is imperative to embrace a broad strategic framework that allows for continuous innovation and adaptation. The potential for ammonia engines and NEFs to change the automotive firms, thus, becomes a test case for the dynamic capabilities (Teece et al., 1997). The transition toward those technologies has become an imperative that necessitates a coherent integration of technological innovation with dynamic capabilities. This means that professionals in the automotive sector need an approach that involves tackling the intricacies of environmental sustainability, regulatory compliance, and market competitiveness, leading the way to a green, innovative, and resilient future (Thomas et al, 2006).

2.4 Ammonia

A shift toward sustainable fuel sources is, therefore, required for the automotive industry. Although the adoption of ammonia poses some challenges, it still presents itself as a potential game-changer in transportation, offering applications in both engines and battery technology.

A crucial advantage of ammonia lies in its ability to produce less greenhouse gas emissions compared to conventional gasoline and diesel engines. The combustion of ammonia generates nitrogen (N₂) and water (H₂O), which are both harmless components of air (Negro, V et al., 2023). In addition to its environmental benefits, ammonia provides a practical advantage: leveraging existing fueling infrastructures. With some slight changes to current fuel pumps, established refueling stations worldwide could be utilized for ammonia engine refueling, significantly reducing adoption costs and time compared to shifting to hydrogen engines (Thomas et al, 2006). Moreover, ammonia has a higher energy density by volume than liquid hydrogen, which translates into increased driving range, addressing one of the major concerns for the worldwide consumer adoption of alternative fuels (Al-Aboosi et al., 2021).

Although ammonia is presented as a better alternative to ICEs, especially regarding GHG emissions, there are some barriers to its widespread adoption. The combustion of ammonia still creates nitrogen oxide (NO_x) pollutants (Chiong, M., et al., 2021). These emissions are still a concern because they reduce air quality, requiring the development of robust controls. The use of selective catalytic reduction (SCR) systems, which are also used in diesel engines, is a promising way to reduce NO_x emissions, with ongoing research focusing on the optimization of SCR systems to ensure compliance with stringent regulations (Gao, F et al.; Cheng, X et al., 2014).

Furthermore, ammonia's toxicity and odor present safety challenges. Gas leaks are a great concern and threat to human health and the environment (Centers for Disease Control and Prevention, 2023). Stringent measures and strict infrastructure designs are paramount to reducing and controlling the risks involved in handling, transporting, and storing ammonia-based fuels (Negro, V. et al., 2023). The transition from gas to ammonia engines presents both challenges and opportunities. Despite the low cost of implementation due to the use of existing infrastructures, the cost of ammonia production and distribution needs to be evaluated (Al-Aboosi et al., 2021). That said, there is potential for the large-scale production of green ammonia from renewable sources, which would lead to large reductions in cost and environmental impact.

Although ammonia's potential for sustainable transportation is related to engines, its potential extends far beyond that. This compound holds promise for use in battery technology. A new compound, ammonia borane (NH₃BH₃), a hydrogen-rich compound, is being examined as a potential fuel source for solid-state batteries. NH₃BH₃ releases hydrogen gas, which can be

used to generate electricity. Work is ongoing to improve the stability and cyclability of ammonia-based batteries, paving the way for revolutionary advancements (Akbayrak, S., & Ozkar, S., 2018). Another interesting application of ammonia is as an additive in battery electrolytes. Meng, J et al. (2024) suggested that ammonia can improve the ionic conductivity of electrolytes, leading to faster charging times and higher energy density. Therefore, ammonia presents itself as a promising compound for sustainable transportation, providing a noteworthy decrease in GHG emissions and groundbreaking progress in battery technology. Although there are some concerns about its NO_x emissions, safety, and economic feasibility, ammonia has emerged as a key component of the future of the automotive world.

2.5 Nano-Electro Fuels

Another innovative avenue toward a sustainable automotive world involves NEFs. This nanotechnology can be used to improve energy storage and release mechanisms. This upcoming part of the study will look at the role of NEFs in sustainability, exploring their potential to improve the overall environmental impact of the automotive sector.

This new technology stands at the forefront of the automotive industry, even transcending the limitations of today's solutions (potentially also outpacing the utility of ammonia). NEFs have the particularity of navigating around the infrastructural challenges of ammonia, especially regarding handling and storage. Ammonia, while promising a carbon-free fuel, requires special handling and storage due to its toxic and corrosive nature. This makes its implementation more complex and costly as they need specific containments and modifications to current infrastructure. In contrast, NEFs do not face the same difficulties, being easier to store and handle. They are produced and utilized in a way that avoids hazardous conditions associated with ammonia. By utilizing renewable electricity and nano-catalysts, NEFs can transform an array of feedstocks, such as water, carbon dioxide, and biomass, into a more sustainable fuel source (Joy, N. et al., 2024; Ababneh, H., & Hameed, B, 2022).

NEFs has considerable production and environmental advantages. By ensuring that renewable energy is employed during the production process of NEFs, all the detrimental extractions of conventional refining processes, characteristic of fossil fuel production, are avoided. Moreover, because NEFs have high potential regarding energy density, they could extend vehicle ranges and enhance efficiency, presenting a clear advantage over current energy sources (Ulaganathan, M., 2015). This adaptability comes from the ability to customize its formulation for specific

energy requirements. This means that by modifying the conversion processes and catalysts, it is possible to engineer NEFs to meet specific demands of various applications, from automotive to maritime, each with its unique requirements for energy density and compatibility (Yang, M et al., 2020).

The potential application and utility of NEFs extend far beyond the automotive world, with great implications for aviation, maritime, and stationary power generation. These fields, which traditionally greatly rely on fossil fuels, could see significant change in the upcoming years with the adoption of such innovations, contributing to improving their global impact (BusinessEurope, 2021; Shahabuddin, S., 2020).

The crossroads between NEFs and battery technology prompts the consideration of their collective impacts on the automotive industry, especially EVs. The use of NEFs in power generation to enhance electric grid sustainability could reduce the lifecycle impacts of EVs. Furthermore, these advancements could lead to innovations in materials and manufacturing processes for batteries, potentially improving their lifespan and performance (Negro, V et al., 2023). Although NEFs present themselves as a great alternative to conventional fuel sources, the road to their global implementation is full of obstacles. Scaling NEFs to meet global energy demands and addressing their environmental and health implications will be key. Furthermore, it will be crucial to work out the economic viability of NEFs compared to existing fuels and explore cost-effective production and distribution strategies. A collaborative effort by scientists, engineers, policymakers, and professionals in the private sector is necessary to maximize the likelihood that such technology will be implemented. Such a collective work is crucial to overcome current challenges and utilize the innovative power of this new technology for a green and sustainable future (Stott, L et al., 2020).

3. Methodology

The following section puts forth the research methodology, including both the research design and data collection process.

3.1 Research Design

This research design aims to gain insight into the automotive industry’s transition from fossil-fuels to new and sustainable innovations (i.e., ammonia and NEFs) and their potential to disrupt the automotive landscape. A systemic research design was utilized to explore significant industry shift. Table 1 outlines the detailed methodology employed:

Introduction	<ul style="list-style-type: none"> ▪ Definition of research scope based on sustainable automotive technologies. ▪ Development of research questions.
↓	
Literature Review	<ul style="list-style-type: none"> ▪ Identification and definition of relevant theory. ▪ Examination of previous studies.
↓	
Methodology	<ul style="list-style-type: none"> ▪ Definition of a two-step approach to validate the RQ. ▪ Development of a semi-structured interview guide. ▪ Selection of participants representing the automotive and energy industries. ▪ Collection of qualitative data through experts’ interviews. ▪ Development and distribution of a survey to quantify the potential adoption of new technologies.
↓	
Analysis & Discussion	<ul style="list-style-type: none"> ▪ Qualitative and quantitative analysis of the potential new technologies to enhance sustainability.
↓	
Conclusion	<ul style="list-style-type: none"> ▪ Summarization of main findings. ▪ Derivation of managerial and academic implications. ▪ Discussion of main limitations and identification of future research needs.

Table 1: Methodology

A thorough literature review was first conducted to uncover the intricacies of the potential transition and establish a baseline understanding of the current dependency on fossil fuels, the economic, environmental, and regulatory pressure driving the industry to shift to green alternatives, and ammonia and NEF technologies. Following this, a mixed-method approach was utilized. First, interviews were conducted with industry experts, including engineers, scientists, and executives, providing qualitative insight into the current state of the automotive world and the perceived benefits, barriers, and market readiness related to the adoption of ammonia engines and NEFs. Then a survey was distributed among stakeholders in the automotive and energy sectors to gain a broad understanding of industry perceptions. Quantitative data on the adoption rate, perceived efficacy, and potential environmental impacts of both ammonia and NEFs was gathered.

3.2 Data Collection

3.2.1 Primary Data: Expert Interviews

The expert interview, as outlined in Table 1, serve as a robust method for gathering qualitative data, particularly in a single interview per interviewee.

#	<i>Expert Current Position</i>	<i>Expertise</i>	<i>Years of Experience</i>
1	Junior Engineer	Automotive engineering	<5 years
2	Automotive Quality Control Engineer	Quality assurance	>10 years
3	Senior Engineer	Advanced automotive technologies	>15 years
4	Senior Research Scientist	Renewable energy	>10 years
5	Head of Material Management	Supply chain management	>8 years
6	Board of Directors	Strategic planning and investments	>25 years

Table 2: Overview of Interviewed Experts

The study focused on examining the potential integration and impact of ammonia engines and NEFs within the automotive industry. The interviews aim to gather practical insights from industry experts, enriching our understanding of these technologies' potential and implementation challenges. A diverse group of experts was approached for their deep knowledge and experience in the automotive and energy sectors. The selection included industry practitioners who provided practical viewpoints on implementing such technologies and academics who offered theoretical and inter-industry insights.

3.2.2 Primary Data: Survey

Building upon the literature review, the survey was designed to gather quantitative data to assess the industry stakeholders' awareness, acceptance, and perceptions of ammonia and NEFs. This approach aligns with the need to understand the diffusion of these technologies within the automotive sector.

The survey was structured into several key sections to ensure comprehensive coverage of the research questions:

1. **Demographics:** Collecting basic information such as age, occupation, education, and involvement in the automotive industry to contextualize responses.
2. **Awareness and Perception:** Measuring the level of awareness about the environmental impact of current automotive technologies and innovative solutions like ammonia engines and NEFs.
3. **Impact on Technology and Sustainability:** Evaluating perceptions regarding the effectiveness of these technologies in promoting environmental sustainability and technological innovation.
4. **Transition Challenges and Opportunities:** Identifying perceived barriers and opportunities in adopting these technologies.

An online survey was set up to facilitate broad participation. This format was selected for its efficiency and ability to reach a more diverse, international audience and administered on Qualtrics. Participants were selected through convenience sampling, targeting industry professionals and stakeholders via social media platforms and professional networks related to the automotive world.

In this study, a total of 161 participants initially engaged with the survey, designed to explore the perception and acceptance of ammonia and NEFs in the automotive industry. Out of the initial participant pool, 145 responses were considered valid after excluding those that failed to pass quality tests. This filtering process helped in maintaining integrity of the data collection, which is essential for the research findings. The detailed discussion of the survey's limitations and the justification of representativeness of the sample size will be further elaborated in section 5 of the thesis.

4. Analysis and Discussion

4.1 Overview of Expert Insights

This section examines the findings derived from expert interviews conducted with six professionals within the automotive industry. These interviews focused on the perspectives surrounding the adoption of ammonia engines and nano-electro fuels (NEFs). By employing thematic analysis, key themes were identified and triangulated with literature review findings and quantitative survey data.

4.2 Thematic Analysis

In order to extract key themes, in-depth interviews were conducted with six industry experts: three engineers in the automotive industry, a research scientist, a head of material management, and a board member at Stellantis ventures.

4.2.1 Limited Knowledge and Awareness

The interviews put emphasis on the lack of knowledge of ammonia and NEFs across the automotive industry. Interviewees all mentioned that while the potential of those technologies is promising, there is a lack of understanding and awareness of those technologies among industry practitioners. This knowledge gap creates a barrier to adoption, as the main stakeholders are not informed of all the benefits and challenges of those technologies.

Interviewee 1 highlighted the industry's rudimentary understanding of NEFs and ammonia engines, noting their promising potential but missing information of their application, stating:

"Ammonia Engines seem like an interesting alternative for the continuation of combustion engines without the drawbacks of CO2 output... No knowledge with regards to nano-electro fuels."

Furthermore, interviewee 2 had no knowledge of NEFs, indicating a lack of understanding and familiarity with these emerging technologies. This sentiment was also mentioned by the other experts, who put forth that the industry is not prepared for the widespread adoption of both NEFs and ammonia due to the existing knowledge gaps.

The literature also supports this, putting emphasis on the importance of knowledge and awareness when implementing new technologies. The International Energy Agency (2023)

stated that education and knowledge dissemination are crucial for the successful integration of technologies.

As mentioned, the overall sentiment from the experts is that the automotive industry is not ready for a rapid integration of these technologies. They also mentioned that the current infrastructure, regulations, and market are not aligned with these innovations, making the adoption difficult in the near future.

4.2.2 High Barriers to Adoption

The industry experts mentioned that both technologies require new infrastructure and regulations. Interviewee 4 highlighted the initial costs and complexities involved in adopting such technologies. Interviewee 1, 2, 5 and 6 mentioned that the infrastructure, regulations, and market are not aligned with the integration of ammonia and NEFs currently. Interviewee 1 further developed on the infrastructure challenges:

"For the automotive industry to implement ammonia engines would take a massive investment by both firms and governments to pursue ammonia-centric infrastructure. Nobody buys a car they can't refuel. Sadly, with the intense focus on electric, there seems to be little appetite to free up money for other alternatives."

Interviewee 2 also discussed:

"I suspect it will be the lack of infrastructure for any vehicle that isn't gas or electric based. Electric vehicles now have the necessary numbers of charging stations to make the whole idea and purchasing of an electric vehicle very viable. I do not think there are any plans to make this true or viable for ammonia engines."

Both of these statements underscore the challenges in adopting these technologies, making them hard to be viable in the near future.

Another notable theme derived from the interviews is the constant discussion about the technical and economic challenges associated with the adoption of ammonia and NEFs. These insights align with hypothesis 3, saying that high costs and technical challenges are the primary barriers to widespread adoption. The literature also supports this, with research highlighting the significant investment needed to pursue the development and maintaining the infrastructure for both ammonia and NEFs (Qi, Y et al., 2023).

4.2.3 Organizational Strategies

Another key theme derived from the interviews is the organizational strategies with emerging technologies. The approach varied among the experts and companies; however, some common practices were found. Notably, interviewee 3 and 6, with organizations knowledgeable of such technologies, described quite a structured approach, starting with technology scouting (other companies working on them, etc), assessing their feasibility, and investments in R&D:

"Starting with detailed technology scouting, we move to initial small-scale testing, then onto larger pilot projects once initial tests are successful."

This structured approach allows organizations to evaluate and integrate new technologies, reducing the risk associated with it. All experts also noted the importance of keeping up with the industry breakthroughs to potentially adopt better practices.

4.2.4 Push for Adoption

Another topic mentioned during the interviews was the push for adoption of such technologies. Interviewees all mentioned that the adoption of ammonia and NEFs are driven by regulatory pressure and policies, aligning with hypothesis 2. They also highlighted the role of governmental incentives and mandates in accelerating the adoption of such technologies, with interviewee 2 stating:

"Environmental regulations are forcing companies to rethink their strategies and invest in cleaner technologies."

Literature also emphasizes this point, stating the importance of policy as a driver for sustainable innovation (Intergovernmental Panel on Climate Change, 2021). Regulatory frameworks play a crucial role in influencing strategic decisions by pushing companies to implement technologies that adhere to new regulations. Interviewee 3 further elaborated:

"Environmental regulations heavily influence our strategic direction. We're constantly analyzing regulatory trends to ensure that our investments align with future legal and environmental standards."

This shows that it will be essential for organizations to have a proactive approach when integrating new technologies.

That said, experts highlighted the complexity and challenges faced by organizations when trying to align with regulatory demands. The need for compliance in those cases creates a significant barrier, with interviewee 1 mentioning:

"Regulation has proved to be complicated and non-intuitive. We are not sure how or where it would benefit us, if at all. Making sure we are in compliance adds time and effort for us to complete work, especially more recent regulation."

Most of the interviewees mentioned the crucial role of governmental incentives. Experts all were critical on the current incentives and wish they were facilitating the transition, with interviewee 3 stating:

"The financial support from the government for research and development in sustainable technologies is essential. Without these incentives, the pace of adoption would be significantly slower."

Interviewee 2 further elaborated:

"Having government officials see the reality and work with industry professionals would be best for such technologies to come to fruition."

Pushing for a collaborative effort between industry experts and policy makers is essential to create a supportive environment for the development and adoption of new technologies.

All in all, the push for adopting both ammonia engines and NEFs is not only a technological matter, but it's also influenced by regulations and policies. Understanding this interplay between external pressure and internal capabilities is crucial to understand the dynamics of innovation, integration, and adoption of technologies in the automotive industry.

4.2.5 Future Outlook

The last key subject mentioned was the future outlook of the automotive world, highlighting the significant investment in R&D needed for a successful integration with interviewee 6 saying:

"Emerging technologies are set to redefine the automotive industry, driven by the need to meet stringent environmental standards and consumer demands for sustainable products. The main barriers will likely be cost, infrastructure readiness, and market acceptance."

This put emphasis on the general sentiment that, while the potential of both technologies is recognized, practical challenges remain a significant hurdle.

Despite the clear enthusiasm from the experts, there was a consensus that the automotive industry is currently not ready for their widespread adoption. The primary reasons, as stated in the aforementioned points, include the knowledge gaps, infrastructure challenges, the current focus on electric vehicles, and the lack of governmental incentives, which dominate the automotive innovative landscape.

"For the automotive industry to implement ammonia engines would take a massive investment by both firms and governments to pursue ammonia-centric infrastructure. Sadly, with the intense focus on electric, there seems to be little appetite to free up money for other alternatives."

"While we see the promise in ammonia and NEFs, the lack of infrastructure and the high initial costs are significant deterrents. We need stronger regulatory frameworks and more substantial government incentives to make this transition feasible."

Overall, the interviews revealed that there is both enthusiasm and caution among experts in the industry regarding the future of these technologies. While there is a clear recognition of the potential benefit of those, all the challenges associated with them remain a prominent hurdle in their adoption.

4.3 Quantitative Analysis – Survey

This section of the thesis focusses on the quantitative findings derived from a survey of automotive and energy industry professionals. It was conducted to support the findings from the literature and expert interviews, focusing on their perception of ammonia engines and nano-electro fuels. The survey targeted people working in the automotive world, focused in Italian and German speaking countries. In Europe, these regions play a significant role in the automotive world, with Germany alone representing about 25% of EU's total car production. This combined to Italy's substantial market presence puts emphasis on their importance for this research (ACEA, 2023).

4.3.1 Demographic Analysis

To contextualize the survey findings, it is necessary to understand the demographics of the respondents. The following section presents a detailed analysis of the demographic data,

highlighting the distribution of gender, age, education, occupation, and involvement in the automotive and energy industry. It is key to point out that, out of the 161 responses, 145 turned out to be valid through data cleaning, ensuring the validity and accuracy of the subsequent analysis.

Gender Distribution

The data shows a great gender imbalance, with 95.2% of the sample being male, while 4.8% female. This disparity reflects the gender dynamics typically present in the automotive world, especially in technical roles where male participation tends to be higher. This imbalance may influence the research findings, particularly where gender-specific perspective could be relevant and interesting.

Age Distribution

The majority being between the age 25-34, with 58.6% of the respondents. This is followed by respondents aged 18-24, who make up 25.5% of the respondents. The results show a dominance of younger professionals, with a small percentage over 45.

Educational Background

The survey revealed that most respondents held a bachelor, master, and technical degree, with 56.6% of holding a bachelor's degree, 26.2% a master's degree, and 11.0% hold technical training.

Occupational Roles

Most of respondents identified professionals working in energy and the automotive industry, with 75.2% of the respondents. Students made up 20.7% of the respondents, while smaller groups included retirees with 2.1%, unemployed with 1.4%, and other with 0.7%. This distribution shows that the survey captured the views of people working within or close to the automotive industry, focusing on working professionals.

Level of Involvement in the Automotive Industry

The survey results demonstrated that 25.5% of respondents reported being highly involved in the automotive industry, while 60% indicated that they were somewhat involved in the automotive industry. The smallest group, consisting of 14.5% of respondents, stated that they were not involved in the automotive industry. Having most of the respondents working in the automotive world likely allows them to understand emerging technologies such as ammonia and NEFs.

4.3.2 Factor and Cluster Analysis

To identify and understand the core dimensions influencing the perception of both technologies, it is important to define factors and segments within the population. Both factor and cluster analysis are great statistical tools that allows us to achieve these goals. This section presents the results, linking them to the research question, hypotheses, qualitative research, and literature.

4.3.2.1 Ammonia

During analysis, it was determined that the data was suitable for a factor analysis, with a sampling adequacy of 72.2% and a significant p-value ($P < 0.001$). An eigenvalue of 0.7 was chosen to keep more factors for a comprehensive exploration of the data, which is very relevant in the context of emerging technologies. Also, a communality threshold of 0.6 was used to make sure that the variables included were well represented by the factors.

The factor analysis revealed five primary factors that account for 75.4% of the total variance (Appendix 7.3.1). These five factors show the concerns and motivation of the survey respondents regarding the adoption of ammonia engines.

Factor	Description	Explained Variance	Key Variables
Environmental and Technological Impact	Reflects the perceived benefits of ammonia engines in reducing environmental impact and fostering innovation	22.4%	<ul style="list-style-type: none"> - Fuel Efficiency of Ammonia - Long-term Sustainability of Ammonia - Emissions Reduction of Ammonia
Awareness	Captures the level of awareness and understanding of ammonia engines among respondents	16.9%	<ul style="list-style-type: none"> - Heard About Ammonia - Understanding Ammonia
Safety and Innovation Concerns	Highlights concerns about safety and health risks associated with ammonia engines and views on technological innovation	14.9%	<ul style="list-style-type: none"> - Safety and Health Concerns - Innovation Technology Ammonia
Operational and Economic Challenges	Emphasizes the perceived challenges, including economic feasibility and operational barriers to adopting ammonia engines	11.5%	<ul style="list-style-type: none"> - Biggest Challenge - Cost Savings of Ammonia
Perceived Effectiveness	Focuses on the specific perceptions of the overall effectiveness of ammonia engines	9.6%	<ul style="list-style-type: none"> - Effectiveness of Ammonia

Table 3: Factors Ammonia

The first factor, *Environmental and Technological Impact*, explained 22.4% of the variance. This factor included variables such as “Fuel Efficiency”, “Long-term Sustainability” and “Emissions Reduction”, with respondents viewing ammonia engines as a crucial development for the automotive world, especially for a reduced environmental footprint. This aligns with

H1, which mentions that the adoption of ammonia engines will reduce the industry's CO₂ and NO_x emissions.

The second factor, *Awareness*, explained 16.9% of the variance. This factor included “Heard About Ammonia” and “Understanding Ammonia”. This factor suggests that the level of familiarity of the technology shapes perceptions about it, which is also relevant to H2. This hypothesis indicates that regulatory pressures and environmental policies, which drives awareness, are important factors in the adoption such technology.

The third factor, *Safety and Reliability Concerns*, explained 14.9% of the variance. The factor included variables reflecting concerns about safety, reliability, and operational challenges associated with this technology. These include variables such as “Understanding Ammonia” and “Heard about Ammonia”. This suggests that respondents were cautious towards this technology, emphasizing the need to strong safety measures and improved reliability before pushing for its implementation. The presence of such concerns can be linked to H3, which suggests that initial high costs and technical challenges are the primary barrier to widespread adoption.

The fourth factor, *Operational and Economic Challenges*, accounted for 11.5% of the variance. This factor captured variables such as “Cost-Saving” and “Biggest Challenges”, putting forth concerns regarding the economic feasibility and infrastructural readiness needed to support the integration of ammonia. This also links to H3, reinforcing the view that technical and economic challenges are barriers to adoption.

The fifth factor, *Perceived Effectiveness*, explained 9.6% of the variance. This factor revolved around the belief of effectiveness of ammonia engines, with “Effectiveness of Ammonia” being the key variable. This can be linked to H4, which puts forth the need for the automotive industry to adapt to technological advancements, highlighting “Effectiveness”.

To further understand how the survey respondents perceive ammonia engines, a cluster analysis was performed based on the factor scores. This analysis found three clusters, each representing different profiles and attitudes towards ammonia engines.

Clusters	Size	Characteristics
Innovators	72 (49.7%)	Not the most supportive of ammonia engines, having not a particularly positive view on its operational and economic advantages.
Realists	39 (26.9%)	The most cautious group towards ammonia engines, with big reserves on its safety and operational reliability.
Pioneers	34 (23.4%)	The most enthusiastic group, viewing it as a key technological advancement.

Table 4: Cluster Ammonia

The first cluster, named the *Innovators*, consisted of 49.7% of the respondents. This group showed a moderate level of support towards the technology, understanding its benefits for the environment but was concerned about operational and economic challenges associated with its adoption. The second cluster, the *Realists*, comprised of 26.7% of the respondents. Notably, these respondents were the most concerned about safety, health, and reliability of ammonia engines, making them the least likely to adopt the technology. Finally, the third cluster, the *Pioneers*, represented 23.4% of the respondents. This group was the most enthusiastic about the innovative and economic potential of this technology. They showed a real belief in its long-term benefits and were confident that the challenges associated with adoption can be overcome, making them the best group to target. This allowed us to create a new variable, including only cluster 3, which was subsequently used in binary logistic regression analysis to gain insights on the factors driving the adoption.

The results of the binary logistic regression showed that the key factors, such as Environmental and Technological Impact, Awareness, and Perceived Effectiveness were significant predictors belonging to this cluster. The forward: Wald method was used to refine the model, excluding non-significant variables and focusing on the most impactful predictors. The results, detailed in regression output (Appendix 7.3.3), showed that the model improved significantly over the baseline, indicated by a p-value below 0.001 in the Omnibus test of Model Coefficients. The model showed a high level of predictive power, with a R-Square value of 0.974., suggesting that the factors included explained a large portion of the variation in the target group membership. The Hosmer Lemeshow test, with a significance level of 1.000, indicated that the

models' predictions were a good fit for the observed data. The classification table further enhanced this, with group membership correctly predicted for 98.6% of the observations. The analysis showed that three factors were significant predictors, with a p-value under 0.05: Environmental and Technological Impact, Awareness, and Perceived Effectiveness. The exponential B-value indicated strong influence for these factors, especially for Environmental and Technological Impact, which had a considerable effect on being in Cluster 3. This results therefore suggested that the target consumers, represented in Cluster 3, valued environmental and technological benefits associated with ammonia engines, and are influenced by their knowledge, awareness and perception of this technology. Although the R-squared value indicated a strong model, the results also suggest that other unexamined factors might further explain the target group membership.

4.3.2.2 Nano-electro Fuels

A similar analysis was conducted for nano-electro fuels. A factor analysis also demonstrated that the data was suitable for examination, with a KMO sampling adequacy of 0.656 and a significant p-value ($p < 0.001$). In this case, however, no eigenvalue was used. Instead, a fixed number, 5 factors, to ensure consistency with the factor analysis conducted for ammonia. This approach allowed for a comparable exploration of the data. A communality threshold of 0.6 was used to make sure that the included variables were represented by all the factors. For this factor analysis, the five factors account for 75.8% of the variance (Appendix 7.3.4).

Factor	Description	Explained Variance	Key Variables
Environmental and Technological Impact	Reflects the perceived benefits of ammonia engines in reducing environmental impact and fostering innovation	21.0%	<ul style="list-style-type: none"> - Fuel Efficiency of Ammonia - Long-term Sustainability of Ammonia - Emissions Reduction of Ammonia
Awareness	Captures the level of awareness and understanding of ammonia engines among respondents	17.7%	<ul style="list-style-type: none"> - Heard About Ammonia - Understanding Ammonia
Safety and Innovation Concerns	Highlights concerns about safety and health risks associated with ammonia engines and views on technological innovation	15.9%	<ul style="list-style-type: none"> - Safety and Health Concerns - Innovation Technology Ammonia
Operational and Economic Challenges	Emphasizes the perceived challenges, including economic feasibility and operational barriers to adopting ammonia engines	10.8%	<ul style="list-style-type: none"> - Biggest Challenge - Cost Savings of Ammonia
Perceived Effectiveness	Focuses on the specific perceptions of the overall effectiveness of ammonia engines	9.3%	<ul style="list-style-type: none"> - Effectiveness of Ammonia

Table 5: Factors NEF

In this case, the factors identified for NEFs are quite similar to ammonia. Both sets of factors reflected common themes in how the respondents perceived these technologies and linked them to the same hypothesis. However, despite these similarities, subtle differences could be observed in how these factors manifest.

The first factor represented 21% of the variance, reflecting the perceived benefits of NEFs in contributing to environmental sustainability. In general, respondents recognized the potential of NEFs to contribute to long-term sustainability in the automotive world. The variables “Fuel Efficiency”, “Long-Term Sustainability”, and “Emissions Reduction” were included in this factor, putting forth its potential to deliver significant environmental benefits.

The second factor reflected the level of awareness and understanding of NEFs, representing 17.7% of the variance. It comprised of variables “Heard about Ammonia/NEFs” and “Understanding NEFs”. This factor was important as it suggested that the familiarity with the technology influences perception. Interestingly, the expert interviews showed a general lack of understanding and awareness of NEFs, and they considered perception to be a barrier to adoption, which corroborates this finding. Being a very niche innovation, efforts to increase its awareness could be crucial in overcoming potential skepticism and encourage acceptance.

The third factor, representing 15.9% of the variance, captured safety concerns and views on technological advancements. It included variables like “Safety and Health” and “Innovation Technology”. This highlighted the fact that, while it is seen as a promising technology, reservations were also made about its safety implications. This sentiment was also shared by experts, where they mentioned the challenges of adopting such technology, especially because of regulatory alignment.

The fourth factor, *Operational and Economic Challenges*, represented 10.8% of the variance, and emphasized perceived challenges with the adoption of NEFs. The variables included “Biggest Challenge” and “Cost-Saving”. These challenges consisted of the high costs, need for infrastructure, and uncertainties as to the economic viability.

The fifth factor, *Perceived Effectiveness*, represents 9.3% of the variance. The variable “Effectiveness NEFs” is included in this factor., indicating that the overall belief as a greener technology plays a crucial role in shaping perceptions.

Clusters	Size	Characteristics
Analysts	63 (43.4%)	They are more concerned about operational challenges and economic feasibility than anything else.
Cautious Optimists	31 (21.4%)	Wary of safety and reliability, they remain aware of the technology's benefits.
Pioneers	51 (35.2%)	The most enthusiastic group, they strongly believe in the technology.

Table 6: Cluster NEF

The first cluster, the *Analysts*, consisted of 43.4% of the respondents. This group was greatly concerned about the operational challenges and economic feasibility of adopting NEFs. They acknowledged the potential benefits of the technology, however, their focus remained on the practical aspects of it. The second cluster, the *Cautious Optimists*, represented 21.4% of the respondents. They remained wary of the safety and reliability concerns of NEFs; however, they recognized the potential benefits that the technology could bring to the automotive sector. Lastly, the third cluster, the *Pioneers*, comprised 35.2% of the respondents. This group was the most enthusiastic about the adoption of NEFs, believing in the technology's potential to change the automotive world, making them the ideal group to target. This analysis led to the creation of a new variable that included both Cluster 2 and 3, which were then used in a binary logistic regression analysis to gain insights into factors driving adoption.

The analysis showed that the key factors, such as Operational and Economic Challenges, Awareness, and Perceived Effectiveness were significant predictors of belonging to the target Cluster 2 and 3. The forward: Wald method was used to refine the model, always excluding non-significant variables and putting forth the most impactful predictors. The results, detailed in the regression output (Appendix 7.3.6), demonstrated that the model improved over the baseline, with a p-value under 0.001 in the Omnibus test of Model Coefficients. The model also had a high predictive power, with an R-squared of 0.937, suggesting that the factors included explained a large part of the variation in the target group membership. The Hosmer-Lemeshow test, with a significance level of 0.998, indicated that the model's prediction was a good fit for the data. The classification table, again, further supported this, with group membership predicted at 96.6% of the observations. The analysis found five key predictors

under the p-value of 0.05, including Operational and Economic Challenges, Awareness, Safety and Reliability Concerns, Environmental and Technological Impact, and Perceived Effectiveness. The exponential B-value highlighted the strongest influence for the Cluster 2 and 3, being the Operational and Economic Challenges. These results suggested that target consumers in Clusters 2 and 3 were highly influenced by their perception of operational and economic feasibility for NEFs. Although concerns of safety and reliability were also playing a role in the perception, the model indicated that these groups were more likely to adopt NEFs if they perceive the technology as both feasible and effective from an operational and economic standpoint. Although the R-squared value shows a strong model, the results still suggests that other unexamined factors could further explain the group membership.

5 Conclusion and Recommendations

The purpose of this research was to investigate the potential impact of ammonia engines and nano-electro fuel technologies on the sustainability and technological landscape of the automotive industry. The study aimed to understand assess the environmental benefits, adoption challenges, and overall market readiness for both technologies, supported by the Dynamic Capabilities framework.

The research question “*How the adoption of ammonia engines and nano-electro fuel technologies impact the sustainability and technological landscape of the automotive industry?*” analysis revealed that both ammonia engines and NEFs offer substantial environmental benefits, especially in reducing CO₂ emissions, making them promising alternatives to current technologies. The literature strongly supports the potential of these technologies for contributing to the industry’s sustainable goals, with studies for ammonia stating engines, for example, mentioning that it could greatly reduce the carbon footprint of vehicles, nearly eliminating CO₂ emissions (Kurien, C, & Mittal, M, 2022). NEFs, on the other hand, are a novel approach to fuel production that leverages on nano-catalysts, promising a greener future for the automotive world (Joy, N. et al., 2024; Ababneh, H., & Hameed, B, 2022). However, expert interviews and survey analysis indicated several barriers to their widespread adoption. Analysis revealed that the automotive industry is currently not ready for large scale integration of such technologies due to a combination of technical, economic, and infrastructural barriers. An expert stated “*For the automotive industry to implement ammonia engines would take a massive investment by both firms and governments to pursue ammonia-centric infrastructure. Sadly, with the intense focus on electric, there seems to be little appetite to free up money for other alternatives.*”, highlighting the considerable financial hurdles that need to be overcome, especially in an industry currently focusing on electric vehicles. As a result, the shift to these new technologies is currently hampered by the current infrastructure, not yet equipped to support new technologies, and economic models still geared towards supporting EV development. The Dynamic Capabilities framework applied in this study highlights how important it is for firms to sense, seize, and transform in response to technological opportunities. However, findings suggest that automotive firms will struggle to capitalize on these technologies due to their commitment to EVs. The current trajectory makes it challenging to shift focus towards alternative technologies like ammonia and NEFs.

- **Hypothesis 1: The adoption of ammonia engines will significantly reduce CO₂ and NO_x emissions in the automotive industry.**

The findings in the research strongly support H1. The literature emphasized that ammonia engines and NEFs offer clear environmental benefits, particularly in reducing CO₂ emissions. This was also supported by industry experts, who recognized both technologies as promising alternative to traditional fossil fuels and EVs, with one expert mentioning “*its potential to reduce CO₂ emissions almost entirely*”. However, the challenge of reducing NO_x emissions, which are a byproduct of ammonia combustion, is well-documented. This was also supported by the experts, who stressed that managing those emissions will require further research in combustion strategies. The survey also revealed a mixed perception between respondents, with many acknowledging the environmental benefits of both technologies, but expressing concerns on health and safety related to NO_x emissions. Overall, while ammonia and NEFs considerably reduce CO₂ emissions, NO_x remains a critical hurdle that must be addressed further.

- **Hypothesis 2: Regulatory pressures and environmental policies are significant drivers in the adoption of ammonia engines and NEFs in the automotive industry.**

Hypothesis 2 was also well supported by the study. Both the literature and expert interviews put forth the importance of regulatory pressure and environmental policies in driving adoption for both ammonia engines and nano-electro fuels. Experts all mentioned that current regulatory frameworks are pushing the automotive industry towards cleaner technologies. One expert stated that “*regulatory pressures are essential in motivating companies to invest in sustainable technologies like ammonia engines and NEFs*”. Survey data supported this, showing that many respondents view regulatory frameworks as critical to promote adoption of such technologies. The research demonstrated that if there are no external pressures, the industry will not prioritize development and adoption of new technologies, especially due to the existing focus on electric vehicles. Thus, regulatory pressure is crucial to overcome this.

- **Hypothesis 3: Initial high costs and technical challenges are the primary barriers to the widespread adoption of new technologies like ammonia engines and NEFs.**

The research strongly confirmed hypothesis 3. The study clearly identified that both ammonia engines and NEFs face barriers related to costs and technical challenges. The literature showed that the development of infrastructure, especially for ammonia, requires a substantial investment. This was also highlighted by the industry experts, where concerns

were raised about the economic feasibility, viability, and operational readiness for these technologies. One expert stated that *“The infrastructure costs and technical challenges are major deterrents to the adoption of ammonia engines”*. The survey results also aligned with these findings, with respondents identifying cost and technical barriers as the primary obstacle to adoption. The study showed that these challenges will not only require technological advancements, but also strategic investments to make them viable at scale.

- **Hypothesis 4: The ability of professionals to dynamically adapt to technological advancements like ammonia engines and NEFs is crucial to the successful integration and scalability of the related technologies.**

Hypothesis 4 was supported by the research. The Dynamic Capabilities framework was used to analyze how well a firm can respond to technological opportunities. The study suggested that while firms have shown some capacity to adapt, especially in the shift towards electric vehicles, there are still significant constraints when it comes to embracing new technologies simultaneously. One expert stated that *“the focus on electric vehicles may limit the resources and attention available for other technologies like ammonia engines and NEFs”*. The survey further showed that while there is interest in those technologies, actual integration is not currently taking place. The current commitments to EVs have absorbed all the resources, leaving little room for the development of alternatives. Thus, firms are not prepared to dynamically adapt and scale to these technologies, highlighting a significant gap between technological potential and market readiness.

5.1 Research Limitations and Future Research

This research put forth findings regarding the potential of ammonia engines and Nano-electro fuel technologies in the automotive industry, particularly regarding market readiness and environmental sustainability. That said, several limitations should be acknowledged, which present opportunities for future research.

Firstly, the sample size of the survey is a limitation. The study gathered data from 145 respondents, which is small for a study aimed at capturing an industry-wide perception of readiness. This sample size means that some of the analysis and findings could not be fully generalizable to the whole industry. In this case, a larger sample size would have improved the reliability of the findings and allowed for a more in-depth statistical analysis. Future research should take the time to gather data from a larger and more diverse sample to improve the validity of the results.

Secondly, the geographic and market focus of the study is a limitation. The research data was mostly gathered from Europe and European markets, focusing on Italy and Germany. Although they are both huge contributors to the automotive industry, these findings may not represent the full dynamic of the other key markets and firms. The limited scope means that the conclusion drawn may not be globally applicable. Future research should expand the geographic scope have a more diverse range of markets.

Thirdly, the research methodology presents some limitations regarding the survey sampling technique. The survey was focused on individuals already involved in the automotive industry (non-probability sampling) to gather insights from those directly involved in the automotive industry or knowledgeable about these technologies. While this approach was intentional and provided valuable insights, it may have introduced bias. This is because the sample might not represent the broader population, including consumers, policymakers, and other stakeholders involved who might influence the adoption of such technologies. Future research should aim to include a more diverse sample to offer a more comprehensive view of these technologies. This could offer deep insights into the potential barriers and drivers to adoption.

Finally, the reliance on the analysis method, logistic regression model, was a limiting factor. While it is a robust tool in identifying relationships between variables, the models in this study may not have fully captured the broader range of factors impacting market readiness and adoption. The complexity of this might require the incorporation of additional variables or alternative analytical approaches. Pushing the analysis to include more diverse predictors or methods, could provide a more nuanced understanding of the factors driving or hindering adoption of both technologies.

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7 Appendix

7.1 Appendix 1 – Interview Guide

Questions	Topic	Question	Follow-up Questions	Intent
1	Familiarity with Technologies	How familiar are you with the concepts of ammonia engines and nano-electro fuels (NEFs)?	What are your primary sources of information on these technologies?	Assess the participant's understanding of the focus technologies and their potential advantages/disadvantages for vehicles.
2	Strategic Integration	Describe your organization's approach to strategizing and integrating early-stage technologies. What processes or frameworks are utilized?	How does your organization assess the potential risks and rewards of investing in emerging technologies?	Understand how the participant's organization identifies, evaluates, and implements new technologies.
3	Environmental Regulations	Discuss how recent and forthcoming environmental regulations are shaping strategic decisions, especially concerning technologies like ammonia engines and NEFs.	How do these regulations impact your organization's long-term sustainability goals?	Explore how environmental regulations influence the organization's approach to emerging technologies.
4	Challenges in Adoption	What are the principal technical or market-related challenges in adopting these new technologies. How are these challenges being addressed?	Are there any regulatory or policy barriers hindering the adoption of these technologies?	Identify obstacles in adopting ammonia engines and NEFs, and how the organization is overcoming them.
5	Future of Emerging Technologies	From your perspective, how will the role of emerging technologies evolve in the automotive sector? What key factors will drive or impede their widespread adoption?	How do you envision the integration of these technologies with existing automotive infrastructure and systems?	Gain insights into the participant's view on the future of these technologies and factors influencing their adoption.
6	Interdisciplinary Collaboration	Could you elaborate on any current or necessary interdisciplinary collaborations that support the development and adoption of these innovative technologies?	Are there any challenges or opportunities in fostering effective collaboration between different departments or industries?	Understand the importance and type of collaborations facilitating the progress of these technologies.
7	Promoting Adoption	What specific actions or initiatives has your organization undertaken or planned to promote the adoption of ammonia engines and NEFs? Are there pivotal partnerships that facilitate these advancements?	How are you addressing consumer concerns or misconceptions about these technologies?	Identify the organization's efforts to advance ammonia engines and NEFs, and any key partnerships involved.
8	Additional Thoughts	Please share any additional thoughts or information that you		Capture any further insights the participant considers

7.1.1 Interview Coding: Ammonia



7.1.2 Interview Coding: NEF



7.2 Appendix 2 – Survey

Section	Question	Answering Options
Introduction Text	Dear participant, thank you for taking part in my survey. Your participation is crucial for my dissertation research at Catolica Lisbon. This study focuses on understanding public perception regarding innovative technologies in the automotive industry, specifically ammonia engines and nano-electro fuels (NEFs). Your feedback will help us explore how these technologies might transform the automotive sector towards greater sustainability. This survey is anonymous and confidential and will take approximately 7 minutes to complete. Your responses will solely be used for academic research purposes. By proceeding, you acknowledge that you are at least 18 years old and agree to participate in this survey. If you have any questions, please contact me at s-lcamerana@ucp.pt. Thank you for your valuable input. Lorenzo Camerana	
Screening Questions	1. Were you aware of the automotive industry's environmental impact before this survey?	Yes / No
	2. In your opinion, how significant is the impact of current automotive technologies on environmental sustainability?	Very significant / Significant / Neutral / Insignificant / Very insignificant
Awareness and Perception	3. Have you heard about ammonia and nano-electro fuels (NEFs) as emerging technologies in the automotive industry?	Yes, both / Only ammonia / Only NEFs / Neither
	4. How would you rate your understanding of ammonia and its potential benefits for the automotive industry?	Very knowledgeable / Somewhat knowledgeable / Neutral / Somewhat unfamiliar / Very unfamiliar
	5. How would you rate your understanding of nano-electro fuels (NEFs) and their potential benefits for the automotive industry?	Very knowledgeable / Somewhat knowledgeable / Neutral / Somewhat unfamiliar / Very unfamiliar
Impact on Technology and Sustainability	6. How effective do you believe ammonia engines are in reducing the	Not effective at all / Slightly effective / Moderately

	environmental impact of the automotive sector?	effective / Very effective / Extremely effective
	7. Rate the following statements regarding your perceived importance of the benefits of adopting ammonia engines in the automotive industry.	Emissions Reduction / Fuel Efficiency / Long-term Sustainability / Cost Savings / Innovation and Technological Advancement / Safety and Public Health
	8. How effective do you believe nano-electro fuels (NEFs) are in reducing the environmental impact of the automotive sector?	Not effective at all / Slightly effective / Moderately effective / Very effective / Extremely effective
	9. Rate the following statements regarding your perceived importance of the benefits of adopting nano-electro fuels (NEFs) in the automotive industry.	Emissions Reduction / Fuel Efficiency / Long-term Sustainability / Cost Savings / Innovation and Technological Advancement / Safety and Public Health
Transition Challenges and Opportunities	10. What do you believe is the biggest challenge in integrating ammonia engines and NEFs into the automotive industry?	Technical challenges / Economic costs / Regulatory and compliance issues / Public acceptance and awareness / Other (please specify)
	11. Rank the following factors based on their importance for overcoming challenges in integrating ammonia engines and NEFs into the automotive industry:	Government policies and incentives / Public education and awareness campaigns / Technological advancements and research / Industry collaboration and partnerships / Increased investment in infrastructure development / Encouraging private sector investment and innovation
	12. Please read the following statement and indicate your level of agreement: "I have safety and reliability concerns regarding the use of ammonia engines in vehicles."	Strongly disagree / Somewhat disagree / Neither agree nor disagree / Somewhat agree / Strongly agree
	13. Please read the following statement and indicate your level of agreement: "I have safety and reliability concerns regarding the use of nano-electro fuels (NEFs) in vehicles."	Strongly disagree / Somewhat disagree / Neither agree nor disagree / Somewhat agree / Strongly agree
Future Outlook	14. Are you optimistic about the role of emerging technologies (ammonia engines and NEFs) in transforming the automotive industry towards sustainability?	Yes / No

	15. What do you believe is the most important factor for the successful integration of these technologies into the mainstream automotive sector?	Consumer acceptance / Cost-effectiveness / Technological reliability / Environmental impact / Other (please specify)
	16. Reflecting on the information provided and your responses, how likely are you to advocate for the broader adoption of ammonia engines and NEFs based on their potential environmental and technological benefits?	Very unlikely / Somewhat unlikely / Neutral / Somewhat likely / Very likely
Demographics	17. What is your age group?	Under 18 / 18 - 24 / 25-34 / 35-44 / 45-54 / 55-64 / 65 or older
	18. What is your gender?	Male / Female / Other / Prefer not to say
	19. What describes best your current occupation?	Student / Professional (specify the industry if applicable) / Unemployed / Retired / Other (please specify)
	20. What is your highest level of education?	Less than high school diploma / High school diploma or equivalent / Trade, technical, or vocational training / Bachelor's degree / Master's degree / Doctorate degree / Prefer not to say
	21. What is your nationality?	[Text Entry]
	22. How would you describe your level of involvement in the automotive industry?	Highly involved / Somewhat involved / Not involved

7.3 Appendix 3 – Quantitative Analysis

7.3.1 Output 1 – Factor Analysis Ammonia

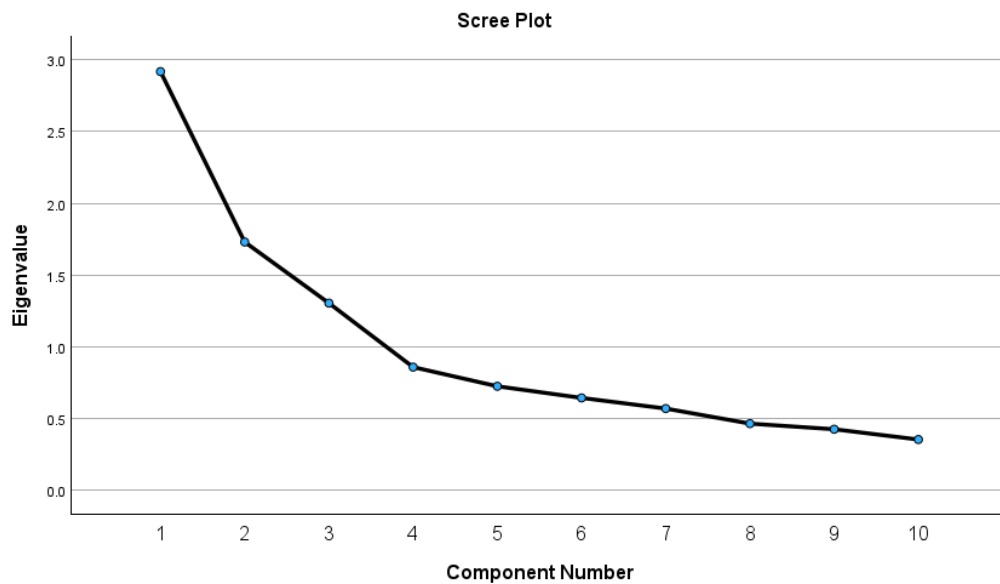
KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		722
Bartlett's Test of Sphericity	Approx. Chi-Square	313.642
	df	45
	Sig.	<.001

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.919	29.187	29.187	2.919	29.187	29.187	2.235	22.352	22.352
2	1.731	17.311	46.497	1.731	17.311	46.497	1.694	16.935	39.287
3	1.305	13.051	59.548	1.305	13.051	59.548	1.497	14.972	54.259
4	.859	8.591	68.139	.859	8.591	68.139	1.151	11.507	65.766
5	.726	7.255	75.394	.726	7.255	75.394	.963	9.628	75.394
6	.644	6.445	81.839						
7	.570	5.702	87.542						
8	.465	4.653	92.194						
9	.426	4.261	96.455						
10	.354	3.545	100.000						

Extraction Method: Principal Component Analysis.



7.3.2 Output 2 – Cluster Analysis Ammonia

Final Cluster Centers

	Cluster		
	1	2	3
REGR factor score 1 for analysis 6	-.16931	-.64941	1.10346
REGR factor score 2 for analysis 6	-.18604	-.41802	.87347
REGR factor score 3 for analysis 6	-.81774	1.10197	.46766
REGR factor score 4 for analysis 6	-.18382	.12261	.24862
REGR factor score 5 for analysis 6	-.00568	.29044	-.32112

ANOVA

	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
REGR factor score 1 for analysis 6	29.955	2	.592	142	50.585	<.001
REGR factor score 2 for analysis 6	17.624	2	.766	142	23.011	<.001
REGR factor score 3 for analysis 6	51.471	2	.289	142	178.012	<.001
REGR factor score 4 for analysis 6	2.560	2	.978	142	2.618	.076
REGR factor score 5 for analysis 6	3.399	2	.966	142	3.518	.032

The F tests should be used only for descriptive purposes because the clusters have been chosen to maximize the differences among cases in different clusters. The observed significance levels are not corrected for this and thus cannot be interpreted as tests of the hypothesis that the cluster means are equal.

Number of Cases in each Cluster

Cluster	1	72.000
	2	39.000
	3	34.000
Valid		145.000
Missing		.000

7.3.3 Output 3 - Binary Logistic Regression Ammonia

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	56.206	1	<.001
	Block	56.206	1	<.001
	Model	56.206	1	<.001
Step 2	Step	59.937	1	<.001
	Block	116.144	2	<.001
	Model	116.144	2	<.001
Step 3	Step	28.072	1	<.001
	Block	144.216	3	<.001
	Model	144.216	3	<.001
Step 4	Step	6.390	1	.011
	Block	150.606	4	<.001
	Model	150.606	4	<.001

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	101.738 ^a	.321	.484
2	41.801 ^b	.551	.831
3	13.729 ^c	.630	.950
4	7.339 ^d	.646	.974

- a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.
- b. Estimation terminated at iteration number 8 because parameter estimates changed by less than .001.
- c. Estimation terminated at iteration number 12 because parameter estimates changed by less than .001.
- d. Estimation terminated at iteration number 14 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	9.904	8	.272
2	.524	8	1.000
3	.067	8	1.000
4	.000	8	1.000

Classification Table^a

	Observed	Predicted		Percentage Correct	
		.00	1.00		
Step 1	TGA	.00	103	8	92.8
		1.00	14	20	58.8
	Overall Percentage				84.8
Step 2	TGA	.00	108	3	97.3
		1.00	5	29	85.3
	Overall Percentage				94.5
Step 3	TGA	.00	109	2	98.2
		1.00	2	32	94.1
	Overall Percentage				97.2
Step 4	TGA	.00	110	1	99.1
		1.00	1	33	97.1
	Overall Percentage				98.6

a. The cut value is .500

7.3.4 Output 4 - Factor Analysis NEF

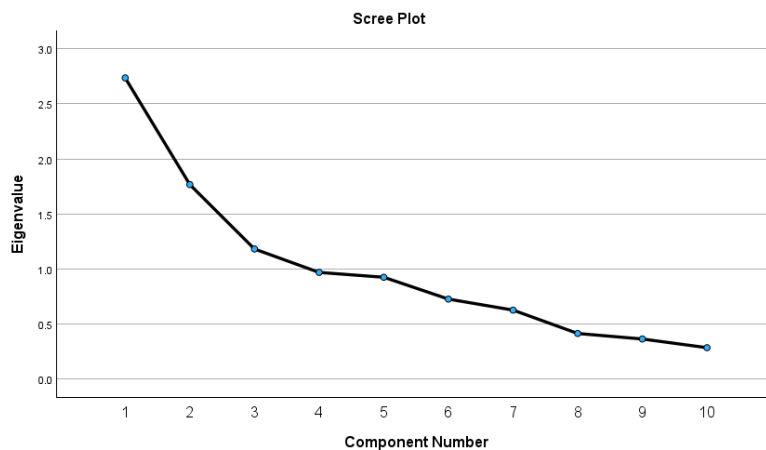
KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.656
Bartlett's Test of Sphericity	Approx. Chi-Square	320.499
	df	45
	Sig.	<.001

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.736	27.362	27.362	2.736	27.362	27.362	2.103	21.027	21.027
2	1.767	17.673	45.035	1.767	17.673	45.035	1.767	17.667	38.694
3	1.182	11.821	56.856	1.182	11.821	56.856	1.592	15.923	54.617
4	.969	9.694	66.550	.969	9.694	66.550	1.084	10.842	65.459
5	.926	9.255	75.805	.926	9.255	75.805	1.035	10.346	75.805
6	.727	7.272	83.078						
7	.627	6.272	89.349						
8	.415	4.148	93.497						
9	.365	3.646	97.143						
10	.286	2.857	100.000						

Extraction Method: Principal Component Analysis.



7.3.5 Output 5 – Cluster Analysis NEF

Final Cluster Centers

	Cluster		
	1	2	3
REGR factor score 1 for analysis 6	-.50531	1.62547	-.36382
REGR factor score 2 for analysis 6	.47712	.03778	-.61234
REGR factor score 3 for analysis 6	.31520	.20811	-.51587
REGR factor score 4 for analysis 6	-.37637	.27997	.29475
REGR factor score 5 for analysis 6	-.35174	-.17853	.54302

Distances between Final Cluster Centers

Cluster	1	2	3
1		2.282	1.774
2	2.282		2.329
3	1.774	2.329	

ANOVA

	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
REGR factor score 1 for analysis 6	52.372	2	.276	142	189.445	<.001
REGR factor score 2 for analysis 6	16.754	2	.778	142	21.532	<.001
REGR factor score 3 for analysis 6	10.587	2	.865	142	12.240	<.001
REGR factor score 4 for analysis 6	7.892	2	.903	142	8.741	<.001
REGR factor score 5 for analysis 6	11.911	2	.846	142	14.073	<.001

The F tests should be used only for descriptive purposes because the clusters have been chosen to maximize the differences among cases in different clusters. The observed significance levels are not corrected for this and thus cannot be interpreted as tests of the hypothesis that the cluster means are equal.

Number of Cases in each Cluster

Cluster	1	63.000
	2	31.000
	3	51.000
Valid		145.000
Missing		.000

7.3.6 Output 6 – Binary Logistic Regression NEF

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	32.888	1	<.001
	Block	32.888	1	<.001
	Model	32.888	1	<.001
Step 2	Step	35.869	1	<.001
	Block	68.757	2	<.001
	Model	68.757	2	<.001
Step 3	Step	28.440	1	<.001
	Block	97.197	3	<.001
	Model	97.197	3	<.001
Step 4	Step	34.322	1	<.001
	Block	131.519	4	<.001
	Model	131.519	4	<.001
Step 5	Step	42.474	1	<.001
	Block	173.992	5	<.001
	Model	173.992	5	<.001

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	165.627 ^a	.203	.272
2	129.759 ^a	.378	.506
3	101.319 ^b	.488	.655
4	66.997 ^c	.596	.800
5	24.523 ^d	.699	.937

- a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.
- b. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.
- c. Estimation terminated at iteration number 7 because parameter estimates changed by less than .001.
- d. Estimation terminated at iteration number 10 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	14.048	8	.081
2	19.807	8	.011
3	4.854	8	.773
4	16.792	8	.032
5	1.022	8	.998

Variables in the Equation

			B	S.E.	Wald	df	Sig.	Exp(B)
Step 1 ^a	REGR factor score 1 for analysis 6		1.192	.252	22.371	1	<.001	3.293
	Constant		.412	.199	4.310	1	.038	1.511
Step 2 ^b	REGR factor score 1 for analysis 6		1.457	.295	24.408	1	<.001	4.294
	REGR factor score 2 for analysis 6		-1.417	.302	21.966	1	<.001	.242
	Constant		.622	.243	6.541	1	.011	1.862
Step 3 ^c	REGR factor score 1 for analysis 6		2.169	.461	22.117	1	<.001	8.753
	REGR factor score 2 for analysis 6		-1.610	.329	23.925	1	<.001	.200
	REGR factor score 4 for analysis 6		1.526	.358	18.172	1	<.001	4.601
	Constant		.940	.315	8.900	1	.003	2.560
Step 4 ^d	REGR factor score 1 for analysis 6		3.302	.732	20.364	1	<.001	27.176
	REGR factor score 2 for analysis 6		-2.547	.555	21.060	1	<.001	.078
	REGR factor score 4 for analysis 6		2.384	.553	18.581	1	<.001	10.850
	REGR factor score 5 for analysis 6		2.075	.484	18.414	1	<.001	7.968
	Constant		1.133	.394	8.269	1	.004	3.104
Step 5 ^e	REGR factor score 1 for analysis 6		11.754	3.823	9.452	1	.002	127301.817
	REGR factor score 2 for analysis 6		-7.180	2.262	10.075	1	.002	.001
	REGR factor score 3 for analysis 6		-5.773	1.857	9.664	1	.002	.003
	REGR factor score 4 for analysis 6		5.568	1.791	9.665	1	.002	261.892
	REGR factor score 5 for analysis 6		5.328	1.692	9.921	1	.002	206.094
	Constant		3.735	1.222	9.334	1	.002	41.885

- a. Variable(s) entered on step 1: REGR factor score 1 for analysis 6.
- b. Variable(s) entered on step 2: REGR factor score 2 for analysis 6.
- c. Variable(s) entered on step 3: REGR factor score 4 for analysis 6.
- d. Variable(s) entered on step 4: REGR factor score 5 for analysis 6.
- e. Variable(s) entered on step 5: REGR factor score 3 for analysis 6.