Rodzaj dyplomu / Diploma type	Rozprawa doktorska / PhD thesis
Autor / Author	Brusiło Paweł
Tytuł / Title	/ Green industrial policy for the establishment and development of the fuel cell electric vehicle market in the US state of California from the perspective of the economics of sustainable development
Rok powstania / Year of creation	2023
Promotor / Supervisor	Drelich-Skulska Bogusława, Jankowiak Anna H.
Jednostka dyplomująca / Certifying unit	Uniwersytet Ekonomiczny we Wrocławiu / Wroclaw University of Economics and Business
Adres publikacji w Repozytorium URL / Publication address in Repository	https://wir.ue.wroc.pl/info/phd/UEWRa5cfe3b243de4488a10fbdc2113932e0/
Data opublikowania w Repozytorium / Deposited in Repository on	25 mar 2024
Rodzaj licencji / Type of licence	Attribution - NonCommercial-ShareAlike CC BY-NC-SA

UNIWERSYTET EKONOMICZNY WE WROCŁAWIU

mgr Paweł Brusiło

ZIELONA POLITYKA PRZEMYSŁOWA NA RZECZ POWSTANIA I ROZWOJU RYNKU POJAZDÓW ZASILANYCH WODOROWYMI OGNIWAMI PALIWOWYMI W AMERYKAŃSKIM STANIE KALIFORNIA Z PERSPEKTYWY EKONOMII ZRÓWNOWAŻONEGO ROZWOJU

Rozprawa doktorska w dyscyplinie Ekonomii i Finansów

napisana pod kierunkiem
prof. dr hab. Bogusławy Drelich-Skulskiej

Promotor pomocniczy:
dr Anna H. Jankowiak, prof. UEW

Katedra Międzynarodowych Stosunków Gospodarczych

we współpracy badawczej z
prof. Davidem G. Victorem
dr Ryanem Hanna
Uniwersytet Kalifornijski w San Diego, USA

Wrocław 2023

I egz.

WROCLAW UNIVERSITY OF ECONOMICS AND BUSINESS

mgr Paweł Brusiło

GREEN INDUSTRIAL POLICY FOR THE ESTABLISHMENT AND DEVELOPMENT OF THE FUEL CELL ELECTRIC VEHICLE MARKET IN THE US STATE OF CALIFORNIA FROM THE PERSPECTIVE OF THE ECONOMICS OF SUSTAINABLE DEVELOPMENT

Doctoral thesis in Economics and Finance

written under the supervision of
prof. dr hab. Bogusława Drelich-Skulska

Assistant supervisor:
dr Anna H. Jankowiak, prof. UEW

Department of International Business

in research cooperation with
Prof. David G. Victor
Dr. Ryan Hanna

University of California San Diego, USA

Wrocław 2023

1st copy

I dedicate this dissertation to my wife, Agata, and my parents, Wanda and Roman Brusiło,
who are my constant source of motivation and inspiration.

***

I am profoundly grateful to Prof. Bogusława Drelich-Skulska,
whose valuable and kind supervision made the preparation of this dissertation possible.
I also thank Dr. Anna H. Jankowiak for her comments on the concept of this dissertation.

***

I am thankful to Prof. David G. Victor and Dr. Ryan Hanna,
whose guidance broadened my horizons and allowed me to conduct empirical research
in California, which significantly contributed to developing this dissertation.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AB	Assembly Bill
BEV	Battery Electric Vehicles
CA	California
CARB	California Air Resources Board
CAWI	Computer-Assisted Web Interview
CEC	California Energy Commission
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CTE	Center for the Transportation and the Environment
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EC	European Commission
EO	Executive Order
EPI	Environmental Performance Index
ESD	Economics of Sustainable Development
EU	European Union
FCEB	Fuel Cell Electric Bus
FCET	Fuel Cell Electric Truck
FCEV	Fuel Cell Electric Vehicles
GHG	Green House Gases
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
IAE	International Energy Agency
ICEV	Internal-Combustion Engine Vehicle
IPCC	Intergovernmental Panel on Climate Change
IRB	Institutional Review Board
IRENA	International Renewable Energy Agency
ISEW	Index of Sustainable Economic Welfare
ISIC	International Standard Industrial Classification of All Economic Activities
KW	Kilowatt
NNWI	New National Welfare Index
OECD	Organisation for Economic Co-operation and Development
PHEV	Plug-in Hybrid Electric Vehicles
RES	Renewable energy sources
RO	Research Objective
RQ	Research question
SB	Senate Bill
SDG	Sustainable Development Goals
SMR	Steam Methane Reforming
TCO	The Total Cost of Ownership
TRL	Technology Readiness Level
UCSD	University of California San Diego
UN	United Nations
US	United States
USA	United States of America
WCED	The UN World Commission on Environment and Development
WEC	World Energy Council
ZEV	Zero-emission Vehicles

INTRODUCTION

Climate change mitigation and the pursuit of sustainable development are associated with numerous socio-economic transformations, including a multidimensional energy transition characterized by diverse shifts in primary and secondary energy source consumption and final energy use. The energy transition can also be perceived as a shift in the industrial structure since it describes quantitative and qualitative alterations in how energy is sourced, processed, and utilized across individual sectors and entire economies to increase energy efficiency and meet climate and sustainable development objectives. Thereby, as a shift in industrial and socio-economic structure, the energy transition can also be a subject of industrial policy impact. Noteworthy, industrial policy, as a concept, is not monolithic but instead can be seen as a complex tool, with its nuances shaped by the socio-economic milieu and developmental context of the country in which it is applied. At its core, industrial policy is fundamentally about the state interventions employed to spur productivity and enhance the competitiveness of its economy and industries, especially the industrial sector. A.A. Ambroziak's comprehensive review underscores the malleability of industrial policy, highlighting that its objectives, scope, instruments, anticipated outcomes, and even implications can vary widely. A particularly pertinent observation is the role played by the country's developmental stage in influencing the design and implementation of its industrial policy (Ambroziak, 2017, p. 3). This suggests that while the overarching objective of industrial policy might be to boost productivity and competitiveness, the specifics of *how* this is achieved might differ between a developing economy and a developed one. Furthermore, in the opinion of the author of this dissertation, the contemporary deliberations about the assumptions and objectives of industrial policy implemented in individual economies ought to consider the sustainable development perspective. Adding this perspective to industrial policymaking seems fundamental during the global energy transition enforced by climate change mitigation efforts and sustainable development facilitation.

In this context, the newly established theory of the economics of sustainable development, as a consequent evolution of neoclassical and environmental economics, can provide a set of normative postulates that can contribute to deliberations about a more environment-oriented industrial policymaking for individual jurisdictions that individually or collectively set its objectives. As B. Poskrobko advocates, the subject of this theory (funded by accomplishments of research on the concept of sustainable development and a postulate of strong sustainability) is the *economics of the society-economy-environment macro-system*

(2012, p. 20). Its primary postulated paradigm is that *sustainability is a broadly understood balance of social, economic, and environmental development* (2012, p. 24). The conceptualization of this theory can also be attributed to H. Rogall, who aimed to establish the main postulates of the economics of sustainable development (2010), which were further developed and discussed, among others, by E. Lorek (2011), K. Midor (2012), S. Czaja (2012), or D. Kiełczewski (2012). It can be stated that based on the pluralist and interdisciplinary approach, the economics of sustainable development normative postulates can change socio-economic conditions using various instruments to develop a sustainable socio-culturally and environmentally oriented market or mixed economy and promote a global responsibility simultaneously. Furthermore, among its normative postulates, it is worth noting the required revision of the *homo oeconomicus* model (and replacing it with the *homo sustinens* model), further operationalization of the concept of *sustainability*, and development of new policy instruments and development strategies.

In the theoretical dimension, this dissertation delves into the normative postulates of the economics of sustainable development and industrial policymaking. Noteworthy is that the author focuses on the existing green industrial policy concept and its framework conditions, which have already incorporated environmental considerations into industrial policymaking to some extent. Hallegatte et al. (2013) described green industrial policy as a specific industry sector-targeted policy that affects the economic production structure to generate environmental benefits. The green industrial policy also refers to any attempt in state intervention to hasten the development of low-carbon alternatives to fossil fuels, thereby guiding the shift in the structure of individual industries of entire economies (Karp & Stevenson, 2012). Furthermore, it can be stated that green industrial policy is designed to stimulate and facilitate the development of environmental technologies using various investments, market-based incentives, regulations, and other policy instruments, such as carbon pricing (Allan et al., 2021, p. 3; Tagliapietra & Veugelers, 2020). Therefore, in this dissertation, the author focuses on developing the concept of green industrial policy based on the normative postulates of the economics of sustainable development.

In pursuing empirical evidence of adopting a green industrial policy approach in state interventions, this dissertation examines one of the multifaceted trajectories of the energy transition. As the green industrial policy incorporates environmental considerations, it has the potential to steer the energy transition towards reduced CO_2 emissions, particularly in sectors like transportation and energy generation. With an increasing number of states prioritizing climate change mitigation and sustainable development facilitation globally, the urgency of transitioning the transportation sector towards low-carbon energy carriers, such as *clean* hydrogen (i.e., produced in low-carbon water splitting electrolysis powered with electricity sourced from renewable energy sources) becomes apparent (Hydrogen Council, 2021; IRENA, 2020). Such a transition requires adjustments in industrial policy frameworks as states work to lay the foundation for a *hydrogen economy* encompassing hydrogen production, storage, distribution, and end-use applications, including powering fuel cell electric vehicles (FCEV).

Simultaneously, the drive for transportation sector decarbonization, supported by a green industrial policy approach, has accelerated innovation in the automotive sector worldwide, resulting in an array of zero- or low-emission vehicles like Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and already mentioned hydrogen-powered FCEVs. Since each of these construction types differs significantly (given their diverse features and operational functionality) and, to some extent, represents competitive markets, it is crucial to consider each type of vehicle individually. Undoubtedly, both PHEVs and BEVs dominate the global market of electric vehicles (IEA, 2023a), so this dissertation focuses on FCEVs, which still represent a *niche* market globally. However, at the same time, they can be recognized as a considerable alternative to conventional Internal Combustion Engine Vehicles (ICEVs) by offering significant potential in transportation sector decarbonization (Saritas et al., 2019) and convincing the potential end-users by factors such as more extended vehicle range, shorter refueling time, comparatively lower to ICEVs and BEVs maintenance costs, and higher energy efficiency as compared to the other ZEV alternatives (Bae et al., 2022; Li et al., 2022; Lopez Jaramillo et al., 2019).

Individual countries and international organizations have already applied diverse green industrial policy instruments and introduced more or less effective strategies to establish and develop FCEV markets (WEC, 2021). Examples of such an approach are demonstrated in the *US National Clean Hydrogen Strategy and Roadmap* (US DOE, 2023), in the *European Green Deal* – precisely, the *EU hydrogen strategy* (European Commission, 2019; 2020), and in strategies at the national level, i.e., in Poland (Polish Ministry of Climate and Environment, 2021). According to Sharifi et al. (2022), most of the studied national hydrogen economy strategies primarily focus on scaling up the hydrogen value chains with further focus on the carbon intensity – following the pattern synthesized as *scale first and clean later*.

In this context, the US state of California represents a more environmentally oriented and sustainable approach, where the increase in *clean* hydrogen utilization as a fuel primarily serves to decarbonize the transportation sector. Based on the *Federal Clean Air Act of 1967*, California was granted a unique federal exemption to enforce its independent vehicle emissions standards, which were much more rigorous than those of other US states. This broad independence from the federal government within the studied domain made California continue in-depth and globally recognized leading efforts to decrease air pollution from the transportation sector, with numerous pioneering green industrial policy instruments that allowed the establishment and development of the low-emission vehicle (LEV) market at first, leading to further development of ZEV markets, including FCEVs.

In 1990, the state of California introduced the *ZEV Regulation*, which was designed to achieve the state's long-term emission reduction objectives by gradually increasing the stringency of ZEV sales and associated actions to support the wide-scale adoption and use of ZEVs in this state. Since then, California has displayed diverse strategies (Brown et al., 2012; Schoenung & Keller, 2017) and implemented various green industrial policy instruments to establish and develop the FCEV market as part of the decarbonization of the state transportation sector and a long-standing history of mitigating climate change and environmental protection. It resulted in a gradually growing FCEV market in light-duty passenger vehicles, fuel cell electric buses (FCEB), and medium- and heavy-duty fuel cell electric truck (FCET) segments. This expansion has coincided with the development of publicly accessible hydrogen refueling infrastructure and increased *clean* hydrogen production, transportation, and storage, making California one of the global leaders in pursuing the FCEV market growth (Forrest et al., 2020a; Turoń, 2020).

However, establishing and developing the FCEV market across all three segments presents a challenge for other, less prosperous US states and many countries, including Poland. Therefore, from the empirical dimension standpoint, it is crucial to determine which green industrial policy instruments were the most effective in establishing and developing the niche FCEV market based on the experience of jurisdictions like the US state of California. It can be assumed that, unlike California, other jurisdictions may possess more limited resources dedicated to the growth of the FCEV market. Furthermore, the supply of clean hydrogen in individual follower jurisdictions could be significantly lower. As a result, the judicious allocation of clean hydrogen would be imperative for the most cost-effective decisions across individual FCEV market segments and throughout the entire energy-intensive industries.

Moreover, in the follower jurisdictions with a substantially lower GDP *per capita*, light-duty passenger FCEVs might be likely less accessible than they are in California. It can underscore the increased importance of FCEB and FCET segments for the overall market expansion and, more broadly, for the decarbonization of the transportation sector. Following these exemplary conceptual distinctions, follower jurisdictions should draw insights from California's long-standing experiences and failures. Therefore, this dissertation aims to provide evidence-based observations from the state of California for the potential follower jurisdictions, becoming a foundation for future in-depth analysis, considering likely different policy objectives and FCEV market development determinants.

Research problem and the scope of the research

Based on the abovementioned synthesis of the initial deliberations, the author developed the cognitive research problem, which can be formulated as a synthesized question - **How did selected green industrial policy instruments impact the establishment and development of the FCEV market in the US state of California from the perspective of the economics of sustainable development?**

Therefore, to solve this research problem, this dissertation has a theoretical and empirical dimension – the theoretical dimension studies the relevance between the green industrial policy framework and the normative postulates of the economics of sustainable development. The empirical dimension investigates the impact of green industrial policy instruments on establishing and developing the FCEV market. The spatial (geographical) scope covers the US state of California. The time scope covers the period from 1990 until 2022. Lastly, the scope of the research in the context of research subjects includes two groups of California's FCEV market participants and four groups of market stakeholders. The structure of the research subjects includes the FCEV market participants on the supply and demand side, as well as the market stakeholders representing the academia, industrial organizations and associations, hydrogen suppliers, and, lastly, the state and federal governments that implement diverse industrial policy instruments. The complete list of 46 research subjects, therefore serving as the research participants, is demonstrated in Table 10 (p. 161).

The research objectives and research questions

The primary research objective of this dissertation is **to evaluate the impact of selected green industrial policy instruments on establishing and developing the FCEV market in the US state of California from 1990 to 2022 from the perspective of economics of sustainable development.** Achieving the dissertation's primary objective required the completion of four detailed research objectives (RO) that are presented and discussed in the four subsequent chapters of this dissertation, thereby reflecting its structure. Hence, this dissertation was developed to:

RO 1. determine the relevance between the green industrial policy assumptions and the normative postulates of the economics of sustainable development;

RO 2. determine the significance of FCEV market growth for the hydrogen economy development from the perspective of the normative postulates of the economics of sustainable development;

RO 3. identify the green industrial policy instruments aimed at the establishment and development of the FCEV market in the US state of California from 1990 to 2022;

RO 4. evaluate the impact of selected green industrial policy instruments on establishing and developing the FCEV market in the US state of California from 1990 to 2022.

As part of conceptual deliberations about this research problem, the author developed a set of research questions corresponding to individual research objectives (marked in the brackets).

RQ 1. What are the origins, problem domains, and normative postulates of the economics of sustainable development? **(RO1)**

RQ 2. How can industrial policy be implemented considering the normative postulates of the economics of sustainable development? **(RO1)**

RQ 3. How does the FCEV market's establishment and development contribute to developing a hydrogen economy? **(RO2)**

RQ 4. How does establishing and developing the FCEV market fit into the normative postulates of the economics of sustainable development? **(RO2)**

RQ 5. What green industrial policy instruments were implemented at the state and federal levels to establish and develop California's FCEV market between 1990 and 2022? **(RO3)**

RQ 6. How did the structure of the FCEV market in the state of California evolve between 1990 and 2022? **(RO3)**

RQ 7. What stakeholders contributed to the establishment and development of the FCEV market in the state of California between 1990 and 2022? **(RO3)**

RQ 8. Why has the state of California been supporting FCEV market establishment and development, even though the other zero-emission vehicles (ZEV), such as BEVs, have seen higher deployment numbers? **(RO4)**

RQ 9. Which selected green industrial policy instruments were the most effective in establishing and developing the FCEVs market in the state of California between 1990 and 2022? **(RO4)**

RQ 10. Looking back in the past on the design and implementation of the selected green industrial policy instruments, what could have been done differently to accelerate the establishment and development of the FCEV market in California? **(RO4)**

RQ 11. Should there be any future corrections in the assumptions, objectives, and design of the selected green industrial policy instruments implemented in the state of California for the further development of the FCEV market? **(RO4)**

RQ 12. What less-prosperous jurisdictions can learn from the experience of the state of California in establishing and developing the FCEV market? **(RO4)**

According to the authors' knowledge from the literature review, an impact evaluation of California's green industrial policy for the FCEV market establishment and development has not been made yet. While a case study focused on California's FCEV market development barriers was done with semi-structured interviews (Trencher, 2020), this dissertation covers a more extended period and a different scope. In undertaking this, the author focused mainly on the impact of introduced green industrial policy instruments on the state level (considering the existence of a federal legislative framework that granted California extensive independence to impose its own stricter vehicle emission standards) in achieving four strategic policy objectives – (1) sustainable and low-cost supply of hydrogen fuel, (2) developing accessible and reliable refueling infrastructure, (3) increasing market supply for FCEVs, and lastly (4) increasing market demand for FCEVs. The author designed and conducted this study based on the need to build on previous research results that partially correspond to the individual research questions. It is worth emphasizing that these previous results generated many unanswered questions, such as: *Which policy instruments were the most effective in establishing and developing the FCEV market in this state?* or *What could have been done differently in the past or should be done differently in the future to accelerate the development* *of this market?* These exemplary two questions (developed based on the literature review) provide the space for conceptual considerations thanks to the retrospective or prospective approach, respectively. Answering these two questions can provide advanced and detailed observations worth applying in California and beyond, considering local or national FCEV market determinants and policy framework conditions. Furthermore, addressing the primary research problem, particularly in 2023, represents the need to update concepts in light of new findings, the new technical advancements (especially within the FCEB and FCET market segments), and, more importantly, post-COVID-19 situation that enforced adoption of sophisticated economic recovery agenda (a result of which is, i.e., the US Federal Inflation Reduction Act). Therefore, undertaking this research is crucial to fill the empirical research gap associated with the abovementioned theoretical considerations.

Research methods

The author implemented a mixed-method approach to achieve the primary and detailed research objectives and answer detailed research questions. The selected quantitative and qualitative research methods complemented each other to ensure an in-depth exploration and analysis of the research problem. The first research method was a **method of analysis and logical construction**, where the author, using a *reductionist approach,* isolated the critical components of the research problem and subjected them to analysis in the subsequent chapters and subchapters. Given the theoretical and empirical background of the research, it was essential to use this *reductionist approach* to assess the impact of selected green industrial policy instruments in establishing and developing the FCEV market from the perspective of the normative postulates of the economics of sustainable development. Then, having reviewed the results obtained, the author synthesized them using a *holistic approach* to develop an answer to the research problem posed. This process was associated with several research methods that included a **review and critical evaluation of the literature** on the theoretical relevance between the green industrial policy assumptions and the normative postulates of the economics of sustainable development. It helped the author detect and present the cognitive research gap and demonstrate a comprehensive portrayal of the current state of research in the studied domain. This particular method was also applied to determine the state-of-the-art of empirical research considering the impact evaluation of the green industrial policy instruments on the FCEV market establishment and development.

Furthermore, using a **case study method**, the author assessed the changes in the structure of the FCEV market and determinants shaping its evolution in a studied period based on a variety of secondary data sourced from literature, market indicators, industrial reports, and policy statements, broadened with the expert perspectives of market participants and stakeholders. This process was supported by the **comparative method**, which allowed the structured analysis and comparison of the assumptions, objectives, and design of selected green industrial policy instruments for establishing and developing California's FCEV market. In addition, the author used a **method for establishing cause-and-effect relationships**, which helped to determine the relationship between the implementation of selected green industrial policy instruments and the establishment and development of the studied market.

Noteworthy is that the core research method deployed in the empirical study was a **diagnostic survey method** employed using two complementary research techniques – individual structured interviews and survey questionnaires (structured with specific ranking questions). The diagnostic survey method was used to assess the impact of selected green industrial policy instruments on establishing and developing the FCEV market in the US state of California between 1990 and 2022. The author conducted 46 individual structured interviews and surveys using the Computer-Assisted Web Interview (CAWI) mode on the Zoom platform. Afterward, the recorded content was rigorously transcribed and analyzed using the NVivo software (version 13.3). Research participants were carefully chosen through a purposive selection (otherwise known as arbitrary selection), which was essentially a non-random sampling based on subjective choices, ensuring a nearly representative sample of California's FCEV market participants and stakeholders. The purposive selection was grounded in an extensive review of literature, legislation, and industry-related publications and reports, targeting entities from each of the six groups of California's FCEV market participants and stakeholders. These groups included the FCEV market participants on the supply and demand side and the market stakeholders representing academia, industrial organizations and associations, hydrogen suppliers, and, lastly, the state and federal governments. The inclusion criteria included holding direct professional affiliation with these market participants and stakeholders, performing a senior management function pertinent to the research problem, and offering voluntary, informed consent to contribute. In addressing ethical considerations and data management, the author received approval from the University of California, San Diego Institutional Review Board, where the study was registered and affiliated.

The author broadened the case study and diagnostic survey methods by deploying a **statistical method**, which allowed for analyzing the quantitative primary data generated from the survey and describing phenomena and processes related to the research problem. It was imperative regarding the assessment, i.e., the distribution of the answers from identified groups of the FCEV market participants and stakeholders to formulate the conclusions based on the variability of the data in terms of the effectiveness of individual green industrial policy instruments in achieving four strategic policy objectives and overall FCEV market establishment and development.

In preparing the dissertation, the author used theoretical knowledge in the field of economics and independently conducted research and analytical work to draw conclusions from the research. The author declares that he has familiarized himself with the Law of September 27, 2017, on *Scientific Degrees and Academic Titles and Degrees and Titles in Art* to ensure that this dissertation meets the conditions outlined in Article 13. of the same Law.

Research procedure

The dissertation's research procedure is delineated into four distinct stages, as depicted in Figure 1. The initial stage involved an extensive exploration of the research field, primarily through a preliminary literature review. The author focused on the leading fields in contemporary academic discourse, especially in energy transition and structural change associated with this multidimensional process. In this field, theoretical and empirical considerations emerged for establishing and developing a hydrogen economy using green industrial policy. This phase involved a thorough literature review to systematize existing research and identify theoretical and empirical gaps deserving further investigation.

In the second stage, the author formulated and further investigated the research problem to distinguish four components of the research problem that constituted the four research objectives – referring to the theoretical research gap (RO1 and RO2) and the empirical research gap (R3 and R4). Subsequently, specific research questions (RQ1 – RQ12) aligned with these objectives were developed, concluding the conceptualization of the research and setting the stage for research implementation.

A mixed-method approach was employed in the third stage, integrating qualitative and quantitative research methods. Combining diverse research methods was instrumental to successful investigations of the research problem. Initially, the research delved into the foundational theories of the economics of sustainable development, establishing the theoretical background for the study. It was followed by an exploration of the role of green industrial policy in aligning industrial policymaking with the normative postulates of the economics of sustainable development. Subsequently, the study focused on the hydrogen economy concept and the significance of the FCEV market establishment and development as one of the core activities for this concept to gain momentum. The author also investigated the growth of this market in the context of the studied theories, filling the identified theoretical research gap. The research continued with a comprehensive case study of the FCEV market in the state of California from 1990 to 2022, including an analysis of green industrial policy instruments at both state and federal levels, market structure, and market participants and stakeholder identification. This empirical component included a quantitative and qualitative evaluation of policy instruments' effectiveness and a retrospective and prospective analysis of policy objectives and instruments, culminating in strategic policy observations for California and other jurisdictions.

The exploration of the impact of green industrial policy on the FCEV market establishment and development in the state of California without simultaneous consideration of the market indicators and people's perceptions would not make it possible to acquire an in-depth analysis of the impacts of individual instruments, and more importantly – i.e., how they could have been implemented alternatively, how they could be improved and what less-prosperous jurisdictions can learn from the experiences of the studied state. Applying the discussed research methods allowed the author to acquire and analyze the primary and secondary data. Generating the primary data was possible thanks to a diagnostic survey method that allowed the author to conduct 46 structured individual interviews with the selected FCEV market participants and stakeholders from this state.

Lastly, in the fourth stage, the author revised and discussed the acquired results from each research phase. Based on that, the author developed conclusions emphasizing the research limitations and recommendations for future research.

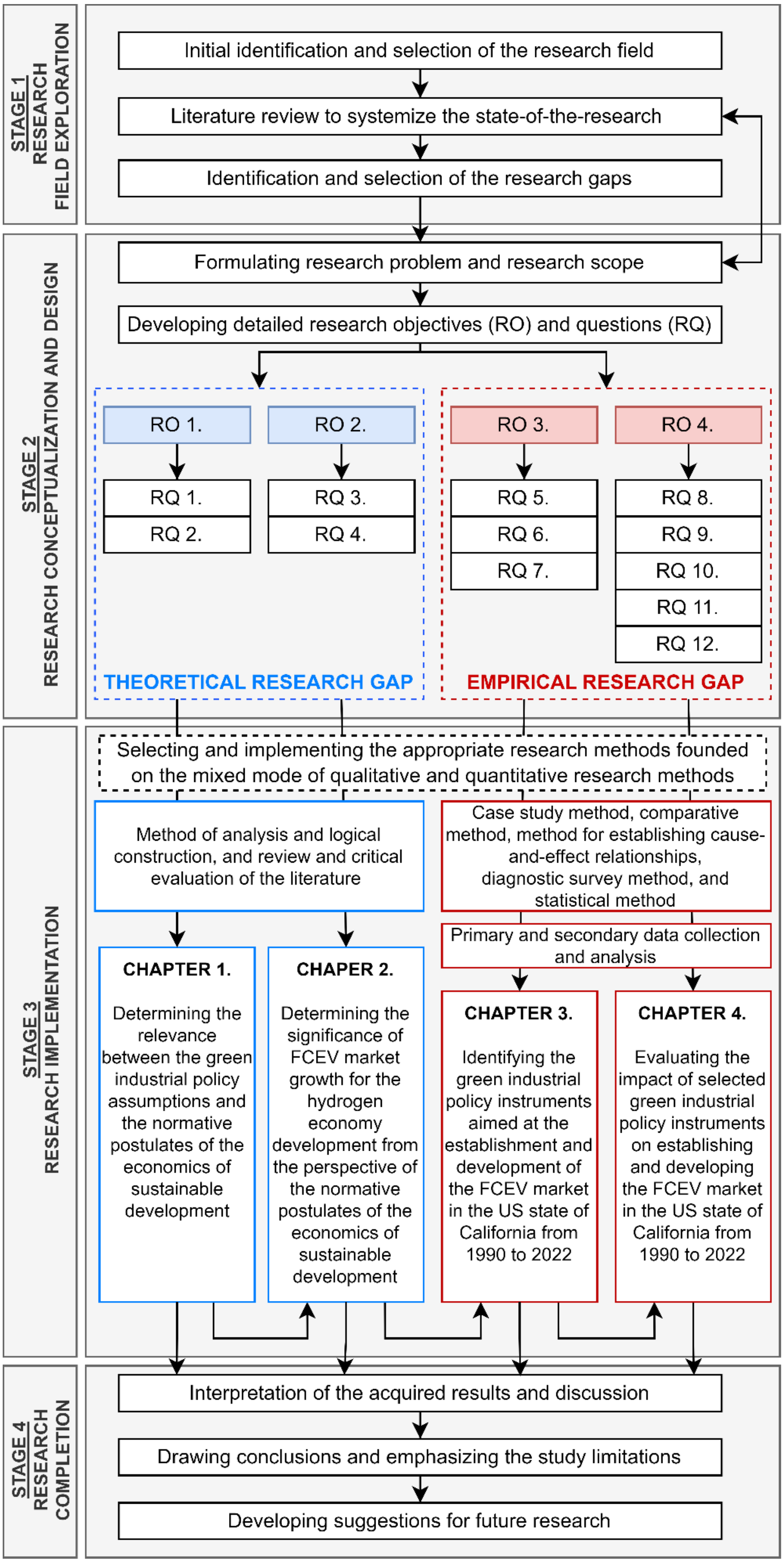


Figure 1. The research procedure implemented in preparing this dissertation with a breakdown to four stages. Source: Own elaboration.

The structure of the dissertation

The structure of the dissertation follows the four subsequent detailed research objectives and demonstrates the answers to detailed research questions presented earlier. The dissertation consists of four chapters. The first two are theoretical in nature, while the third and fourth constitute the empirical and normative part of the work.

The first chapter is devoted to determining the relevance between the theory and normative postulates of the economics of sustainable development and the green industrial policy assumptions, which can be identified as a new paradigm in industrial policy. The initial subchapter of Chapter 1 delves into the economics of sustainable development, tracing its historical evolution within economic sciences. Establishing its foundational postulates is discussed alongside the main three problem areas, which include economic, socio-cultural, and environmental domains. In addition to that, the author presented the energy transition phenomenon and discussed the leading theories that describe it. The latter part of the chapter pivots to green industrial policy, examined through the prism of the economics of sustainable development. At first, the chapter explores the intricacies of economic policy and, therefore, the state interventions, shedding light on these concepts across selected theoretical schools. Subsequently, it underscores the role of industrial policy in shaping structural changes. Lastly, this chapter introduces the emergent green industrial policy concept, positioning it as a forward-thinking approach that aligns with the overarching tenets of the economics of sustainable development.

The second chapter delves into the establishment and development of the FCEV market, integrating insights from both the concept of the hydrogen economy and the economics of sustainable development (therefore achieving the second detailed research objective). Initially, the chapter sheds light on the hydrogen economy concept, delineating its origins and foundational assumptions. The narrative then elaborates on the value chain associated with a hydrogen economy. The chapter emphasizes the role of green industrial policy in facilitating the transition to this energy transition model. The latter part of the chapter pivots to a detailed exploration of the FCEV market and the key factors influencing its trajectory. It commences with a comparative analysis of FCEVs against other ZEVs, discussing and presenting the distinctive attributes of hydrogen-powered propulsion. The conceptual framework of the FCEV market is then elucidated, providing a comprehensive understanding of its structure and inherent historical dynamics. A critical examination follows, presenting barriers that have historically posed challenges to establishing and developing the FCEV market. Concluding the chapter is an integrated analysis, viewing the genesis and growth of the FCEV market through the lens of the economics of sustainable development, thereby highlighting the symbiotic relationship between emerging automotive FCEV technologies, the market growth, and fulfilling the normative postulates of the studied theory.

The third chapter of the dissertation delves into the FCEV market in the state of California. The chapter begins with examining the green industrial policy pivotal for establishing and developing the FCEV market in California, scrutinizing both state and federal dimensions. To provide a foundation for this exploration, the initial subchapter focuses on the historical emergence and distinctive features of the political and economic system of the United States. From there, the discourse shifts to highlight the progression of the federal green industrial policy, dissecting the underpinning assumptions, objectives, and instruments designed to support the development of the FCEV market at the state levels. Parallelly, the evolution of similar policies and strategies emanating from the state itself is also studied by the author of this dissertation. The latter part of the chapter begins with the characteristics of the FCEV market within the state of California. This subchapter disentangles the distinct phases marking the establishment and development of this market, followed by a thorough analysis of its structure distinguishing the passenger light-duty, FCEB, and FCET segments as well as identifying the main market stakeholder categories. Thereby, the third chapter fulfills the third detailed research objective by identifying the structure and green industrial policy instruments aimed at establishing and developing the FCEV market in the US state of California from 1990 to 2022.

The last chapter of the dissertation is a comprehensive evaluation of the impact exerted by selected green industrial policy instruments on the establishment and development of the FCEV market in California, based on empirical research findings sourced from expert perspectives. At first, the chapter delves into the debate on the methods and techniques of policy impact evaluations and demonstrations of specifics of the research process, starting with delineating the detailed objectives, progressing to the methods employed, and finally detailing the criteria for participant selection and the research's overall progression. This foundational framework leads to an in-depth presentation of the empirical results. These findings cover various aspects: diverse reasons backing the implementation of green industrial policies for this market's establishment in California, the subjectively perceived effectiveness of these selected green industrial policy instruments, as well as author's observations that could be contextually studied to serve as potential observations for further development of the studied market in California. The chapter concludes by synthesizing these empirical outcomes, offering normative guidelines for follower jurisdictions considering their likely different policy objectives and FCEV market determinants.

Finally, the dissertation includes a summary of theoretical and empirical considerations followed by an overview of the research limitations and the recommendations for future studies. The last integral part of this dissertation is the appendices, which include several documents directly linked to the course of the empirical study, including the informed consent form and the coding sheets.

International cooperation and source of funding

The author solely conducted this empirical research as part of the research project titled: *Deployment of the hydrogen and fuel cell technologies in California's energy and transportation sectors: Evidence from the case study research, short-term forecast, and evaluation of California's policies in 2008-2022 – as compared to strategies adopted in the EU, precisely in Poland and Germany*. The US Department of State and the European Commission co-financed the project under the Fulbright-Schuman Award 2022/2023. The research project was implemented from August 1, 2022, until February 1, 2023, in cooperation between the author, Prof. David G. Victor, and Dr. Ryan Hanna from the University of California San Diego (UCSD). At that time, the author was a Visting Graduate Student at the UCSD School of Global Policy and Strategy. The further evaluation of the research findings and constitution of this dissertation was possible thanks to the supervision and guidance of the supervisor at the Wroclaw University of Economics and Business. The content of this dissertation, findings, and normative postulates are solely the authors' responsibility and do not necessarily represent the official views of the Fulbright Program, the Government of the United States, or the European Commission.

1. THE ECONOMICS OF SUSTAINABLE DEVELOPMENT AND GREEN INDUSTRIAL POLICY

Since its foundation in the 20th century, the sustainable development concept has been a subject of interdisciplinary debates. It led to developing new fields of study and theories within economic sciences and beyond. As an example of a new theory and a research domain, the economics of sustainable development is defined by assumptions and postulates strongly related to ecological and environmental economics, focusing on economic, socio-cultural, and environmental problem domains according to the sustainable development concept. Implementing the postulates developed within the economics of sustainable development requires diverse adjustments regarding how economic development is perceived, studied, and shaped. The role of economic policy in this process is undisputed, especially in the context of sectoral policies, such as industrial policy, which provides incentives for multidimensional structural changes and steers the industrial sector's growth. Considering the assumptions and postulates of the economics of sustainable development, the concept of green industrial policy can be further developed and demonstrated as a direct response to the economic, socio-cultural, and environmental problem domains. The following chapter is divided into two main subchapters. The first subchapter presents an overview of the origins, theoretical assumptions, problem domains, and postulates of the economics of sustainable development. It is followed by reviewing and analyzing the key determinants, objectives, and functions of green industrial policy to present the role of this new paradigm in industrial policy-making in fulfilling normative postulates of the economics of sustainable development.

1.1.The economics of sustainable development

1.1.1. The genesis and evolution of the sustainable development concept in economic sciences

Before discussing the sustainable development concept and its numerous interpretations, it is worth conducting an overview of the theoretical background of economic development as a starting point for these deliberations. It is vital to distinguish economic development from economic growth. In contrast to economic growth, economic development covers a broader conceptual scope and refers to *qualitative* transitions, while economic growth is more associated with *quantitative* transitions within the economy. Undoubtedly, the studies focused on the nature of economic growth have their roots in the origins of economic sciences.

However, the ground-breaking moment occurred in the middle of the 20th century, when economists focused their research on the foundation of neoclassical growth theories and models (Balcerowicz & Rzońca, 2015). Several significant neoclassical growth models were from that time (Cass, 1965; Harrod, 1939; Solow, 1956). Despite significant differences, they demonstrated theoretical models predicting that in closed economies, the *per capita* growth rates are inversely proportional to the initial value of output or income *per capita*. For instance, if two closed economies are comparable in their economic structure and technological advancement, the low-income economy will grow faster than the high-income economy (Barro & Sala-I-Martin, 1992). The wide cross-country dispersion in the growth rates was also a subject of the research conducted by R.E. Lucas, who shed new light on this matter by presenting another economic growth model that fits the Solow-Denison model assumptions and the pieces of evidence from the US and other countries from the 20th century (Lucas, 1988).

Economic growth can be defined as a long-run rise in capacity to supply increasingly diverse economic goods to a country's population. Furthermore, this capacity should be based on technological advancements and suitable institutional adjustments. In this context, S. Kuznets characterized economic growth with six quantitative factors that can measure the dynamics of this process. He associated economic growth with (1) a high rate of growth in domestic product *per capita*, (2) the rise in productivity of output *per* product unit of all units, (3) structural transformation of a country's economy from agriculture to non-agricultural pursuits or away from industry to services, (4) increasing urbanization, (5) application of technological advancements and innovations, and last but not least, (6) the equal spread of economic growth in the society (Kuznets, 1973).

Economic growth, as a broad-based improvement through quantitative changes in an economy, does not implicitly translate to the growth of every aspect of a country's economy. Interestingly, even if the gross domestic product (GDP) *per capita* grows, the dynamics of economic growth can spread unevenly among sectors or individual industries. Such disproportional distribution of economic growth dynamics may also occur in seasonal fluctuations, i.e., a country's economy may experience a quarterly economic decline. However, at the end of the year, it will not affect aggregated economic growth (Woźniak, 2008). In other words, economic growth is a *sine qua non* for the economic development process. Moreover, this transformative process is also entwined (with the aforementioned) qualitative socio-economic changes that, in the long run, result in a rise in living standards and social welfare. G. Myrdal described economic development as a movement upward of the entire socio-economic system, by which he meant all economic and non-economic aspects, including production growth, rising distribution of income and wealth among the various social groups, educational and health issues, the role of institutions and broadly understood social attitudes (Myrdal, 1974).

Undoubtedly, the structural changes[1] in an economy are the source of those improvements. Those changes can arise from two categories of factors: (1) state interventions through adequate economic policy and (2) external or internal shocks, i.e., supply or demand shocks, innovations and technological advancements, natural disasters, or wars (Constantine, 2017). The changes in a country's economic structure may also occur due to the mentioned violent events or in the form of a slow evolutionary process. However, in the face of global anthropogenic environmental crises, such as climate change or a decrease in biodiversity, the concept of economic development must embrace the environmental limitations and capacities of natural services that the environment can offer. In addition, social issues, such as poverty, hunger, unemployment, or overpopulation, present another dimension of the contemporary problem domains. The need to incorporate environmental and social issues into economic development led to the foundation and development of a new interdisciplinary concept of sustainable development.

Noteworthy, the historical context of sustainable development in economic sciences can be traced back to the origins of economic sciences since the scientific works of D. Ricardo and T. Malthus have already identified the crucial role of natural resources in economic development (Kneese, 1988). T. Malthus can also be perceived as one of the first economists who recognized the limits of economic development caused by resource scarcity, especially in the context of the fixed amount of land available (*absolute scarcity limit*). *The Malthusian theory of population* indicated that, if left uncontrolled, population growth will follow

---

[1] According to S. Kuznets (1973, p. 248), structural changes represent a shift from the dominance of agricultural production toward industrial production (industrialization) and further toward increasing the share of services. It should be acknowledged that structural changes can also be perceived as shifts in the structure of consumption, entrepreneurship, employment, or trade. In general, the multi-dimensional character of structural changes leads to diverse outcomes. Still, most importantly, it contributes to a shift from low- to high-productivity activities, standing as a critical driver for productivity growth and economic development (Gabardo et al., 2017). Structural changes have diverse determinants, including sector-biased technological progress, nonhomogenous preferences of consumers, international trade, and fluctuations in resource costs across sectors (Święcki, 2017). It is worth emphasizing that numerous theoretical models now propose that nations engaging in technologically progressive endeavors are likely to experience elevated rates of productivity growth when compared to other countries (Fagerberg, 2000; Lucas, 1988). Therefore, technological innovation is one of the primary drivers of structural changes. It should also be noted that structural changes in economies are stimulated by the depletion of renewable and non-renewable natural resources and emerging issues resulting from climate change (Altenburg & Assmann, 2017).

a geometric progression, while the growth of resources to sustain that population will only follow an arithmetic progression, meaning that the population will inevitably grow until it reaches the limit of available resources. Even though this theory was well-grounded, it lacked consideration of the importance of technology innovation, which allows the growth of efficiency in exploiting available resources (i.e., sophisticated fertilizers were shifting the total production curve upwards, increasing output *per unit* of input and offsetting) (Mebratu, 1998).

The subsequent economists developed the concept of the importance of environmental consideration for economic development (Ditlev-Simonsen, 2022). The origins of the concept of sustainable development can be associated with the research conducted by economists such as E. Schumacher, who developed these assumptions, as exemplified by his introduction of the concept of *natural capital* in 1970, which emphasizes the importance of the environmental ecosystem in the management process (Missemer, 2018). Some other examples of the first publications discussing sustainable development in reconciling economic development with the conservation of the natural environment can be found in the work of W. Clark and R. Munn (1986). In 1987, E.B. Barbier developed a concept of sustainable economic development, indistinguishable from the development of society, where *sustainability* is directly related to socio-cultural and environmental transformations. From Barbier's perspective, sustainable economic development is two-dimensional: the *quantitative* dimension is related to the availability of material means that allow physical and social well-being and security (especially against becoming poorer), while the *qualitative* dimension is associated with the long-term ecological, social, and cultural potential to sustain economic activities and structural economic changes. Barbier also emphasized the complexities of measuring sustainable economic development, which differed significantly from the conventional economic consensus at the end of the 20th century (Barbier, 1987, p. 104). Like this approach, M.K. Tolba (1987) advocated for rational management of the world's most threatened natural resources and avoiding a loss in environmental quality to enhance sustainable economic development.

Simultaneously, the concept of sustainable development has been vitally developed by the United Nations (UN), which shaped the international debate in that domain, an example of which can be found in the selected examples.

<u>1972:</u> *The UN Conference on the Human Environment*, organized in Stockholm, defined the critical areas of improvement and rules of economic development that consider environmental limitations (United Nations, 1972)[2].

<u>1986:</u> The UN World Commission on Environment and Development published *Our Common Future* report (*Brundtland's Report*) recognizing the concept of sustainable development, concluding that *it is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: (1) the concept of 'needs,' in particular the essential needs of the world's poor, to which overriding priority should be given, (2) and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs* (WCED, 1986).

<u>1992:</u> The UN expressed the continuation of this approach during *The Earth Summit* conference that resulted in *The Rio Declaration of Environment and Development* (United Nations, 1992). This document established a list of principles to achieve sustainable development, regardless of local, national, regional, or international level, including the crucial role of environmental protection, underlined the necessity to establish equitable global partnerships and international initiatives, as well as it recognized the need to balance economic, social and environmental dimensions of human activities with the new concepts and models. The *Earth Summit* also resulted in adopting *Agenda 21* (an initial strategy to achieve sustainable development in the 21st century), the *UN Framework Convention on Climate Change*, and the foundation of the UN Commission on Sustainable Development (Jabareen, 2008).

2015: After decades of intensive multilateral negotiations and evaluations, the UN codified the 17 Sustainable Development Goals (SDG) and presented 169 specific targets as part of the *2030 Agenda for Sustainable Development*. Noteworthy is that this strategy was

---

[2] In 1972, The Club of Rome published a report titled *The Limits to Growth* that defined the nature and limits of exponential economic growth. Moreover, this report emphasized the dangers of environmental decay and acceleration of industrialization, predicting severe resource depletion and population collapse by the end of the XXI century. One of the messages the report presented is that *Man can create a society in which he can live indefinitely on Earth if he imposes limits on himself and his production of material goods to achieve a state of global equilibrium with population and production in carefully selected balance* (Meadows et al., 1972).

built on the *Millennium Development Goals* (adopted by the UN in 2000 with a time horizon until 2015) to complete its unachieved goals by 2030 (United Nations, 2015).

It is worth adding that implementing the sustainable development concept requires broad cooperation between stakeholders, including a university-industry-public partnership in research activities (Pezzoli, 1997). Furthermore, B. Poskrobko (2013) postulated that sustainable development analyzes the links between the economy and the natural environment as a habitat for human life and a place for doing business, as well as the relationship between the economy and the social sphere and the institutional environment. Considering the need to bridge the gap between the anthropogenic character of environmental and social issues and the concerns about economic development, sustainable development was a logical solution and a new paradigm in economic sciences that shaped the current discourse. The merge between neoclassical economics and the ethical justification of sustainable development can be found in J. Pezzey's (1992) work, which defined the conceptual and analytical framework for this new paradigm.

Measuring the level of sustainability of the development is challenging due to the multidimensional character of this concept. A broad review of sustainable development measures can be found in numerous research (Parris & Kates, 2003). Besides the Human Development Index, an example of a well-defined measure is *The Environmental Performance Index* (EPI) published by the Yale University Center for Environmental Law & Policy. EPI offers a comprehensive and evidence-based overview of sustainability levels on the national level. By evaluating 180 countries on their performance regarding 40 indicators across 11 categories of environmental concerns, the EPI assesses their standing in terms of climate change, environmental health, and ecosystem vitality and is a well-established base for many research (Hsu et al., 2013; Munksgaard et al., 2007; Neves Almeida & García-Sánchez, 2016; Szymczyk et al., 2021; Zuo et al., 2017).

Even though the concept of sustainable development has been discussed in interdisciplinary academic, political, and business discourse, its diverse definitions and interpretations present a worth noting vagueness and confusion (Mebratu 1998; Hopwood, Mellor, and O'brien 2005). This diversity of meaning led J. Robinson (2004, pp. 375–377) to identify two primary delusions of sustainable development concepts. First, sustainable development can be *internally inconsistent*, reflected in the concerns about whether it is possible to increase global industrial output many-fold in an environmentally sustainable way. The oxymoronic nature of this concept can be perceived from the perspective of social limitations of development, suggesting that we may run up against the social consequences of industrialization before we reach any environmental limits or balance. Nevertheless, the emergence of *eco-efficiency*, *dematerialization*, *design for the environment*, *industrial ecology*, *biomimicry*, and *corporate social responsibility* are necessary steps towards a more sustainable world, regardless of the debate over environmental or social limits to growth. The second delusion associated with the sustainable development concept is its *potential to distract us* from critical problems and potential solutions by focusing our attention on the wrong issues. From an environmental point of view, sustainable development is a purely anthropocentric concept, missing the point of the need for a new ethic, a new set of values, and a new way of relating to the natural world. On the social side, sustainable development is seen as innately reformist, mostly avoiding questions of power, exploitation, and even redistribution. The need for more fundamental social and political change is ignored. The critique of the concept of sustainable development poses the question of whether an entirely different path could be taken to bridge the environmental, economic, and social challenges. Despite new conceptual and practical developments in the area of sustainable development, it is not clear whether such developments can become significant enough to challenge the influential contrary trends in indicators such as energy use, CO_2 emissions, land appropriation, and economic globalization.

The diverse spectrum of definitions and interpretations of the sustainable development concept has led to the establishment of several new approaches toward this concept in economic sciences, which address the challenges associated with environmental, economic, and social issues differently. Examples of attempts to map the evolution and characteristics of those new trends can be found in C.A. Ruggerio (2021), who focused on the sustainability being conceptualized according to the school of thought ranging from *weak* to *strong* sustainability, or in R. Chang et al. (2017), who focused primarily on linking the sustainable development concept to incorporate social responsibility, stakeholder theory, corporate sustainability, and green economics. In this context, it is also worth mentioning the concept of a **degrowth economy** (or **negative growth economy**), which postulates, i.e., the gradual economic decline rather than growth, to use less of the world's dwindling resources and reduction in global consumption and production. It can be then defined as a collective and deliberative process aimed at the equitable downscaling of the overall capacity to produce and consume and of the role of markets and commercial exchanges as a central organizing principle of human lives (Fournier, 2008; Kallis et al., 2012, 2018; Schneider et al., 2010; Sekulova et al., 2013).

The **circular economy** is also a concept that is based on sustainable development assumptions and can be defined as an economic system that replaces the *end-of-life* concept with reducing, alternatively reusing, recycling, and recovering materials in production, distribution, and consumption processes (Kirchherr et al., 2017). Based on the broad analysis and synthesis of the circular economy definitions, J. Korhonen et al. postulated that circular economy is *a sustainable development initiative with the objective of reducing the societal production-consumption systems' linear material and energy throughput flows by applying materials cycles, renewable and cascade-type energy flows to the linear system. The circular economy promotes high-value material cycles alongside more traditional recycling and develops systems approaches to the cooperation of producers, consumers, and other societal actors in sustainable development work* (2018, p. 547).

Lastly, it is worth emphasizing the concepts of a low-carbon, resource-efficient, and socially inclusive **green economy** alongside **green growth** (Loiseau et al., 2016; Mealy & Teytelboym, 2022). As defined by the OECD, green growth is the process of promoting economic expansion and progress while concurrently safeguarding natural resources to maintain their ability to provide essential resources and environmental services that contribute to our well-being. Accomplishing this goal necessitates encouraging investment and innovation that support ongoing growth, resulting in new economic opportunities (OECD, 2011).

1.1.2. Establishment and postulates of the economics of sustainable development

In the past decades, the role of environmental issues in economic sciences has been discussed within two economic theories – environmental economics and ecological economics. Environmental economics, a subset of neoclassical economics, applies economic theory and methods, such as cost-benefit analysis, impact analysis and modeling, resource pricing, and environmental quality indicators to address environmental issues, aiming to improve the efficiency of resource allocation and mediate the externalities that come with the use of the environment and natural resources (Neo, 2009). While ecological economics, still based on some neoclassical assumptions (such as opportunity costs), has a fundamentally different, transdisciplinary approach, perceiving the economy as an open system interacting with the natural environment in a greater ecosystem (Daly & Farley, 2004).

Simultaneously, sustainable development concepts have become a new paradigm in economic sciences, implicating new research and theories impacting both environmental and ecological economics. It also provided an opportunity for further discussion on the refinement of neoclassical economic theory that is based on the paradigms, such as (1) perfect competition that allows an efficient market mechanism of resources allocation within an economy, (2) supply and demand forces that create self-stabilizing market equilibrium, (3) firms that aim to profit maximization, and (4) individuals that are modeled as *homo oeconomicus* emphasizing their willingness to utility maximization, rationality, individual cognitive capacity, possession of perfect information, limited self-interest, and consistent subjective preferences. The need to revise neoclassical economic theory concerning the sustainable development concept was expressed, i.e., by R. Goodland and G. Ledec (1987).

Further deliberation on the *economization* of the sustainable development concept can also be found in the research by D.W. Pearce et al. (1994), who underpinned the model of the optimal economic growth model with the *sustainable* and *unsustainable* allocation of natural resources over time (especially, considering elements of natural capital that possess distinct characteristics, and the depletion of which may lead to unpredictable and possibly irreversible consequences on human welfare, warrant special attention). In this context, it is also worth noting that H.E. Daly, one of the theorists of ecological economics, published an in-depth discussion on the economics (or an economic perspective) of sustainable development (Daly, 1996). Among many postulates, Daly strongly advocated replacing the *growth-oriented* economy with the *steady-state economy*, referring to J. S. Mill's *stationary state* concept from 1857, characterized by zero growth in population and physical capital stock but with continued improvement in technology and ethics. His contribution to the conceptualization of sustainable development concept from the economic perspective can also be seen, i.e., in proposing, together with J. B. Cobb, the *Index of Sustainable Economic Welfare* (ISEW) and four operational principles of *sustainability of economic development* (1991, p. 40):

Optimal scale - the main principle of sustainable development involves limiting human scale to a level that is within carrying capacity, necessitating the choice of population size and average resource consumption. Optimal scale is achieved when long-term marginal costs and benefits of expansion are equal, but this remains a theoretical concept until operational measures are developed.

Efficiency-focused progress: Sustainable development should prioritize enhancing technological efficiency instead of increasing resource consumption, with limitations on resource throughput serving as a catalyst for this change.

Balanced utilization: renewable resources should be utilized based on a profit-maximizing sustained-yield approach to prevent extinction, becoming increasingly vital as non-renewable resources deplete. Harvesting rates must not surpass regeneration rates, and waste emissions should stay within the environment's renewable assimilative capacity.

Sustainable substitution: non-renewable resources should be used at a rate equal to the creation of renewable substitutes, with both types of investments paired and evaluated based on their perpetual income components. If a renewable resource is partially divested, the same pairing rule should apply, ensuring a dynamic mix of renewable resources with compensating investments made for every divestment.

Nevertheless, environmental and ecological economics have been leading economic theories discussing the incorporation of the natural environment perspective in economic sciences. As S. Czaja postulates, currently, there are four main scenarios for the further evolution of those economic theories (2012, p. 34): (1) independent, separate, and partially autonomous development of these two theories; (2) a path toward a synthesis involving merging of one discipline into the other, with either of them gaining dominance; (3) the disappearance of both disciplines and the takeover of their research problems by theoretical schools from the mainstream neoclassical economic theory; (4) the emergence of a new discipline using the achievements of both disciplines as the theoretical basis for sustainable development strategies, namely *economics of sustainable development and sustainability*.

The last scenario reflects the need to define a new theoretical and methodological framework for the sustainable development concept. Among the attempts to develop a new economic theory that would incorporate the sustainable development concept, it is vital to emphasize the **economics of sustainable development** (pol. *ekonomia zrównoważonego rozwoju*) that gains importance in contemporary economic discourse, especially in European countries like Poland or Germany. As B. Poskrobko advocated, the subject of this newly established theory is the *economics of the society-economy-environment macro-system* (2012, p. 20). This macro-system can be perceived from a *narrow perspective* involving social, economic, and environmental domains. At the same time, from a *broad perspective,* it also considers the spatial and institutional domains. The primary postulated paradigm of this theory is that *sustainability is broadly understood as a balance of social, economic, and environmental development* (2012, p. 24). It is vital to emphasize the contribution of H. Rogall, who aimed to establish the central thesis of the economics of sustainable development (2010). These postulates were further developed and discussed, among others, by E. Lorek (2011), K. Midor (2012), S. Czaja (2012), and D. Kiełczewski (2012) and are presented below.

The first postulate of **strong sustainability** within the economics of sustainable development assumes that the economy should be treated as a subsystem of nature and that natural capital is not subject to substitution. There are absolute limits to nature's tolerance, which must be taken into account in the process of economic development. Therefore, the objective of the economics of sustainable development is not only the optimal use of natural resources but, first and foremost, their sustainable maintenance for future generations instead of optimal consumption, especially since many of them are non-renewable.

Secondly, the **pluralist approach** in the economics of sustainable development involves delineating and incorporating particular aspects of environmental economics. Within this approach, the economics of sustainable development recognizes and utilizes specific achievements of neoclassical and environmental economics, such as socio-economic explanations for the overexploitation of natural resources. As a result, it leads to a discussion of the need for political and legal instruments to implement sustainable development principles.

Thirdly, it can be stated that the **consequent evolution of neoclassical economics and environmental economics** leads to the emergence of the economics of sustainable development, which distances itself from some of their aspects. In relation to environmental economics, the economics of sustainable development challenges the absolute sovereignty of the consumer and the assumption of the substitutability of all resources, including natural resources. At the same time, it emphasizes equity in the context of national economic policies and global conditions to achieve sustainable development.

Furthermore, the crucial thesis of the economics of sustainable development emerged from the **accomplishments of research on the concept of sustainable development**, focusing on the problems of achieving economic, socio-cultural, and environmental standards within the limits of nature's tolerance. Also important is the application of the principle of intra- and intergenerational justice. There are numerous debates within the economics of sustainable development, such as the need to replace the traditional absolute growth paradigm with a sustainability paradigm, which becomes a necessary condition for sustainable development since growth in geometric progression combined with intensive exploitation of natural resources is impossible for eternity. The scientific debate in the economics of sustainable development focuses on clarifying these issues and finding appropriate solutions for sustainable development.

In addition to those postulates, it is essential to **revise the *homo oeconomicus* model** used in neoclassical economics and to propose an alternative model of *homo sustinens* that would better reflect the assumptions of the sustainable development concept (Fiedor, 2006). As D. Kiełczewski presents (2016, p. 273), *homo sustinens* operates based on multidimensional rationality, including:

Individual rationality – meeting material needs should be one aspect of quality of life. At the same time, intangible goals such as happiness, good relationships, self-realization, satisfying work, leisure time, and a high-quality environment are also important. In an unlimited timeframe, material needs should not overshadow other values.

Economic rationality in the mezzo- and macroeconomic contexts – translates to making decisions with a view to the need to support local, regional, and national businesses, boycotting entities that engage in unfair practices, and avoiding actions that destabilize the local, regional, and national economy.

Social rationality – dictates the decisions and actions that involve building complex relationships with the social environment, including engaging in charitable activities, accepting a progressive tax and social welfare system, and respecting workers' rights.

Ecological rationality – considers the limitations of the natural environment and accepts the non-substitutability of natural capital with human capital. It results in making decisions and taking actions that have minimal or no negative impact on the natural environment and contribute to increasing its quality and diversity.

While *homo oeconomicus*, as a positive model, was developed to capture the characteristics of the rational economic agent, *homo sustinens* is a normative model corresponding to modern economic, socio-cultural, and environmental issues. Implementing such a theoretical model requires two main factors – adjustment of an educational system to shape the rationality of individuals oriented toward sustainable development and state intervention through the public policies that would promote the postulates of this concept. According to A. Horodecka (2011), the *homo sustinens* model is also vital in economic policy to respond to the current economic crisis and perpetual challenges.

An **interdisciplinary approach** in the economics of sustainable development would make itpossible to analyze economic processes in a broader sociocultural and environmental context. An important role is played here by using knowledge and close cooperation with other social sciences, humanities, legal, natural, and technical sciences. Through this interdisciplinary approach, the economics of sustainable development can better understand the complexity of sustainability issues and more effectively support sustainable, balanced economic policies.

Another normative postulate in the economics of sustainable development is the need to **change framework conditions using political and legal instruments** to influence the sustainable behavior of consumers and producers (according to the discussed *homo sustinens* model). For instance, as H. Wiesmeth (2022) advocates, in a manner akin to the *command-and-control* policy, the *price-standard* method emphasizes achieving specific environmental objectives by incentivizing economic participants to contribute their expertise and information. This approach involves incorporating the environmental impacts into the market system by filling in the gaps. By decentralizing decision-making, the *price-standard method* emulates the price mechanism to attain the desired standards, which can be accomplished by implementing, i.e., Pigou's tax. It can be seen as the *balance price* in a hypothetical market or by creating a market for tradable permits. By employing political and legal instruments, the framework conditions are changed so that adherence to sustainable development is more beneficial to consumers and producers than their existing behavior. As a result, a sustainable approach to economic development based on environmental responsibility is being promoted.

The need to **operationalize the concept of sustainability and develop new measures and strategies** is crucial to the economics of sustainable development. Unlike neoclassical economics, which equates quality of life with well-being as measured by, i.e., GDP *per capita*, the economics of sustainable development seeks to develop defined objectives, indicators, and management principles and rules to measure sustainability and quality of life. In response to criticism of GDP as an indicator of well-being, the economics of sustainable development is developing new measurement systems in the form of goals and outcome indicators. Examples of such indicators selected by E. Lorek (2011) include the already mentioned *Index of Sustainable Economic Welfare* and the *New National Welfare Index* (NNWI). Through the formulation of principles, management rules, and new systems for measuring the degree of sustainability and quality of life, the economics of sustainable development seeks to establish the concept of sustainability as a basis for analyzing and evaluating economic processes.

Global responsibility is another fundamental postulate of the economics of sustainable development, which focuses on reducing people's resource consumption in industrialized countries and limiting population growth in developing countries. Given their historical development and achievements, industrialized countries should be particularly concerned with realizing intergenerational justice, global sustainability, and fair terms of trade. The realization of the UN SDGs internationally requires introducing global coordination of regulatory frameworks, such as controlling financial markets and introducing fees for using global environmental goods. According to the economics of sustainable development, the fiscal policy ought to aim to, i.e.,: (1) tax financial transactions to curb financial speculation and regulate financial markets (for instance, by introducing the Tobin tax); (2) increase the maximum rate of personal income tax and the standard rate of value-added tax to subsidize substantive goods, environmental investments, and the social security system; (3) abolish jurisdictions that have meager taxes and no residency requirements (*tax havens*); (4) introduce of severe sanctions for underreporting of tax liabilities; (5) introduce of preferences in direct taxes (income, property) to encourage pro-environmental behavior (Cieślukowski, 2014, p. 198; Rogall, 2010). Global responsibility should also involve industrialized countries fulfilling their responsibility by actively supporting global sustainability and fair trade relations.

Lastly, a **sustainable socio-culturally and environmentally oriented market or mixed economy** is a crucial approach in the economics of sustainable development. Representatives of this concept reject both market economies and centrally controlled economies altogether, recognizing that the future lies in market economy systems operating under sustainable orders. Active political interference by governments is necessary to ensure sustainable development and minimize the effects of market failure.

It can be concluded that the economics of sustainable development has three main research domains directly related to sustainable development. In addition, H. Rogall describes key contemporary challenges for the economics of sustainable development presented in Table 1.

Environmental domain	Economic domain	Socio-cultural domain
Climate change	Lack of stability in the national economy, such as the insufficient supply of employment.	Insufficient realization of the principles of democracy and the rule of law
The devastation of ecosystems, species, and landscape diversity	Insufficient satisfaction with basic needs, high prices	Poverty, social insecurity, demographic problems (e.g., population growth)
Depletion of non-renewable resources	Inflation, Large concentration of economic power	Inequality (e.g., gender)
Overexploitation of resources renewable	Non-economic imbalances, Dependence on the supply of raw materials	Internal and external insecurity, violent conflict resolution, competition for benefits
Human health hazards (e.g., harmful substances, radiation, noise)	State debt, inadequate provision of collective goods, and inequitable distribution of income	The burden on health and quality of life

Table 1. Research domains and challenges for the economics of sustainable development. Source: own elaboration based on H. Rogall (2010), Midor (2012), Michalik (2016).

The broadly recognized and systematically presented challenges that the economics of sustainable development can address can be found in the *UN 2030 Agenda for Sustainable Development* (United Nations, 2016). Nevertheless, very promising in the first years of its existence, *The Sustainable Development Goals Report 2022* concludes that cascading and interlinked crises, such as COVID-19, regional conflicts, and climate change, are impacting the *2030 Agenda for Sustainable Development* and limiting its potential of achieving in a given time frame. Nevertheless, appropriate policy adjustments must address the economic, socio-cultural, and environmental domains (and associated contemporary challenges). As. D. Zilberman (2014) suggests, policy adjustments should be focused on the four fundamental objectives: (1) investing in technological R&D and the qualitative and quantitative development of human capital, (2) introducing policy incentives to induce the adoption of technologies and practices consistent to the sustainable development concept, (3) introducing strict regulations that transform the markets, and last but not least, (4) improving the educational system that promotes the sustainable development postulates. An example of the issue that fits into the three main research areas and that requires broad policy adjustments is the energy transition, defined, i.e., by V. Smil as *the change in the composition (structure) of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system* (2010, p. VII).

1.1.3. *The concept of energy transition in the economics of sustainable development*

Since the field's foundation, economic sciences have contemplated fundamental energy processing and usage transitions. In 1865, British scientist W.S. Jevons highlighted that as the energy efficiency of coal-powered mechanical devices improved, overall consumption of coal, iron, and other resources increased rather than decreased significantly (Alcott, 2005; Jevons, 1865). This so-called *Jevons Paradox* remains a subject of an ongoing debate regarding the effects of technological innovation and development on resource consumption (Sorrell, 2009). The 19th and 20th centuries were a time of rapid growth in the energy sectors, with fossil fuels being the leading primary energy source. During this time, the global economy experienced widespread electrification alongside the emergence of alternative energy sources, such as nuclear power (Soliński & Gawlik, 2012). The need for increased energy efficiency drove technological advancements, leading to substantial energy processing, storage, and usage alterations. V. Smil (2010) posits that these shifts in primary energy consumption structures and the gradual transition to new energy systems can be termed energy transitions, encompassing technology, energy policy, economy, culture, and social behaviors. As the energy sector became increasingly vital to economic growth and development, specific theoretical schools emerged to explore these topics. Economic growth and sustainable development concepts continue to examine energy processing and usage changes. More importantly, these changes are subject to energy policy, which aims to overcome the *energy trilemma*. This term refers to a complex challenge countries face in developing and maintaining a sustainable, secure, affordable energy system. It comprises three primary dimensions (challenges) that must be balanced to achieve an optimal energy strategy (Figure 2).

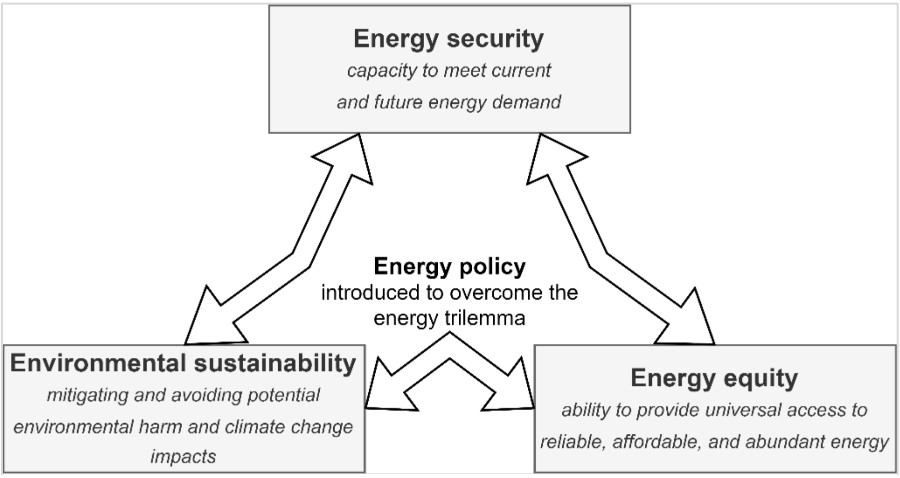


Figure 2. Energy trilemma and the role of energy policy. Source: Own elaboration

In the energy trilemma, ***energy security*** refers to ensuring a stable and uninterrupted energy supply, which includes diversifying energy sources, investing in infrastructure, and promoting energy efficiency to reduce dependence on imported fuels and mitigate risks associated with supply disruptions. Energy security can also be defined as protection from or adaptability to threats that are caused by or impact the energy supply chain (Winzer, 2012). The following issue is ***energy equity***, in other words, providing affordable and accessible energy services by keeping energy prices affordable for consumers and businesses and ensuring social inclusion in the energy transition process to low- or zero-carbon energy sources. The last challenge of the energy trilemma is the need to consider ***environmental sustainability*** by reducing the environmental impact of energy production and consumption, including minimizing greenhouse gas emissions and other pollutants. This often involves promoting the development and adoption of low-carbon and more efficient technologies, as well as supporting renewable energy sources. Balancing these three challenges can be challenging since improvements in one area may come at the expense of another. For instance, focusing on *environmental sustainability* may lead to higher energy prices, affecting *energy equity*. Similarly, a push for *energy security* may increase reliance on fossil fuels, which can have negative environmental impacts. Therefore, the energy trilemma highlights the complex interplay between these factors and the need for carefully considered energy policies to achieve a balanced and sustainable energy system (Marti & Puertas, 2022).

Research by D.I. Stern (2011) and others provides theoretical and empirical evidence that energy consumption and production are closely linked to energy availability, playing a crucial role in economic growth. Technological progress and the increasing accessibility and diversity of energy resources have lowered energy consumption *per* production unit, allowing for shifts in economic growth dynamics and structure (Khan et al., 2022). The more rapid the technological development, the more significant the energy processing and consumption changes within the economy (Stern, 2004). Moreover, the relationship between energy consumption, economic growth, and environmental pollution has been extensively studied over the past three decades, revealing strong connections between these factors (Acaravci & Ozturk, 2010; Belke et al., 2011; Ozturk, 2010).

Long-standing research indicates that the environmental consequences of utilizing fossil fuel-based energy resources have led to substantial environmental degradation and climate change. As a result, transitioning to renewable energy sources is crucial for achieving sustainable development (Khan et al., 2021). A. Graczyk (2017) suggests that sustainable development is unattainable without a sustainable energy sector, which he defines as a process that ensures energy provision in an economical, secure, and efficient manner. The environmental Kuznets curve hypothesis, proposed in the 1990s by G. Grossman and A. Krueger, explains the quantitative and qualitative shifts in energy production and processing. This hypothesis describes the relationship betw een economic growth and environmental pollution (Grossman & Krueger, 1991, 1995). Based on their observations, the researchers concluded that while economic development initially exacerbates environmental degradation, after a certain income level is reached to cover environmental protection and technology costs, further development has less environmental impacts. The inverted "U"-shaped Kuznets curve comprises three segments, influenced successively by the ***scale effect*** (a period of intensive, energy-consuming economic growth), the ***composition effect*** (structural changes in the economy, including a decline in industrial importance), and the ***technological effect*** (significantly reducing negative environmental impacts through advanced technology and facilitating energy transformation) (Frodyma et al., 2022). However, research findings reveal that this hypothesis, when tested, does not fully confirm this relationship for all developing and highly developed countries or every type of pollution (Gentswa, 2020; Hill & Magnani, 2002). Nonetheless, the increasing reliance on non-renewable energy sources has significantly contributed to the rise in carbon dioxide and other greenhouse gas emissions, leading to multidimensional adverse environmental and climate effects, including global warming (IPCC, 2007). Due to its complex character, energy transition should be studied and perceived from the perspective of individual sectors to define main trends and challenges.

United Nations' *Earth Summit* in 1992 recognized the role of energy and transportation sectors in sustainable development and emphasized their importance in concluding document – *Agenda 21*. Furthermore, the UN outlined the modern framework for these changes in the *2030 Agenda for Sustainable Development*. The review of related SDGs is listed in Table 2 (United Nations, 2016).

SUSTAINABLE DEVELOPMENT OF ENERGY SECTOR	**SUSTAINABLE DEVELOPMENT OF TRANSPORTATION SECTOR**
SDG 7: *Affordable and clean energy*	**SDG 11:** *Make cities and human settlements inclusive, safe, resilient, and sustainable*
Specific targets	***Specific target***
7.1 *- By 2030, ensure universal access to affordable, reliable, and modern energy services.* ***7.2*** *- By 2030, increase substantially the share of renewable energy in the global energy mix.* ***7.3*** *- By 2030, double the global rate of improvement in energy efficiency.* ***7.A*** *- By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.* ***7.B*** *- By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support.*	***11.2*** *- By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.*

Table 2. Sustainable Development Goals related to energy and transportation sectors. Source: United Nations (2015).

The complex structure of these SDGs and specific targets requires breaking down these goals and discussing the individual identified issues separately to understand their multidimensional character holistically.

Modern energy services refer to using clean and efficient energy technologies, such as renewable energy sources, energy-efficient appliances, and clean cooking fuels and technologies characterized by low- and close to zero-carbon emissions. Modern energy services help reduce greenhouse gas emissions and improve air quality and the overall quality of life and economic opportunities for individuals and communities (Pachauri, 2011).

Universal access means that everyone, regardless of their location, income, or social status, should have access to electricity, heating, and clean cooking fuels and technologies. Evidence shows that access to energy is crucial for human development but does not benefit all its components equally and is not distributed equally in each region (Acheampong et al., 2021). As G. Falchetta and S. Tagliapietra (2022) suggest, it is fundamentally an economic problem. It can be overcome by coordinated policies that involve energy pricing and subsidies reform, the mix of technological solutions that involve advancements in the power grid, gas pipelines networks, digitalization, and smart payment schemes, the increasing role of an international organization which can unlock the flows of capital and investments in developing countries and coordinate global efforts to provide universal access to energy services, as well as the need to conduced in-depth cost-benefit analysis of energy access projects to assure the synergy between them and the climate change mitigation. Unfortunately, according to a joint 2022 report of the custodian agencies (WTO/IAE/IRENA/UN/WHO, 2022), the COVID-19 pandemic and the full-scale Russian aggression on Ukraine have noticeably slowed down the progress toward universal energy access due to severe lockdowns, disruptions to global supply chains, and shortages of conventional fuels in many parts of the world (IEA, 2022b).

Affordable energy services refer to the cost of energy services that should be available regardless of income. This term is directly related to energy poverty, which affects approximately 1.3 billion people who lack access to electricity and 2.6 billion people who rely on wood as their primary energy source. It is both a cause and consequence of poverty and contributes to health, economic, and environmental issues. While progress has been made in some areas, such as China, many countries in sub-Saharan Africa still lack improvement in energy access. Energy poverty has significant implications on health, with indoor air pollution causing an estimated 1.3 million deaths per year in low-income countries. Addressing energy poverty requires substantial investments, but these costs are lower than the subsidies given to fossil fuels. Adopting renewable energy sources and distributed generation can benefit poorer countries by providing more affordable and sustainable energy. To tackle energy poverty, specific policies and programs must be developed, and access to energy should be a priority in development programs (González-Eguino, 2015). An example of an index that measures energy poverty is *Multidimensional Energy Poverty Index* (Nussbaumer et al., 2012) which has been implemented in many studies nowadays (Mendoza et al., 2019; Sadath & Acharya, 2017; Sokołowski et al., 2020) It is worth emphasizing that energy poverty is a challenging issue in both developing and developed economies (Bednar & Reames, 2020; Sovacool, 2012).

Reliability and availability of modern energy services, regardless of time and location, require systems that can deliver energy services even during high demand or supply disruptions. The issue of defining and measuring the reliability of energy services was investigated by J. Ayaburi et al. (2020), who estimated that nearly 3.5 million people lack reasonably reliable access (primarily focusing on access to electricity in rural and remote areas). Building effective relationships and networks within communities and entrepreneurs can facilitate technology adoption and energy access. In addition, fostering collaboration with local and national stakeholders may help develop supportive policy frameworks and encourage higher private-sector participation. Lastly, supporting new entrepreneurs in this sector can help stimulate economic growth, reduce social inequities, and protect the environment (Reddy, 2015). The reliability of energy services and the systems that provide them can be enhanced and achieved through optimizing and developing existing infrastructure. Renewable energy sources (RES), such as solar, wind, geothermal, or hydropower, offer clean and affordable energy. According to the IEA analysis, the share of RES in the global energy mix has grown dynamically in the last decades. It can be stated that this decade will be a breakthrough and materialization of energy transition phenomena on a global scale (IEA, 2022b). Renewables will most likely become the largest source of global electricity generation by early 2025, surpassing coal (in 2027, the installed capacity of solar photovoltaic panels is poised to surpass that of coal by 2027). The policies and strategies for hydrogen production using RES substantially accelerate the development of the capacity of solar photovoltaic and wind power installations, becoming a disruptive factor for the energy sector (IEA, 2022b). The evidence shows a highly positive and statistically significant relationship between renewable energy utilization and sustainable development, with renewable energy having a more substantial positive effect on sustainable development than non-renewable energy. Developed and developing countries must prioritize renewable energy sources to increase sustainable development levels (Güney, 2019). The constantly declining cost of harnessing renewable energy makes these sources more and more competitive with conventional energy sources. More importantly, this process can be accelerated with an additional engagement of the scientific, financial, and public-policy communities (Chu & Majumdar, 2012).

The relationship between RES deployment and geopolitics has a long-standing tradition in academic research dating back to the beginning of the 1970s. Integrating into international organizations and joining the transnational climate change mitigation commitments and efforts to decrease CO2 emissions using renewable energy sources is a powerful incentive to increase access to clean energy (Przychodzen & Przychodzen, 2020). The consequences for international relations of the global transition from fossil fuels to renewables more broadly *may be a leveling of energy relations from asymmetric dependencies to mutual, horizontal dependencies, a shift away from existing energy alliances towards regional grid communities, and a greater diversity of actors involved in energy policy. Overall, renewables are expected to democratize domestic politics and international relations, stabilizing them in the process* (Vakulchuk et al., 2020, p. 9). The research also provides evidence that the growth of energy efficiency positively impacts sustainable development (Zakari et al., 2022).

As N. Hanley et al. emphasize, *energy efficiency improvements result in an effective cut in energy prices, which produces output, substitution, competitiveness, and income effects that stimulate energy demands* (2009, p. 692). The research and development of innovative technologies to generate, transmit, store, and utilize energy are crucial to achieving sustainable development goals. However, innovation requires significant investments in research and development, and the commercialization and diffusion of new renewable energy technologies can be challenging (Naber et al., 2017; Tabrizian, 2019).

The sustainable development of the transportation sector requires comprehensive access to safe, affordable, accessible, and sustainable transport systems. Several challenges can be identified in that domain. So does the energy sector, transport is responsible for a significant share of CO_2 emissions (which differs on the national and local levels). To address this challenge, it is necessary to reduce CO_2 emissions through cleaner initial combustion engine technologies or, most importantly, continue the deep decarbonization of this sector through its electrification. In addition, CO_2 emissions can be decreased by using alternative liquid transportation fuels, especially bio-fuels or hydrogen (Chu & Majumdar, 2012).

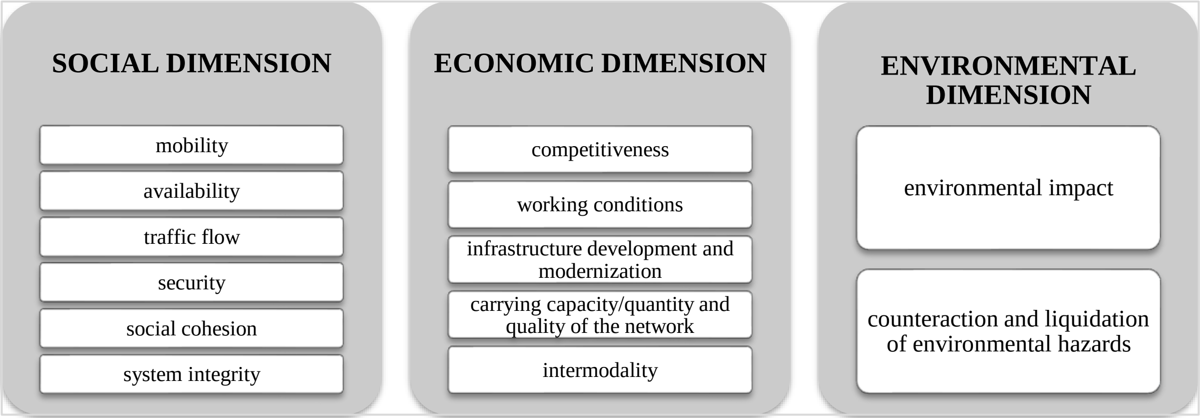


Figure 3. The social, economic, and environmental dimensions of sustainable development of the transportation sector. Source: Own elaboration based on T. Borys (2014).

T. Borys (2014) described the three dimensions of sustainable development of the transportation sector, underlining the social, economic, and environmental dimensions (Figure 3). The COVID-19 pandemic and the concurrent shift toward remote working and e-commerce are some factors that positively impact the decarbonization of the transportation sector (Zhang & Zhang, 2021). As B. Pawłowska concludes, effective transportation can be defined as meeting the demand for transportation services while minimizing the resources needed. Achieving a balanced and rational approach requires using effective tools to decrease the overall transportation intensity of the economy. This can be achieved by encouraging technological and organizational changes in transportation, reducing resource and energy consumption, and minimizing the negative environmental impact. Promoting efficient transportation practices can help reduce resource use, minimize energy consumption, and mitigate environmental issues (2015, p. 63).

In conclusion, based on the presented discussions, it is evident that incorporating environmental considerations in economic sciences has a long-standing tradition. However, it was not entirely emphasized until the latter half of the 20th century that integrating environmental, social, and economic aspects became a central topic in scientific and political debates. A key outcome of these debates was the concept of sustainable development, paving the way for subsequent theoretical advancements. One notable example explored by the author is the economics of sustainable development, which comprehensively tackles the three core challenges of sustainable development and introduces several guiding principles. To effectively address these principles, state interventions need refinement in both design and implementation, especially in areas like the energy and transportation sectors. Such policy-making should respect the constraints of our natural environment and drive state interventions toward fulfilling the postulates of the economics of sustainable development. These considerations will be expanded upon in the following subchapter.

1.2. The green industrial policy from the perspective of the economics of sustainable development

Before introducing and presenting the author's deliberations dedicated to green industrial policy, which could be identified as a new paradigm in industrial policymaking, it is crucial to discuss diverse aspects of state interventions in the form of economic policy as a broader concept. This overview will be followed by a demonstration of the conceptual framework of the industrial policy itself, considering its objectives, instrumentation, and horizontal and sectoral scopes. Finally, the author will seek to determine the relevance between the green industrial policy assumptions and the normative postulates of the economics of sustainable development.

1.2.1. State interventions and economic policy in selected theoretical schools

The intentional (purposive) and coordinated set of interventions made by state authorities or international organizations to shape an economy – its structure, functioning, and economic relations – can be referred to as economic policy (Winiarski et al., 2012, p. 18). According to J. Tinbergen (1956, pp. XIII–XIV), the aims of economic policy may be summarized as *(1) maintenance of international peace; (2) maximum real expenditure per capita with a "full" employment and monetary equilibrium; (3) improvement of the distribution of real expenditure over social groups and countries; (4) emancipation of certain underprivileged groups; and (5) as much personal freedom as compatible with the other aims.* However, economic policy aims are inconsistent, as they are derived from inconsistencies in the aims and behaviors of individuals. The essence of state intervention in economic policy was captured by J. Tobin, who noticed that economic growth has come to occupy an exalted position in the hierarchy of economic policy goals (1964, p. 1).

Nevertheless, since the 20th century, the role of state intervention in shaping economies through economic policy has been primarily a debate between two economic theories – **Keynesian economics** and **monetarism** (Sargent & Wallace, 1976). Keynesian economics[3] classically postulated that many economic decisions – public and private – influence aggregated demand. Choices made within the private sector contribute to adverse macroeconomic effects, such as decreased consumer purchases amidst an economic contraction. These instances

---

[3] Based on the need to explain the causes of market failures that led to economic crises, such as the Great Depression, J.M. Keynes developed an economic theory, named after his name, and presented it foundational postulates in *The General Theory of Employment, Interest, and Money* (1936).

of market failures may warrant proactive governmental measures, like the introduction of fiscal stimulus initiatives. As a result, the principles of Keynesian economics endorse a hybrid economic system, primarily steered by the private sector, while incorporating a significant degree of state intervention. According to Keynesian economics, while the market mechanism efficiently manages countless minor decisions, it falls short of ensuring equity, efficiency, and stability in crucial matters, especially during and after major economic shocks (Minsky, 1986, p. 324). Secondly, prices, especially wages, respond slowly to changes in supply and demand, leading to intermittent scarcities and excesses, particularly in labor resources. Thirdly, changes in aggregated demand, whether anticipated or unanticipated, have their most significant short-run effect on real output and employment, not on prices. Keynesian theorists posit that due to a certain degree of price rigidity, variations in any aspect of expenditure — be it consumption, investment, or government outlays — lead to alterations in output (Jahan et al., 2014, pp. 53–54). C*lassical* Keynesian economics recognizes the persistence and fluctuations of unemployment, distinguishes savings and investments, and underlines that disturbances in demand, not supply, underlie the cyclical behavior of macroeconomic aggregates[4] (Greenwald & Stiglitz, 1987). However, this approach evolved over the last decades toward new Keynesian economics as a response to observed discrepancies between Keynesian economics and real-world economic phenomena, much like Keynesian economics was a reaction to classical economic analysis[5]. New Keynesian economics identifies and underlines market imperfections, such as monopolies, non-competitive labor markets, and deviations in real interest rates, which challenge the self-regulating nature of market mechanisms[6]. It can be summarized that the critical postulates of new Keynesian economics revolve around fundamental tenets: (1) markets function based on imperfect competition, (2) private costs of rigidity are second order, (3) the demand determines output, (4) economic booms raise welfare, (5) wage rigidity causes unemployment through low aggregate demand, (6) real wages need not be countercyclical, (7) nominal rigidities have aggregate demand externalities, (8) real wages need not be countercyclical, and lastly, (9) wage and product prices

---

[4] According to this approach, economic policy should be focused on diminishing unemployment, and state interventions should rely significantly on fiscal policy.

[5] Specifically, new Keynesian economics recognizes that imperfect competition exists in price and wage determination, explaining the *stickiness* of prices and wages. This *stickiness* signifies that they do not immediately respond to fluctuations in economic circumstances. The presence of wage and price *stickiness*, along with other market imperfections observed in New Keynesian models, suggests that the economy may not necessarily achieve full employment.

[6] In the 1960s, this approach shifted towards examining the interdependencies between micro- and macroeconomics, with price and wage rigidity emerging as two primary areas of concern (Gordon, 1990).

rigidity (Mankiw et al., 1988, pp. 13–16).

Monetarism, as an opposite school of economic thought, was developed in the 1960s by, among others, M. Friedman, A. Schwartz, and F.A. von Hayek, who postulated that the money supply is the primary driving force influencing short-run economic activity from the demand side, as it impacts spending, investment, and overall aggregate demand within an economy. According to monetarism, the state, responsible for the money supply, should maintain *long-run monetary neutrality* since an increase in the money stock leads to a corresponding increase in the general price level, without affecting real variables like consumption or output, as these factors eventually adjust to the changes in the money supply. The state should also keep *short-run monetary non-neutrality* since an increase in the money stock temporarily affects real output (GDP) and employment, as wages and prices exhibit a delayed adjustment process, often referred to as *stickiness* in economic terms. The state should maintain a *constant money growth rule* – since predetermined monetary policy suggests that the central bank should aim to align the growth rate of the money supply with the growth rate of real GDP, maintaining a stable price level[7]. Lastly, the state that aims to follow the monetarist approach should keep *interest rate flexibility, which influences the cost of credit.* This adaptability allows borrowers and lenders to consider both anticipated inflation as a monetary phenomenon and fluctuations in real interest rates when making financial decisions (Jahan & Papageorgiou, 2014, pp. 38–39). In monetarism, the role of state intervention should be limited since it can cause adverse effects on economies, destabilizing them since the interventions are lagged in time concerning necessary interventions. This delay results from the time-consuming process of formulating and implementing appropriate economic policy responses.

Despite the discrepancies in perceiving the role of state interventionism, economic policy plays a role in stabilizing contemporary market economies (Blanchard & Summers, 2017). According to A. Lindbeck (1976, p. 1), stabilization of an open market economy can be achieved through four types of economic policies, including (1) policies designed to influence relative prices, (2) market-improving and mobility-increasing policies, (3) supply management, and (4) selective demand management. Noteworthy, implementing these policies may result in changes in an economic system's structure. It happens so that an economic policy may affect different subjects. There are three categories of economic policy subjects –

---

[7] For instance, if the economy is projected to grow by 2 percent in a specific year, the central bank should permit a 2 percent increase in the money supply. Adhering to established rules in implementing monetary policy is recommended, as exercising discretionary authority may introduce economic instability.

policymakers, stakeholders, and subjects (Buko, 2015). The first category of policymakers encompasses entities directly engaged in formulating economic policy, comprising state authorities, predominantly national (governmental) institutions, and those at regional or local administrative levels[8] (Persson & Tabellini, 2004). The second category of stakeholders comprises entities that seek to influence economic policy after it has been instituted, including civil society, non-governmental organizations, market participants (individual or collective), political parties, labor unions, media outlets, lobbyists, and other stakeholders (Kerr et al., 2014). The third category of subjects includes entities impacted by the implementation of economic policy, which generally includes all subjects of a national economy to a lower or greater extent. However, when considering specific sectoral policies within economic policy, it could describe a more precise group of subjects, such as particular demographics of citizens or market participants.

Economic policy depends on a multifaceted set of **determinants**, which can be divided into two primary categories: *external* and *internal*. *External determinants* include the international economic and political landscapes and affiliations with international organizations and alliances. It is worth emphasizing that international economic organizations influence economic policy and directly contribute to economic transformations and political, social, and cultural shifts within the member states. A nation's membership in these organizations, coupled with the interest of transnational enterprises in that country, confers credibility and fosters integration into the global economic system (Polak & Polak, 2017). On the other hand, *internal determinants* of economic policy comprise, i.e., the economic structure and conditions, the unique economic, socio-cultural, and environmental assets, country-specific spatial governance, intra-economy relations, and, critically, the domestic politics and public opinion regarding the political state of affairs (Winiarski et al., 2012, p. 52). In addition, the economic and political system, the administrative and social structures, and system solutions constitute an environment to formulate and implement economic policy. Undoubtedly, this institutional setting and division of power and competencies represent a set of crucial internal determinants of economic policy translating to its effectiveness or failure, as G.W. Cox and M.D. McCubbins (2007) advocate.

---

[8] International organizations, such as those responsible for regional economic integration, may also be included if they directly contribute to determining economic policy objectives or implementing economic policy instruments.

According to P. Deszczyński (2009), *space* and *time* are other determinants of a state's economic policy. Within these categories, significant changes occur, all of which are bound by the ongoing process of globalization. Considering *space*, the concern lies in the progressive attenuation of state sovereignty within its territory and the entities operating therein, a process commonly referred to as *deterritorialization*[9]. Besides already mentioned globalization and regional economic integration, it is crucial to mention technological developments, natural environment degradation and climate change, demographic shifts, urbanization growth, and geopolitics changes (Malik & Janowska, 2018).

Considering the mentioned determinants, economic policy within modern market economies can be succinctly delineated into distinct **functions**, as outlined by E. Szostak and M. Klamut (2016, p. 33). Primarily, it asserts influence on economic dynamics to perpetuate the influx of resources requisite for state-provisioned public goods. This encompasses judicial systems, public security, infrastructure maintenance and development, and the provision of educational services, healthcare, and social care. From a temporal perspective, economic policy can align its objectives on short- and long-term horizons. These functions predominantly revolve around incentivizing the market economy via stimulating development within specific national sectors or industries. This can be achieved through, i.e., the stimulations of export or import, fostering research and development, or safeguarding national defense capabilities.

Furthermore, the economic policy can facilitate efficient operations and necessary growth in sectors either (1) traditionally overlooked by the private sector or (2) those that have been nationalized, thereby removing them from private sector participation. Instances of such sectors may include energy generation and distribution, rail transportation, education, healthcare, and social care systems. The economic policy also has a protective function in insulating national economies from foreign competition. This can be done, i.e., by implementing a protectionist trade policy or subsidizing domestic enterprises. In identifying and addressing barriers to economic development, economic policy can potentially neutralize their detrimental impacts on the economy. The economic policy thus serves as a significant instrument in economic redistribution, stabilization, and in facilitating national spatial governance in the distribution of production factors throughout the nation. Consequently,

---

[9] Within the context of globalization, especially at the turn of the 20th and 21st centuries, the element of time exerts a dynamic influence. As such, the range of changes occurring within a single generation significantly surpasses previous limits, necessitating a comprehensive reassessment of the established economic development paradigm. Assuming that economic policy is a state response to the ongoing challenges, the contemporary trends in the global economy are separate determinants that influence economic policy.

it can be posited that economic policy in contemporary market economies principally fulfills three fundamental functions: *allocation, stabilization,* and *distribution*. State intervention in market mechanics, structures, operations, and economic relations, exercised through the instrumentality of economic policy, can serve to accomplish specific objectives.

Upon discussion of these outlined functions, it can be inferred that the central objective of economic policy is to foster economic development while concurrently upholding social welfare. As such, economic policy objectives can be organized into five comprehensive categories: *political*, *economic*, *social*, *environmental*, and *defense*, as presented in Table 3.

Category	Specific economic policy objectives
Political	• sustaining national sovereignty, • upholding justice in both social and economic domains, • safeguarding human rights, • strengthening fundamental political system operations.
Economic	• sustain economic development, • sustain effective exploitation and allocation of resources and structural changes, • increase in entrepreneurship and international division of labor. • correct the weaknesses of the market economy mechanism in three dimensions: *ineffectiveness of the market economy mechanism* (i.e., imperfect competition, monopoly, and extensive external costs (caused by natural environment disruptions)), *income inequality* (i.e., subjectively acknowledged excessive disparities in income and living conditions of the population), and *instability of the economy* (i.e., economic cycle fluctuations, recession or low economic growth rate, and unemployment).
Social	• ensure equitable income distribution, • guarantee employment and lower unemployment rates, • provide universal access to education and healthcare systems, • maintain an effective social security system.
Environmental	• preservation of the natural environment, • remediation and restoration of degraded areas, • preservation of the uninterrupted functions of the natural environment.
Defense	• development of specific industries related to national or international security • preserving necessary strategic asset reserves

Table 3. The examples of the specific economic policy objectives within five categories. Source: Own elaboration based on (Winiarski et al., 2012, p. 60).

Economic policy, as it focuses on fostering economic development and concurrently upholding social welfare by shaping a structure, functioning, and economic relations within an economy, may use a variety of policies to achieve this primary objective. Two policies are fundamental to economic policy - **monetary policy**[10] and **fiscal policy**[11]. In addition to these two policies

---

[10] The monetary policy regulates overall money supply and demand by introducing monetary policy instruments by respective authorities, such as central banks, to provide a stable background for a country's economic development (Friedman, 1967).

[11] The fiscal policy can be used to, for instance, influence economic conditions, stabilize economic cycles,

and within an economic policy framework, a state can stimulate economic development and increase social welfare by introducing other comprehensive state interventions formulated and implemented as specific policies toward shaping entire economic structures or relations within an economy.

1.2.2. The role of industrial policy in the process of structural change

An economic structure encompasses an economy's multifaceted composition of components and interactions with typologies highlighting product, spatial, ownership, and institutional approaches. The *product approach* sees the economy in terms of sectors and industries based on the nature of goods and services, comprising primary (raw material extraction), secondary (manufacturing), and tertiary (services) sectors[12] (Fisher, 1939). *Spatially*, economic structure elements are distributed across territorial units like regions or cities, emphasizing the importance of understanding regional contributions to a nation's total economic structure. The *ownership approach* segregates the economy based on ownership type—private (for-profit entities), public (state institutions and state-owned enterprises), and a notable third sector of non-profit voluntary activities emphasizing their socio-economic significance (Frumkin, 2002). From an *institutional approach*, established on the assumptions of institutional economics[13], the economic structure is categorized into five entities: non-financial corporations, financial corporations, general government, households, and non-profit institutions behavior[14] (Constantine, 2017). Structural change, perceived considering these four approaches, can be shaped by state interventions to achieve various objectives, including increased economic effectiveness, growth acceleration, unemployment reduction, technological advancement, global competitiveness, and barrier removal to foster economic

---

and increase or decrease aggregate demand for goods and services, employment, inflation, and economic growth (depending on if the applied fiscal policy is *contractionary* or *expansionary*).

[12] Many economic structure taxonomies classify industries and businesses based on the offered products or services. For instance, since its adoption in 1948, the United Nations has applied the *International Standard Industrial Classification of All Economic Activities* (ISIC), categorizing goods into 21 sections followed by divisions, groups, and classes (United Nations, 2008). Such a detailed set of activities allows for tracking changes in a country's economic structure on macro- or microeconomic levels and comparing the economies.

[13] Institutional economics analyses the role and evolution of institutions. The foundation of institutional economics is dated back in 1918 when Walton Hamilton announced its first assumption at the American Economic Association meeting and was substantial in the first half of the XX century. From that moment, institutionalism has undergone great changes, but it is still based on the postulate that underlines the crucial role of institutions in shaping human economic behaviors and economic activities (Hodgson, 2000).

[14] Many statistical institutions use this differentiation method to present various changes within economies. Those market participants constitute a complex network of relations and dependencies that translate to the dynamics of equity flows and transfers within an economy.

development. Notably, state interventions can modify industry resource allocation, amplifying or opposing market-induced allocative impacts (Rodrik, 2007).

According to C. Johnson, industrial policy means initiating and coordinating governmental initiatives to leverage the productivity and competitiveness of the whole economy and particular industries in it upward (Johnson, 1984). Industrial policy can also be perceived as an intervention made by a government to encourage resources to move into particular sectors that the government views as essential to future economic growth (Krugman & Obstfeld, 2009). Industrial policy can also be perceived as a state intervention that influences the relationship between business and government on a microeconomic level (Wachter & Wachter, 1981). A broad definition that is worth considering at the beginning of the following deliberations was brought up by K. Warwick (2013, p. 15), based on the initial explanation provided by H. Pack and K. Saggi (2006) - *industrial policy is any type of intervention or government policy that attempts to improve the business environment or to alter the structure of economic activity toward sectors, technologies or tasks that are expected to offer better prospects for economic growth or societal welfare than would occur in the absence of such intervention*. It also broadens the sphere of interventions beyond structural change to enhance the external and internal business environment. Within this definition, industrial policy is limited to shifting the allocation of resources across sectors and individual industries and technologies or tasks that go beyond a single stage in the value chain. Based on this approach, K. Warwick concludes that industrial policy aims to shape industrialization, enhance productivity growth, advance specific sub-sector development, generate or maintain employment, or rectify income disparities. Discerning the specific objectives of industrial policy bears significant implications for executing *ex-post* implementation assessments of its efficacy.

Furthermore, it is worth emphasizing that the industrial policy can be liberal and institutional in its nature, as underlined by M. Gorynia (2016, p. 35), who identified its four directions, including policy that supports economic development, competition, privatization, and economic self-government. As an example of industrial policy supporting economic development, M. Gorynia emphasized that the liberal and institutional industrial policy should support (1) investment, (2) innovation, research, and development, (3) education and training, (4) the development of information systems and the diffusion of information, and lastly, (5) spreading business risk. This approach demonstrates that the concept of industrial policy has evolved. According to J.E. Stiglitz, J.Y. Lin, and E. Patel (2013), the modern industrial policy represents a governmental effort focused on a sectoral allocation of resources to increase innovation and R&D advancements, infrastructure development and education system growth to support the integration of markets, thereby enduring economic stability. Emphasizing the socio-cultural (educational) dimension of industrial policy falls into contemporary discourse, where industrial policy must be revised and adjusted to modern challenges. Such an approach could be found in a synthesized industrial policy definition by M. Peneder (2017), who emphasized the necessity of fostering industrial development closely related to a society's long-term rise in living standards.

Noteworthy, industrial policy encompasses sectoral or horizontal state intervention. The sectoral industrial policy is characterized by its specificity to specific industries, such as steel, textiles, or automotive. The primary objective of this policy approach is the targeted support, development, or restructuring of these selected industries. This can be achieved through specific instruments such as direct subsidies, fiscal incentives like tax breaks, research and development grants tailored to the industry's needs, or protective tariffs to shield domestic enterprises from external competition. A representative application of this approach can be observed in tax incentives allocated exclusively for the renewable energy sector.

In contrast to the sectoral industrial policy, the horizontal industrial policy operates with a broader purview, encompassing multiple sectors. It aims to address systemic, economy-wide challenges and enhance the overall business and investment climate. This is achieved through measures that have a broad-based impact, such as infrastructure development, capacity-building initiatives in education and training, and general research and development support that is not sector-specific. For example, this approach exemplifies a country's strategic focus on improving nationwide broadband infrastructure or making research and development tax credits available across all industrial sectors.

As A.A. Ambroziak advocates, based on the comprehensive review of definitions and approaches, the interpretation of *industrial policy* varies based on its objectives, scope, tools, anticipated outcomes, and implications for the economy and the economic milieu in which it is applied. Concerning the objectives and mechanisms of industrial policy, the level of development in the country implementing such a policy appears to exert a substantial influence on the policy itself (Ambroziak, 2017, p. 3). However, it can be synthesized that industrial policy can perform many functions, including (1) facilitating a shift in the economy towards more productive industries, (2) stimulating innovation and technological progress by supporting research and development activities, (3) providing incentives for innovation, and (4) fostering collaboration between businesses, research institutions, and government. By supporting the growth of individual industries, industrial policy can facilitate job creation, contributing to economic stability and social development. It can also develop the skills and capabilities of the workforce through support for education and training programs and by fostering linkages between businesses and educational institutions. By regulating market mechanisms and promoting fair competition, industrial policy can help prevent monopolistic or unfair practices that harm consumers and other businesses. Industrial policy can support the transition towards environmentally sustainable industrial practices by providing incentives for low-carbon technologies, regulating polluting activities, and promoting sustainable resource management. Lastly, industrial policy can help to enhance a country's international competitiveness by supporting export-oriented industries, fostering the development of globally competitive businesses, and negotiating advantageous trade agreements.

It can be stated that industrial policy can represent two fundamentally different approaches – the *active approach* and the *defensive approach*. *The active approach* represents a focus on incentivizing structural changes within industries, growing innovativeness, and growing effectiveness and international competitiveness of industry, While the *defensive approach* translates to the protective function of industrial policy that may focus, i.e., on securing the jobs in declining industries, sustaining currently nonprofitable industries that might be strategically important in the future, providing independence from external insecure sources of supply (especially during the supply and demand shocks), or leveling monopolistic or unfair market practices. In detail, state interventions within the industrial policy framework can affect market supply and demand and be conducted concerning domains presented in Table 4.

Industrial policy domains	Examples of industrial policy incentives
Economic incentives	protecting intellectual property rights, price regulations, or countercyclical fiscal policy and tax breaks;
Scientific and technological innovation	high-tech lead projects, funding of university research, the establishment of research centers, R&D subsidies and/or tax credits;
Learning and improving technological capabilities	education and training campaigns, foresight exercises to identify national research priorities, labor training subsidies and/or tax breaks, skills formation and upgrading schemes, international educational and research collaboration, and incentives for foreign direct investment
Selective industry support	imposing import tariffs and/or quotas, providing export subsidies/credit/support, establishing special economic zones using state-owned enterprises, privatization, creating public utilities providing inputs (e.g., electricity), directed finance/subsidies, providing public guarantees, and direct state procurement policy.
Selection mechanisms	shaping entry and exit regulations for firms, providing anti-trust and competition regulations, as well as offering financial support to national trading companies.
Distribution of information	collective action mechanisms, promotion of standards, using consultative forums and business chambers, encouraging firm cooperation and firm linkages, supporting the marketing of export industries, and public dissemination of successful experiences.
Improving the productivity of firms and entrepreneurs	providing or subsidizing management training, establishing firm (SME) monitoring and assistance, offering funding and management for incubators and cluster formation, promoting public-private partnerships, conducting location marketing and enhancement alongside upgrading of economic Infrastructure, and stimulating the creation of venture capital funds.

Table 4. Industrial policy domains and types of incentives. Source: Own elaboration based on Naudé, 2010, p. 8.

The synthesis of these industrial policy domains and instruments may lead to the conclusion that industrial policy operates based on the vast portfolio of policy instruments. However, according to Criscuolo et al. (2022), who conducted a broad study within the OECD, different types of instruments represent different effectiveness. In their opinion, well-designed and structured R&D tax credits and subsidies can effectively stimulate R&D and innovation, while policies fostering skill and knowledge transfer serve as critical ancillary mechanisms. Evidence supporting the efficacy of targeted grants and subsidies is limited. The available data indicate a heightened effectiveness for small, young firms compared to large enterprises and multinationals. These instruments mitigate information asymmetry between investors and innovative ventures, thus relieving financial constraints. These findings propose that financial instruments, like public loans, guarantees, or public venture capital, might serve as more intriguing tools for targeted interventions, as opposed to grants. Framework conditions, particularly competition and trade policies, which sculpt the business environment, are vital to empowering high-productivity firms to expand, serving as a significant conduit for structural transformation. Inter-firm reallocation is a primary catalyst for productivity growth and structural change. Specifically, a substantial corpus of evidence indicates that competition policy promotes resource reallocation for heightened efficiency and, indirectly, encourages firms to innovate and adopt emergent technologies. Lastly, demand-side tools can effectively augment supply-side measures to stimulate innovation. Scholarly findings indicate that carbon pricing and environmental regulation are potent mechanisms for promoting firms' green transition, with minimal adverse effects on competitiveness. However, command-and-control regulations may constrain business dynamics over a prolonged duration. The contemporary discourse surrounding industrial policies has shifted away from debating their necessity towards strategizing their effective implementation and extracting transferrable lessons from successful instances of industrialization. This signifies a transition towards a practical and learning-oriented approach in industrial policy- making (Campos et al., 2021). Since the majority of the economies across the world fund their economic development on industrialization, this type of policy represents a significant part of state interventions. It also has a direct impact on decisions that are made in the context of the other areas of state interventions. At the end of these deliberations, it is worth citing K. Aiginger and D. Rodrik (2020, p. 203), who stated that in the 21st century (…), *industrial policy is a systemic approach that coordinates innovation, regional policy, and trade policy, with manufacturing at its core, while affecting upstream and downstream industries, sectoral change, clusters, and networks. It should be steered by societal goals that lead to sustainability and responsible globalization. Extending far beyond the correction of market failures* (…). Elements of such a modern approach to industrial policy-making can be found in green industrial policy, which will be further explained in the subsequent subchapter.

1.2.3. Green industrial policy as a new paradigm reflecting the postulates of the economics of sustainable development

In the 20th and 21st centuries, industrial policy was shaped by evolving approaches determining the objectives and extent of state interventions. As W. Naude postulates (2010), from the 1940s to the late 1960s, industrial policy concerning the structuralist approach prioritized industrialization as a prerequisite for development, addressing pervasive market failures in developing countries through strategies such as infant industry protection, state ownership, and coordinated state intervention. However, from the 1970s to the late 1990s, the perspective shifted, acknowledging significant practical obstacles to industrial policy and recognizing state intervention failures as potentially more detrimental than market failures. Industrial policy became synonymous with waste and rent-seeking, with a transition to trade liberalization, privatization, foreign direct investment attraction, macroeconomic stability, and minimal state interference as essentials for growth and industrialization, a mindset encapsulated in the *Washington Consensus* era. Transitioning into the 2000s to 2010s, the focus pivoted to balancing market and government failures. The emphasis rested more on the *how* than the *why* of industrial policy, recognizing the significance of institutional settings, policy design difficulties, and the necessity for flexibility in policy practice. Distinctions arose regarding the degree to which comparative advantage should be challenged, while innovation, technological upgrading, and fostering national innovation systems became central objectives of industrial policy. As discussed before, the contemporary approach to industrial policy has restored its place as a central domain of state intervention to foster economic development and social welfare, for example, can be found, i.e., in the postulates of new structural economics[15]. However, in the author's opinion, the modern approach to industrial policy requires considering the postulates of the economics of sustainable development. The *traditional*, or in other words, *positive* approach toward industrial policy implies that it encapsulates the necessity to anticipate long-term technology and market trends and incentivize structural adaptation of a national economy, enabling it to capitalize on these changes. As climate change mitigation and other environmental challenges increasingly steer the course of economic development, it becomes crucial to incorporate environmental considerations into industrial policymaking. This integration is the essence of green industrial policy (Altenburg & Assmann, 2017, p. 11). The fundamental meaning of environmental-oriented objectives within the green industrial policy can be found in the definition by S. Hallegatte (2013), who describes it as a specific industry sector-targeted policy that affects the economic production structure to generate environmental benefits. The green industrial policy also refers to any attempt in state intervention to hasten the development of low-carbon alternatives to fossil fuels

---

[15] This new doctrine attempts to build a bridge between structuralism and neoclassical economics with a wide range of interventionist instruments to promote an effective catching-up process for developing economies. New structural economics is founded on the following main assumptions which state that: (1) economic development is a result of perpetual technological and industrial innovation, (2) a country's economic structure is endogenous to the economy's endowment structure, (3) transformations of a country's economic structure stimulates economic development. Also, NSE postulates that mentioned structural changes increase labor productivity and reduce transaction costs. Moreover, new structural economics underlines the critical role of states in transforming a country's comparative advantages into competitive advantages by appropriate economic policies adjusted to selected sectors (Lin & Nowak, 2017). J.Y. Lin summarised the role of state interventions in new structural economics with this statement: (…) *the role of the state in industrial diversification and upgrading should be limited to the provision of information about the new industries, the coordination of related investments across different firms in the same industries, the compensation of information externalities for pioneer firms, and the nurturing of new industries through incubation and encouragement of foreign direct investments* (Lin, 2012, p. 29). It can be discussable if the phrase ‘new structural economics’ is suitable with no doubt since this doctrine mainly corresponds to many aspects of the structuralist approach to economics (also known as structuralism). Possibly, the name new structuralist economics or neostructuralism would underline those references more directly. From the other point of view, it is just a matter of onomastics, and the name new structural economics is explicit enough to explain those connections without a shadow of a doubt.

(Karp & Stevenson, 2012). This definition could be expanded with the assumption that green industrial policy is designed to stimulate and facilitate the development of environmental technologies using various investments, incentives, regulations, and other policy instruments (Allan et al., 2021, p. 3). S. Tagliapietra (2020, p. 20) suggests that green industrial policy necessitates applying specific instruments that exceed *traditional* industrial policy instruments. These instruments may not necessarily be new but should be adapted to align with a green industrial policy. Any green industrial policy mix should be coordinated with the policy tools employed for climate and industrial policies. For instance, carbon pricing is critical to the green industrial policy mix. If the carbon price remains insufficient to stimulate low-carbon technology innovation across industry and other economic sectors, the green industrial policy must resort to secondary alternatives.

D. Rodrik (2014) proposed two primary arguments for green industrial policy. Firstly, the emergence of new technologies, including low-carbon technologies, yields positive spillovers that exceed the initial investors' benefits, manifesting as cross-firm externalities, industry-wide learning, skill development, or agglomeration effects. The innovative nature, the highly experimental approach, and the significant risks faced by pioneering entrepreneurs suggest that low-carbon technologies might be exceptionally susceptible to these market failures. Secondly, low-carbon technologies warrant public subsidization due to the significant mispricing of carbon, a proxy for greenhouse gases (GHGs). This mispricing, rooted in fossil fuel subsidies and the absence of taxes or controls that would internalize climate change risks, reduces the user cost of carbon considerably below the sustainable level from a long-term societal standpoint. Consequently, the private return on low-carbon technologies falls significantly below the societal return, even when traditional R&D spillovers are not considered. Thus, the argument for subsidizing low-carbon technologies aligns with the general case for mitigating R&D-related market failures and is fortified by the independent rationale stemming from carbon under-pricing, necessitating industrial policy intervention in this domain.

As M. Wu & J. Salzman (2014) suggest, the convergence of environmental and industrial policy domains is primarily influenced by political and economic pressures, technological evolution, and energy security apprehensions. Due to years of research, technological advances have reduced the cost of renewable energy, making it more affordable. Simultaneously, justifying governmental expenditures supporting renewable energy policies solely on environmental bases has become challenging in the current era of fiscal austerity.

Governments are increasingly required to assure tangible benefits for their constituencies to validate spending on environmental policies. Consequently, to win public backing, governments are integrating expenditure on renewable energy projects into a comprehensive industrial policy to create well-compensated jobs in industries related to renewable energy technologies. Moreover, governments highlight industrial policy contribution to national security by reducing dependence on foreign energy sources, thereby accentuating the need to retain domestic manufacturing support for the renewable energy sector. The green industrial policy represents a normative approach toward industrial development and structural change with societal and environmental objectives and ethical imperatives as its essential foundation, thus fulfilling the normative postulates of the economics of sustainable development. Green industrial policy can perform four general functions, as W. Lütkenhorst et al. postulate (Lütkenhorst et al., 2014; Lütkenhorst & Pegels, 2014): *responding to pervasive market failures, addressing high uncertainty and long-time horizons, creating new pathways*, and, lastly, *disrupting old pathways*, which are further discussed:

Responding to pervasive market failures means that green industrial policy addresses a variety of market failures, such as imperfect competition, asymmetric information, externalities, coordination failures, and public goods. While price correction using market-based instruments such as taxes and quotas are vital, these policies also tackle other facets, acknowledging that more than pricing instruments are required, including feed-in tariffs and emission trading systems.

Addressing high uncertainty and long-time horizons**:** Given the exceptionally high uncertainty level and long causal chains inherent in green industrial policy, these strategies must contend with a plethora of factors. These include the dynamics of complex socio-economic systems, scientific modeling of climate change, unpredictable global policy approaches, and risks related to implementing innovative policy instruments.

Creating new pathways**:** Given the realities of path dependency, substantial carbon lock-in effects, and entrenched behavioral patterns favoring unsustainable production and consumption, green industrial policy is tasked with forging new industries that will contribute to sustainable development. These pathways require nurturing new advanced and transformative technologies while pushing for their commercial scalability and uptake, which calls for well-calibrated decisions and risk-taking, coupled with efforts to counter various behavioral biases.

Disrupting old pathways results in dismantling the industries with an adverse environmental impact while simultaneously transforming their structure and economic relations. This shift necessitates investment-discouraging incentives alongside investment-encouraging ones, with an acute focus on addressing the challenges of stranded assets and the pressing issue of limiting carbon emissions.

However, due to markets' inability to adequately price environmental externalities, green industries are predominantly propelled by policy measures that bolster the market by stimulating both demand and supply. While the optimal policy would involve pricing the relevant externalities, various obstacles prevent countries from achieving this. Consequently, green industrial policies are deployed as a practical (second-best) alternative. For this reason, green industrial policy is distinct from *traditional* industrial policy in three dimensions (Schwarzer, 2013). Firstly, green industrial policy relies on a larger scale of state intervention in the market. For instance, industries may be disinclined to invest in green R&D or adopt low-carbon technologies if future emissions ceilings are less stringent, reducing the profitability of current investments. Green industrial policies can provide the necessary impetus for such investments. Concurrently, future governmental policies are shaped by present investments. The feasibility of future carbon taxes hinges on the future availability of alternative fuels, which is inextricably linked to current investments. Secondly, the duration of industrial policies' necessity may extend based on the nature of the market failure. If the market failure is enduring and cannot be rectified through market-based policies for any reason, it would be necessary for industrial policies to persist similarly to maintain a level playing field. Thirdly, and lastly, the lack of fully matured competitive markets and industries of low-carbon technology-related products and services complicates the practical evaluation of green industrial policy performance. The global immaturity of those markets and industries and the lack of coordinated industrial policies worldwide lead to various distortions, rendering indicators like export data less helpful in assessing a policy's success.

The green industrial policy proposes exploiting various additional instruments based on the traditional portfolio of industrial policy instruments. It is worth noting direct public spending in infrastructure, education, training, and research and development relating to low-carbon technology. Another instrument is removing or reducing distortive subsidies for supporting industries representing adverse influence on sustainable development. The green industrial policy also involves sustainable public procurements and a conducive regulatory framework by, i.e., setting targets and limits. Green industrial policy should also provide sufficient protection of intellectual property rights. Like *traditional* industrial policy, green industrial policy may utilize targeted financial subsidies, grants or equity infusions, tax credits and rebates, low interest-rate loans, and loan guarantees (UN PAGE, 2017). For the use of the following deliberations, the green industrial policy instruments, as those which contribute to achieving environmental and climate objectives, will be categorized into seven categories, which include (1) regulations and standards; (2) taxes and charges; (3) tradable permits; (4) voluntary agreements; (5) subsidies and market-based financial incentives; (6) information instruments; (7) research and development incentives (Gupta et al., 2007).

Based on the abovementioned characteristics of the green industrial policy, it can be stated that it can have a crucial role in achieving the normative postulates of the economics of sustainable development. First, it is worth noting that green industrial policy directly corresponds to the postulate of strong sustainability since, at its core, this postulate emphasizes the irreplaceable nature of specific natural capital, asserting that human-made capital cannot entirely substitute for natural capital. The green industrial policy seeks to transition industries towards more environmentally oriented practices, among others, by fostering innovation in this domain, implementing regulations and incentives to protect natural resources, and integrating the value of natural capital into economic strategies. Therefore, green industrial policy is a practical concept to uphold and enact the strong sustainability postulate by underscoring the importance of a long-term sustainable vision over fleeting gains and reinforcing the symbiotic relationship between preserving the natural environment and shaping economic development. Secondly, with its instruments, green industrial policy can provide the framework for operationalizing the concept of sustainability by developing new measures and strategies oriented mainly at substituting non-renewable resources with renewable sources. Thirdly, the structural changes within an economy shaped by green industrial policy can lead to establishing and developing new markets for goods and services related to disruptive environmentally-oriented technologies. It can also be coupled with job creation and increase labor skills, i.e., in the context of the mentioned industries and renewable energy-related low-carbon technologies. Therefore, green industrial policy can strengthen the action toward achieving a sustainable socio-culturally and environmentally oriented market or mixed economies. Fourthly, thanks to the contribution of international organizations and institutions in promoting green industrial policy, this approach gradually becomes a new paradigm in industrial policy worldwide. Thereby, it can incentivize increasing global responsibility and cooperation in this domain.

On the other hand, the green industrial policy implementation is still based on the assumption of the complete rationality of individual economic agents (a positive *homo oeconomicus* model), whose decisions are incentivized by a presented set of instruments. These instruments, yet environmentally oriented, are not relevant to a requirement posed by the economics of sustainable development theorists – adjustment of an educational system to shape a new multidimensional rationality of individual economic agents postulated by the *homo sustinens* model. However, by offering a set of possible state interventions, the green industrial policy shall indirectly promote this new model by expressing *ecological rationality*, considering the natural environment limitations, and making policy decisions with the lowest possible adverse impact on the natural environment. Noteworthy, the green industrial policy is still a category of sectoral policies, limiting its overall potential impact on a particular sector or industry (depending on whether it is deployed horizontally or sectorally). In other words, it is certainly not a holistic solution to all issues within the three problem domains raised on the theoretical ground of the economics of sustainable development. However, it can provide a comprehensive policy framework for the necessary transition in modern industrial policy-making to fulfill some of the normative postulates of this newly established theory. An example of practical implementation of the green industrial policy approach, which fits into these normative postulates, is a policy for establishing and developing hydrogen-powered fuel cell electric vehicles (FCEV), which will be discussed in the following chapters, starting with the overview of the model value chain of a hydrogen economy and a market for these zero-emission vehicles.

2. THE ESTABLISHMENT AND DEVELOPMENT OF THE FCEV MARKET FROM THE PERSPECTIVE OF THE HYDROGEN ECONOMY CONCEPT AND THE ECONOMICS OF SUSTAINABLE DEVELOPMENT

One of the contemporary global shifts in the multidirectional energy transition is a broad spectrum of changes within the consumption of secondary energy sources. For decades, liquid fuels (such as gasoline and diesel from refined oil), electricity, and heat dominated the energy carriers' consumption. However, in response to the need to increase energy efficiency and decrease the adverse environmental impact of the energy sector, new energy carriers, including bio- and synthetic fuels, methanol, ammonia, and elemental hydrogen, have been broadly introduced in recent decades. The deployment of these energy carriers required structural changes in energy sectors worldwide, encompassing how they are produced, stored, transported, and finally used. Among those alternatives, hydrogen became one of the most promising energy-efficient alternatives to common liquid fuels[16]. The potential of hydrogen to become a considerable energy carrier became evident in the 1970s, leading to the development of the concept of hydrogen economy, which offers a theoretical concept of the hydrogen value chain. The following chapter aims to demonstrate this concept and, most importantly, emphasize the significance of establishing and developing the FCEV market to implement this concept successfully. As this concept is also based on the assumption that hydrogen can be a low-carbon alternative to fossil fuels in the transportation sector, the establishment and development of the FCEV market will be further discussed from the perspective of the normative postulates of the economics of sustainable development.

2.1.The hydrogen economy concept

2.1.1. The origins and assumptions of the hydrogen economy concept

The hydrogen economy concept was first formulated by J. Bockris and A.J. Appleby in the article titled *The hydrogen economy - an ultimate economy* (1972), where the authors identified the potential of hydrogen to replace gasoline and electricity and become one of the fundamental energy carriers for the industry (serving mainly as a carrier of energy sourced

---

[16] Hydrogen has the highest energy density by weight among common fossil fuels, roughly three times that of gasoline. However, as a liquid, its energy density by volume is about a quarter of gasoline's. This difference nesitates hydrogen comprassions to significantly higher pressures than common fossil fuels (as compared to CNG or LPG). Yet, due to availability of low- and zero-carbon-emission hydrogen production methods and the highest energy density-weight ratio, it demonstrates the most energy efficient and low-carbon alternative to common fossil fuels.

from the nuclear reactors). The term *economy* was used to explain the hypothetical value chain of hydrogen production, storage, transportation, and usage and its cost as estimated back in 1972. Some other early-stage contributors to this concept were T. N. Veziroglu, D.P. Gregory, D.Y.C. Ng, C.M. Long, and H. Robinson (Bockris, 2013).

Over the past decades, the hydrogen economy has been defined differently. Originally, J. Bockris (1977) defined hydrogen economy as a system where industry, transportation, and households are significantly dependent on energy from piped hydrogen, which would require the development of a large-scale pipeline system to transport hydrogen on the same basis as natural gas or together with natural gas in a balanced blend. Since hydrogen is not a primary energy source[17], S. Penner (2006) described the hydrogen economy as an industrial system in which one of the universal energy carriers is hydrogen (the other is electricity), which can be oxidized to water that may be reused by applying an external energy source to dissociate water into its components – hydrogen, and oxygen. M. Conte (2009) associated the hydrogen economy concept with the idea that hydrogen can be a dominant energy carrier and fuel in an economy that largely depends on electricity generated from renewable sources to decrease carbon emissions. The hydrogen economy was also described by N. Hashem and C. Wang (2016) as an economy that relies on hydrogen as the commercial fuel that would deliver a substantial fraction of a nation's energy and services.

In addition, it is worth mentioning that this concept covers a set of processes and technological methods, starting from the production stage, through its storage and transport, to conversion into the desired forms of final energy (Chmielniak et al., 2017). Since the growth of the importance of the hydrogen economy translated to the industrial policies of individual countries and international organizations, it is worth mentioning the European Union's approach toward this concept. According to the *Hydrogen Strategy for a Climate-Neutral Europe*, developing a hydrogen economy in Europe requires a complete value chain approach. The production of hydrogen from renewable or low-carbon sources, the development of infrastructure to supply hydrogen to end-use consumers, and the creation of market demand need to go in parallel, activating a virtuous circle of increased supply and demand for hydrogen

---

[17] Primary energy sources are those, which have not been subjected to any human-engineered conversion process. This category includes all fossil fuels (oil, natural gas, coal), nuclear energy, biomass, and waste, and all renewable energy sources such as hydro, solar, wind, geothermal power, or tide wave energy. Secondary energy sources represent a broad group of energy carriers, mainly electricity, but also refined oil (gasoline), hydrogen, and steam in municipal heating systems.

(2020). Based on the demonstrated review of definitions, it can be stated that *hydrogen economy* refers to the concept that assumes the economy-wide use of hydrogen (produced with the use of renewable or low-carbon energy sources) as a carrier and method of storing energy, replacing fossil-fuel-based primary energy sources and, at the same time, balancing surpluses and losses in the energy sector resulting from sourcing energy from renewable sources.

Since the hydrogen economy concept emphasizes the opportunity to decrease carbon emissions intensity in energy conversion, storage, and distribution, it can significantly contribute to the energy transition and sustainable development. It is essential to emphasize that hydrogen penetration of the global energy sectors is potentially feasible, as demonstrated in the study by Chapman A. et al. (2020). In this research, the authors developed a detailed global linear optimization model of hydrogen's role in the future global energy sector considering various factors and scenarios, including the impact, i.e., of Carbon Capture and Storage (CCS) delays in implementation in the hydrogen production methods or the future role of nuclear energy in the global energy mix. Their results show that hydrogen can be crucial in the global energy mix, accounting for approximately 2% of global energy needs by 2050. However, the share of hydrogen in the energy mix can be regionally differentiated, as A. Odenweller et al. (2022) suggest, i.e., accounting for the EU up to 11.2% (0.7–3.3% globally). Establishing a hydrogen economy requires in-depth changes in contemporary methods of hydrogen production, storage, and transportation, allowing diversification of the hydrogen end-use applications, where this energy carrier may replace fossil fuels, i.e., in transportation, thanks to the application of fuel cells. The opportunities for such a change exist alongside the entire value chain of a hydrogen economy.

2.1.2. The value chain of the hydrogen economy

A value chain can be defined as the complete range of value activities that are required to bring a product or service from conception through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use (Kaplinsky & Morris, 2012). According to M. Porter (2000, p. 57), the appropriate degree of disaggregation of value activities that constitute a complete value chain depends on the economics of the activities and the purposes for which the value chain is being analyzed. The basic principle is that value activities should be isolated and separated in that (1) either have different economics,

(2) have a high potential impact of differentiation, or (3) represent a significant or growing proportion of costs alongside the value chain. As a secondary energy source, hydrogen can be produced from, i.e., water, biomass, or fossil fuels. For this reason, the hydrogen economy concept encompasses various value activities that constitute a complete value chain, including hydrogen production, storage, transportation, and end-use applications. At the same time, those activities are supported by state interventions (Demirbas, 2017), which will be further discussed in the following subchapters.

Hydrogen production

Hydrogen can be produced using diverse industrial methods (Figure 4), which differ according to primary energy feedstock, CO_2 emissions intensity, energy efficiency, cost-effectiveness, and scalability. Hydrogen is mainly produced from fossil fuels using either hydrocarbon pyrolysis (decomposition of hydrocarbon compounds by heating in the absence of oxygen) or conversion of syngas[18]. The most cost-effective, scalable, and, at the same time, the most frequently used method of hydrogen production worldwide is steam reforming of methane (SMR) or steam reforming of other light hydrocarbons, such as propane-butane (Nikolaidis & Poullikkas, 2017). The energy feedstock in this method is natural gas, which consists mainly of methane. This method is characterized by the lowest emission intensity among all other hydrogen production methods from fossil fuels, including coal gasification, natural gas pyrolysis, or hydrogen separation from coke-oven gas (Ball & Weeda, 2016).

---

[18] Syngas (also known as synthesis gas) is a mixture of hydrogen and carbon monoxide in various ratios, produced from hydrocarbons using partial oxidation, steam reforming, autothermal reforming, or coal gasification.

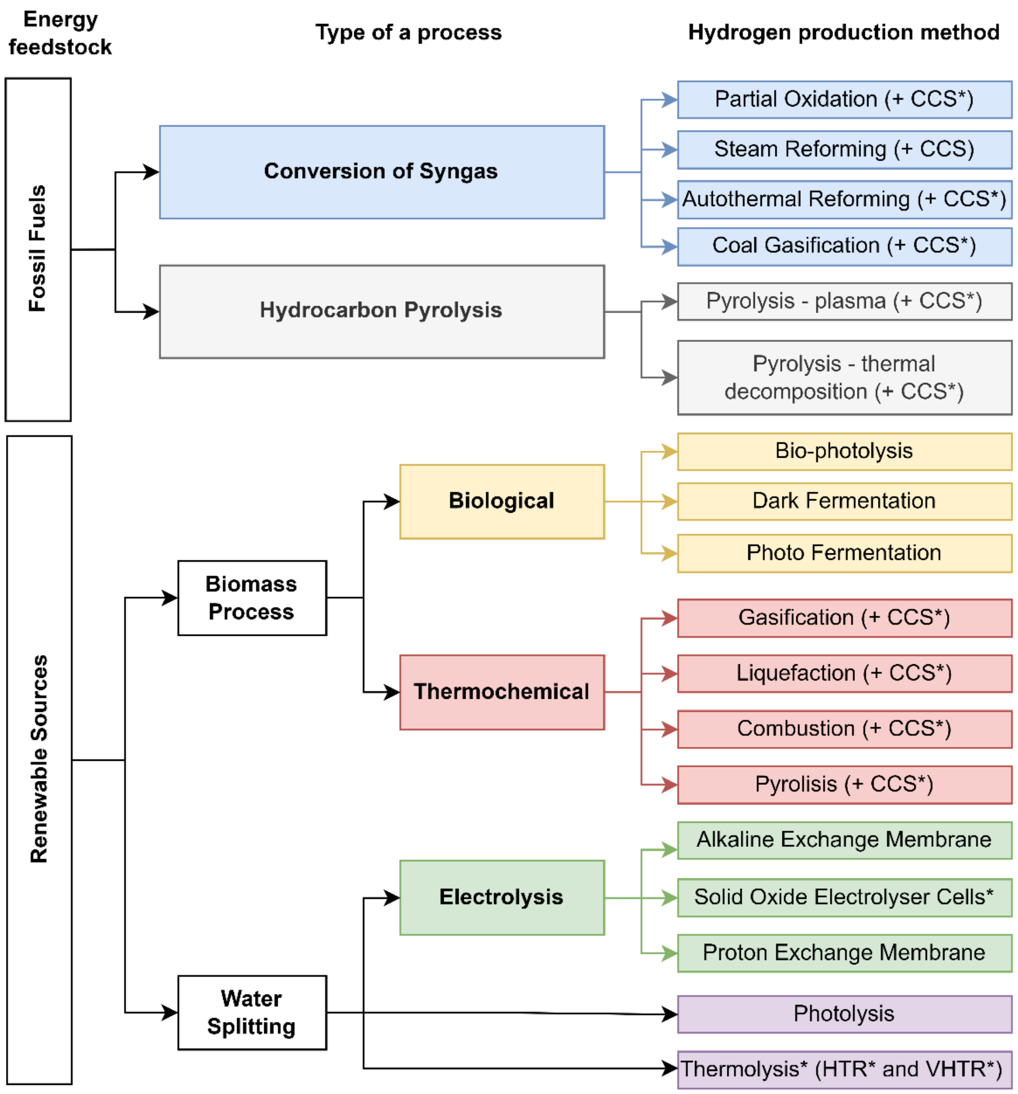


*Figure 4. An overview of the hydrogen production methods (CCS - Carbon Capture and Storage, * = a technology is at a low Technology Readiness Level, including small prototype (1-4), large prototype (5-6), and demonstration (7-8) levels). Source: Own elaboration based on: Kumar et al. (2019), Frowijn and van Sark (2021), and IEA (2021b).*

The SMR method is often used to produce hydrogen due to its high-efficiency rate (70 to 85%), low operational energy feedstock, and production cost. On top of that, it is worth mentioning that hydrogen also plays an essential role in producing other fuels. In refining crude oil, hydrogen recovery units allow hydrogen production from syngas using nanomembranes or low-temperature liquefication methods at various stages. Hydrogen in refineries is produced and used continuously, so there is no need to build installations for its storage. According to the International Energy Agency, in 2021, 62% of global hydrogen production came from SMR, 19% from coal gasification, and 18% from refinery processes. The remaining 1% of global hydrogen production was either generated using SMR with Carbon Capture and Storage technology (which significantly reduces the carbon footprint of this process) or produced using other alternative methods, including electrolysis or biomass processes (IEA, 2022a). Hydrogen production in the electrolysis process uses electricity to power electrolyzers (industrial devices that allow hydrogen generation from splitting purified water). Electrolyzers can be powered with power grid electricity or installed as part of renewable energy installations using solar or wind energy in a microgrid.

The emissions intensity of hydrogen production varies widely depending on the production route. Estimations of the emissions intensity of each method require a broad approach to the lifecycle analysis of those processes. The average CO_2 emissions intensity of global hydrogen production in 2021 was 12-13 kg of CO_2 equivalent per 1 kg of hydrogen (kgCO_2-eq/kgH2). The emissions intensity of fossil-fuel-based methods can be reduced with Carbon Capture and Storage applications, which offer a wide range of carbon capture rates (up to 98%). However, most low-carbon emission intensity production methods, including those that apply CCS, are still at low Technology Readiness Levels, meaning they operate as small or large prototypes or have reached a demonstration phase. As mentioned, comparing hydrogen production methods in terms of carbon emission intensity requires a lifecycle analysis and consideration of the impact of the CCS application. Based on the global data provided by IEA (2023), it can be stated that the median emissions intensity of hydrogen production using steam reforming of hydrocarbons is 15 kg CO_2-eq/kgH2 (4 kgCO_2-eq/kgH2 with CCS), and for coal gasification is 23 kgCO_2-eq/kgH2 (3 kgCO_2-eq/kgH2 with CCS). The emissions intensity of water electrolysis depends on the energy source: for solar, wind, and nuclear energy, it is less than 1 kgCO_2-eq/kgH2, but considering the utilization of power grid electricity and the current global energy mix, this rate can exceed 23 kgCO_2-eq/kgH2, but certainly it will vary across individual countries. It is worth noting that biomass processes are the only group of hydrogen production methods that may offer a *negative* emissions intensity (in the case of CCS applications) equal to -22 kgCO_2-eq/kgH2.

In the context of individual countries, it is worth mentioning the US hydrogen economy, where the hydrogen production in 2021 mainly relied on hydrocarbon reforming without CCS (95% of total production), offering emissions intensity at a 10-15 kgCO_2-eq/kgH2 levels. The remaining 5% of hydrogen production was shared by hydrocarbon reforming with CCS (2-6 kgCO_2-eq/kgH2), water electrolysis using electricity coming from renewable or nuclear energy (less than 0.5 kgCO_2-eq/kgH2), and water electrolysis using power grid electricity (25-27 kgCO_2-eq/kgH2). Such high emissions intensity from water electrolysis using power grid electricity can be mainly associated with the relatively low share of RES (13%) in the US energy mix (US DOE, 2023). As it shows, the differentiation of hydrogen production methods based only on the type of primary energy feedstock or technology might be misleading since the low-carbon hydrogen production from fossil fuels with CCS can reach much lower emissions intensity than, i.e., water electrolysis using power grid electricity.

The diversity in carbon emission intensity levels translated to the nomenclature used to categorize the hydrogen production methods. Even though hydrogen is an odorless and colorless gas in standard conditions, it has been symbolically named with different colors based on the source of energy feedstock from which it came (Mohideen et al., 2023). For instance, if hydrogen was produced using electrolysis powered with renewable energy sources, it was named *green*, electrolysis powered with nuclear energy – *pink*, hydrocarbon reforming – *grey*, hydrocarbon reforming with CCS – *blue*, and coal gasification – *black*. This nomenclature can be perceived as highly discussable since it is not relevant to the entire lifecycle emissions intensity, and more importantly, it is not consistent across individual countries or even research groups. Therefore, the *hydrogen rainbow* can be perceived nowadays as a misleading concept or, in some cases, as a *green-washing* activity that was recognized by international institutions such as IEA, which advocate for a complete and internationally agreed system of hydrogen labeling and certification based on lifecycle emissions intensity (IEA, 2023b).

The recent growth of the importance of hydrogen certification also led individual countries to unify the national rules of hydrogen labeling. This ongoing process focuses on establishing the carbon emission intensity levels that will recognize the sufficiently low carbon emission intensity of hydrogen production methods. It is crucial to align the hydrogen production requirements with the energy transition and climate neutrality objectives. For instance, the US Department of Energy (US DOE) classified low-carbon emission intensity of hydrogen as ***clean hydrogen*** (< 2 $kgCO_2$-eq/kgH_2), while the European Union established a standard of *renewable hydrogen* (< 3.38 $kgCO_2$-eq/kgH_2) (EPRS, 2023; US DOE, 2023). In the following deliberations, the author will use the term *clean hydrogen* to describe the low-carbon emission intensity of this energy carrier since *renewable hydrogen*, according to the EU nomenclature, excludes the low-carbon emissions intensity production methods that use CCS from fossil fuels. The following link of the value chain is hydrogen storage.

Hydrogen storage

Before discussing the storage methods, it is worth emphasizing one crucial physical attribute of hydrogen that impacts every other link of the hydrogen economy value chain – hydrogen embrittlement. It is a metallurgical phenomenon that occurs when metals, particularly high-strength steels, absorb hydrogen, leading to a reduction in ductility and load-bearing capacity. This can cause the metal to become brittle and fracture at stress levels below its normal yield strength. The process usually occurs in three stages: hydrogen ingress into the metal, hydrogen interaction with the metal lattice causing lattice defects, and failure due to the reduced tensile strength and ductility caused by these defects (Robertson et al., 2015). Hydrogen embrittlement can significantly impact the hydrogen value chain by posing technological barriers to hydrogen storage, transportation, and use. The high-pressure storage tanks and pipelines used in hydrogen infrastructure are generally made of high-strength steel susceptible to embrittlement, leading to potential fractures and leaks that pose safety risks and efficiency losses. Similarly, components of fuel cell electric vehicles or other hydrogen-powered devices made of susceptible materials may be prone to early failure or reduced performance due to embrittlement, impacting the reliability and adoption of these technologies. The broad discussion of the advantages and disadvantages of storing energy in the form of hydrogen was brought up by A.T. Szablewski (2021), who also emphasized the critical need to construct hydrogen storage installations insusceptible to extremely low temperatures (up to -253 ^{o}C), and pressures (example of which are hydrogen fuel storage tanks in FCEVs available in two standards – 350 bar and 700 bar). Nevertheless, among other low-carbon energy carriers and energy storage methods, hydrogen might be perceived as a solution worth further research and development (especially in countries planning to reach climate neutrality soon).

Despite the abovementioned chemical and physical limitations, there are dozens of differentiated stable and safe hydrogen storage methods, but generally, they can be divided into **above-ground** and **underground installations**. Hydrogen can be stored in above-ground high-pressure vessels (including storing hydrogen in liquefied form) (Züttel, 2004). Even though this method is widely used, the ultimate future of hydrogen storage is the solid-state storage method. The solid-state storage method comprises complex hydrides, chemical hydrides, magnesium-based alloys, and intermetallic compounds (Tarhan & Çil, 2021). More importantly, due to the emerging role of hydrogen in transportation and energy system stabilization concerning RES operations, high-pressure vessels will also become essential for hydrogen storage (Elberry et al., 2021).

Alternatively, large-scale hydrogen storage can be done with underground installations. As R. Tarkowski underlines, there are four main techniques: utilization of salt caverns (underground caves), deep acquires, as well as depleted oil and gas fields (which are not different from underground CO_2 storage techniques) (Tarkowski, 2019). Underground hydrogen storage faces challenges related to geological and technical factors, choosing appropriate cost-effective and efficient storage methods, and regulatory issues. Identifying suitable geological formations, assessing the risk of hydrogen leakage, and evaluating potential impacts on surrounding ecosystems and groundwater resources are fundamentally important to developing these installations. Potential technical barriers include project scalability, operation safety, hydrogen embrittlement, and blending with other gases. Furthermore, clear regulations and guidelines are necessary for the development of underground installations and public acceptance of these storage projects. Lastly, coordinating international efforts is vital to promoting a hydrogen economy and its infrastructure for storing hydrogen (Zivar et al., 2021).

Hydrogen transportation

Hydrogen can be transported using all modes of transportation, including road, rail, air, sea, and gas pipelines. Road transportation is the most common method for short distances, while rail is suitable for longer distances and larger quantities. Air transport offers advantages for liquid hydrogen, while sea transport, yet cost-effective, requires better insulation for long distances. Gas pipelines can effectively transport hydrogen over long distances, with many natural gas pipelines capable of carrying hydrogen blends (up to 20% of hydrogen). When comparing different transportation methods, liquefied hydrogen is more cost-effective than compressed hydrogen. Decentralized hydrogen production is advantageous for market uptake, as it minimizes the need for distribution infrastructure but is less efficient than large-scale, centralized production (Salvi & Subramanian, 2015). Despite this progress, hydrogen storage and transportation methods have not advanced simultaneously. As a result, scientists are now exploring different blending techniques (exploiting conventional fossil fuels) to improve the safety and efficiency of hydrogen storage and transportation (Kar et al., 2022).

Hydrogen end-use applications

It is essential to emphasize that, nowadays, hydrogen is widely used in various industrial applications. First, hydrogen is used in oil refining processes, such as hydrocracking and hydrotreating, to remove impurities like sulfur from petroleum and its products. These processes help to produce cleaner fuels and reduce carbon and other emissions.

The most significant use of hydrogen is in the Haber-Bosch process for ammonia production, primarily used to create fertilizers for agricultural processes[19]. Hydrogen is used to produce methanol through a process that combines carbon monoxide and hydrogen in the presence of a catalyst. Methanol is widely used as a feedstock in the chemical industry, particularly for producing formaldehyde and a variety of plastics. In some steelmaking processes, hydrogen can be used as a reducing agent to remove oxygen from iron ore. This process, known as direct reduced iron, is increasingly used to produce low-carbon steel. Hydrogen is also used as a carrier gas to deliver silicon and germanium precursors during epitaxy, a process in which a thin semiconductor layer is deposited onto a semiconductor wafer. Hydrogen is also used for cleaning chambers where silicon wafers are processed and as a reducing agent for producing semiconductors. Lastly, it is worth mentioning hydrogen utilization in hydrogenation[20]. As the world moves towards deep decarbonization of individual sectors and entire economies, there is increased interest in clean hydrogen, which could significantly reduce the carbon footprint of these industrial processes. In other words, the transition toward the hydrogen economy is a dual process of simultaneous (1) replacement of conventional (high-carbon) hydrogen with clean hydrogen to decrease carbon emission intensity of the mentioned industrial process and (2) expansion of the portfolio of hydrogen end-use applications to decarbonize the industries where hydrogen was not used so far leading to overall decarbonization of economies.

Therefore, hydrogen has many potential new applications, particularly in the energy and heating sectors. It can serve as a stabilizing factor for installations that process renewable energy sources, enabling the storage of excess energy, such as surplus electricity from renewable sources, and co-combustion with natural gas in gas turbines. Additionally, hydrogen can be utilized in co- and polygeneration heating installations, where more than one primary energy feedstock is used.

Another important potential application of hydrogen is as an alternative fuel in the transportation sector, particularly in heavy-duty vehicles such as trucks and buses. Fuel cells are expected to reduce carbon emissions in all transportation segments, including sea, river, rail, and air transportation. Moreover, clean hydrogen can reduce carbon emission

---

[19] This process combines hydrogen (usually derived from natural gas) and nitrogen under high pressures and temperatures in the presence of a catalyst to produce ammonia.

[20] Hydrogenation is a chemical process used in the food industry to produce margarine and other foods containing trans fats). This process involves the addition of hydrogen atoms to unsaturated fats and oils, which makes them more solid.

intensity in energy-intensive industries, particularly in the chemical, petrochemical, refining, and nitrogen fertilizer production sectors. As hydrogen and fuel cell technologies continue to advance, it is conceivable that they will be used even more in these industries and potentially in other sectors of the economy where conventional methods are used. As Oliveira et al. suggest (2021), clean hydrogen ought to be applied in a specific order, starting with the industrial sector, where clean hydrogen can reduce CO_2 emissions significantly, and subsequently leveraging hydrogen's compatibility with existing fossil fuel infrastructure for the transportation and building sectors, while also fulfilling the power sector's seasonal storage demands. However, the application of *clean* hydrogen may vary across individual countries depending on the nationally recognized priorities. The distribution and allocation of *clean* hydrogen projects worldwide are diverse. According to the IAE database of 1478 clean hydrogen technology projects commissioned so far worldwide, certain countries and international organizations are the leaders in this domain, as presented in Figure 5, including the European Union (mainly Germany), the United States of America, Australia, China, South Korea, and Japan.

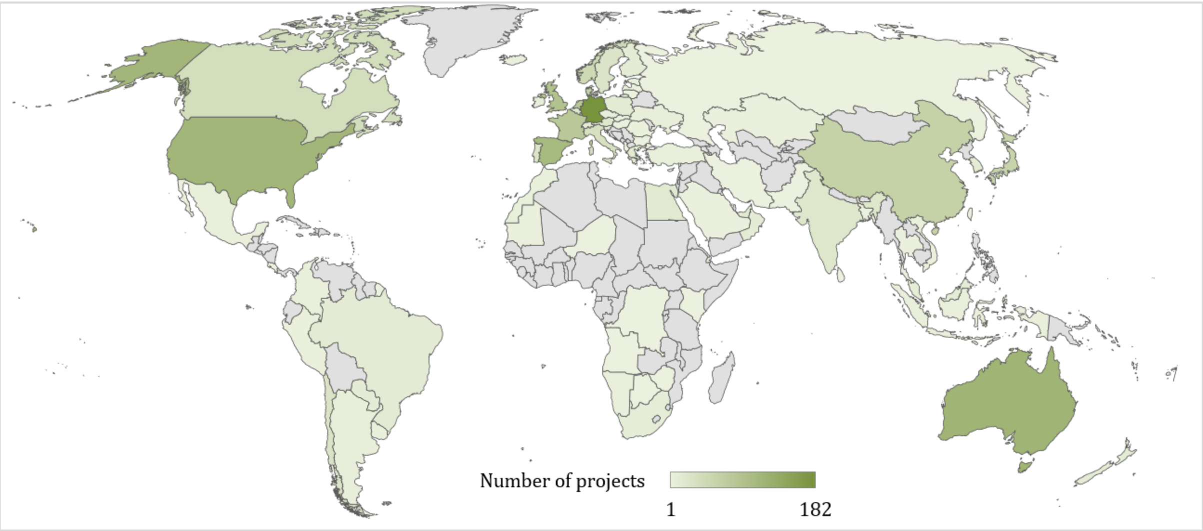


Figure 5. The number of low-carbon and clean hydrogen technology projects commissioned worldwide. Source: Own elaboration based on the IAE worldwide database of hydrogen projects (2021a).

Each of these countries and international organizations represents different motivations for establishing and developing hydrogen economy value chains. However, they are aligned with the nationally adopted hydrogen strategies. The study shows that major global economies such as Japan, the United States, the EU, and China have implemented targeted development plans and technology roadmaps to ensure a cost-effective progression toward a hydrogen economy. While the strategic outlook of these countries exhibits a consensus on the opportunities and challenges associated with the hydrogen economy, their competitive positioning would invariably instigate long-term rivalry. The strategic emphasis of these nations, particularly in the realm of technology innovation, underscores significant differences. Japan's substantial initial investment in research, development, and demonstration projects has made it a patent leader. At the same time, the United States prioritizes the development of breakthrough technologies despite inherent risks, given the high potential returns. The visions for the hydrogen economy also vary. While the United States aims to produce hydrogen from local resources in hydrogen hubs, Japan expects to import it from politically stable countries with abundant, low-cost fossil fuel resources. The EU presents a balanced strategy, and China sees hydrogen as a significant part of its energy restructuring (Dou et al., 2017). Furthermore, the revived attention towards the hydrogen economy, resulting in the creation of ambitious targets incorporated into both national and international strategies, suggests that hydrogen is expected to play a crucial role in the energy transition of the 21st century (Capurso et al., 2022). While progress has been made in *clean* hydrogen production, the storage and transportation lag, prompting research into safe blending options, which do not significantly contribute to the overall decrease in carbon emission intensity. Noteworthy, countries like Japan, South Korea, and Germany lead in applications such as hydrogen-powered fuel cell electric vehicles and stationary fuel cells. The bibliometric review shows that research trends indicate a growing focus on reducing hydrogen economy barriers, policy formulation, hazard mitigation, and safe hydrogen blending. This necessitates extensive interdisciplinary collaboration among researchers and hydrogen economy stakeholders from state governments and international organizations (Kar et al., 2022). Besides, it is worth noting that the potential of a hydrogen economy in the deep decarbonization of many industries can significantly contribute to sustainable development, which was already recognized at the beginning of the 21st century (Barreto et al., 2003; Conte et al., 2001). This contribution is feasible, especially in the context of SDG 7, which is discussed further at the end of this chapter. Still, it requires well-crafted industrial policies addressing various trade-offs, considering cross-sectoral impacts on other SDGs, and navigating hydrogen technology uncertainties while addressing socio-technical needs and expediting the transition to a green hydrogen economy (Falcone et al., 2021). Moreover, state interventions will counter potential market failures, stimulate the widespread use of hydrogen, and establish international governance and regulations (Beck et al., 2021). It can be stated that the presented strategies will navigate the development of a hydrogen economy by setting the objectives for green industrial policies and strategies on national and international levels.

2.1.3. *The significance of green industrial policy for the hydrogen economy development*

Establishing and developing a hydrogen economy requires multi-dimensional structural changes as part of the energy transition process, which can be significantly shaped by horizontal green industrial policy. In this context, the green industrial policy may address the necessity to merge long-term technology and market trends with environmental considerations by incentivizing the relocation of resources within and across entire sectors. Such a horizontal state intervention is fundamental to forming low-carbon alternatives to fossil fuels by establishing and developing hydrogen economy value chains.

Furthermore, green industrial policy becomes even more relevant in the context of the hydrogen economy due to the significant mispricing of carbon and the resulting underpricing of greenhouse gas emissions. Fossil fuel subsidies and the absence of appropriate carbon pricing mechanisms create an economic environment where the user cost of carbon is considerably below its actual societal value. As a result, the private return on low-carbon technologies, including low-carbon and clean hydrogen technologies, falls short of the broader societal return. By implementing green industrial policy measures such as public subsidization, states can bridge this gap and incentivize the development and deployment of sustainable hydrogen solutions. Therefore, green industrial policy plays a crucial role in the transition toward a hydrogen economy by addressing market failures, facilitating positive spillovers, and correcting the mispricing of carbon. By providing targeted support and incentives, policymakers can promote the growth of the low-carbon hydrogen economy, foster innovation, and help realize the potential of hydrogen as a clean and sustainable energy carrier. It could be synthesized that the adoption of this new paradigm in industrial policy will perform four functions in the context of the transition toward a low-carbon hydrogen economy (following the identified functions (Lütkenhorst et al., 2014; Lütkenhorst & Pegels, 2014):

Responding to pervasive market failures – Green industrial policy can help address market failures in the context of establishing and developing a hydrogen economy by providing subsidies or incentives for clean hydrogen production. For instance, while fossil fuel-based hydrogen is cheaper to produce due to existing infrastructure, clean hydrogen has more considerable societal benefits regarding reduced carbon emissions. Government interventions can help correct this by making clean hydrogen production more financially appealing to businesses, thereby encouraging a shift towards cleaner practices.

Addressing high uncertainty within long-time horizons – Green industrial policy can also reduce uncertainty and risks associated with investing in the low-carbon hydrogen economy. This can be achieved through long-term commitments, such as guarantees for clean hydrogen purchases, robust regulatory frameworks, or direct investment in R&D and infrastructure. These actions provide certainty for investors, stimulate innovation, and signal a sustained commitment to the development of the hydrogen economy.

Creating new development pathways – by providing support for education, training, and R&D in the field of green hydrogen, green industrial policies can help create new pathways for the hydrogen economy. This includes fostering collaborations between academia, industry, and government to drive innovation, promoting clean hydrogen in sectors where it was previously unfeasible or inefficient, and creating the necessary legal and infrastructure frameworks for clean hydrogen production, storage, and distribution.

Disrupting old development pathways – Green industrial policy can disrupt old, carbon-intensive development pathways by implementing regulations limiting greenhouse gas emissions or removing subsidies for fossil fuels. Such actions make clean hydrogen more competitive, encouraging industries to transition towards more sustainable energy sources. Additionally, standards and regulations can be implemented to ensure new infrastructure is compatible with clean hydrogen, making it harder for industries to continue down the old, fossil fuel-based pathways.

Following D. Rodrik's postulates (Altenburg & Assmann, 2017), the significance of green industrial policy in the transition toward a hydrogen economy lies in its ability to address market failures and promote the development and adoption of low-carbon hydrogen technologies. The emergence, adoption, and deployment of these technologies, including those related to hydrogen production and end-use utilization, often lead to positive spillover effects and externalities that extend beyond the initial investors. These spillovers can include cross-firm collaborations, industry-wide learning, diffusion of knowledge and innovation, and skill development. Green industrial policy can provide targeted industrial policy instruments to foster and accelerate the growth of the hydrogen sector, thereby facilitating the realization of these positive spillovers and maximizing the societal benefits.

One example of industrial collaboration is the formation and functioning of innovative industrial clusters[21] specializing in deploying hydrogen and fuel cell technologies, which in the USA are recognized as *regional clean hydrogen hubs*. According to the US Department of Energy (2023), these hubs are regionally distributed across the United States to develop and deploy innovative hydrogen technologies and demonstrate effective operations encompassing clean hydrogen production, storage, transportation, and utilization. Additionally, these hubs include transportation corridors and various transport modes such as pipelines, rail, and ports to convey clean hydrogen efficiently. Where feasible, these hubs also have the potential to dual function as centers for clean hydrogen and carbon capture, utilization, and storage. The hubs are also funded to demonstrate and develop networks of clean hydrogen producers, potential consumers, and connective infrastructure. This is a significant step forward in establishing entire clean hydrogen value chains and markets. An example of such a network can be found in California, where cluster cooperation led to the demonstration and deployment of hydrogen-powered FCEVs alongside the necessary refueling infrastructure and clean production sites (J. Ogden & Nicholas, 2011). However, it is worth emphasizing that establishing and developing a market for this type of electric vehicle represents severe challenges shaped by various determinants.

---

[21] Clusters, in the classic approach to this concept, presented by M. Gorynia and B. Jankowska (2010), have four key components: (1) the industry forming the cluster core (core businesses) as the key participant of the cluster, (2) supporting industries as companies servicing the cluster core, (3) soft support infrastructure as a scientific base, local government institutions, economic development agencies, and (4) hard (traditional) infrastructure. Clusters, as B. Drelich-Skulska et al. (2014) emphasize, can therefore be defined as (...) *spatial concentration of entities connected by a network of interdependencies of a diverse nature, which through cooperation achieve the synergy effect, contributing to the creation of knowledge, increase in innovation and competitiveness of enterprises and regions*. Among different typologies, there is an essential category of innovation clusters, which, according to the European Commission (2014), are *structures or organized groups of independent entities, the aim of which is to stimulate innovation activity by promoting the provision of facilities and the exchange of knowledge and experience, and by effectively contributing to knowledge transfer, networking, information dissemination, and cooperation between enterprises and other organizations in the cluster*. Innovative cluster development also has a vital role in stimulating the energy transition, for instance, by demonstrating innovative solutions for using renewable energy sources (Burzyńska, 2015).

2.2. The FCEV market model from the perspective of the economics of sustainable development

This subchapter investigates the FCEV market as an integral constituent of the transition toward a hydrogen economy. FCEVs, distinguished by their utilization of hydrogen as an energy source and their singular by-product, water vapor, represent a significant stride toward low-carbon and zero tailpipe emission mobility. The discourse presented in this subchapter includes an overview of FCEVs' characteristics (compared to the other ZEVs) and the FCEV market itself. It also considers the barriers to FCEV market uptake and the role of mapping the development barriers by proposing a concept of the *FCEV deployment trilemma*. In the final part, the FCEV market development is discussed from the perspective of the postulates of the economics of sustainable development.

2.2.1. Characteristics of hydrogen-powered FCEVs as compared to the other ZEVs

Like battery electric vehicles (BEVs), fuel cell electric vehicles employ electricity to operate an electric motor. Distinguishingly, FCEVs generate this electricity via a hydrogen-powered fuel cell, a deviation from other electric vehicles that rely solely on battery-derived electricity. The manufacturer predetermines the vehicle's power by sizing the electric motor(s), fed by a suitably sized fuel cell and battery combination. Contemporary FCEVs predominantly use the battery for recapturing energy during braking, providing additional power during brief acceleration instances, and for power regulation, including the capability to idle or switch off the fuel cell during periods of reduced power necessity. Onboard energy storage is dictated by the size of the hydrogen fuel tank, a departure from all-electric vehicles where power availability and energy are intrinsically tied to the battery's size. These vehicles produce no harmful emissions but release only pure water vapor and warm air (US DOE, 2022).

Another advantage of FCEVs is their ability to generate electricity while driving, providing a more extended range. Additionally, hydrogen charging (refueling) time is typically quick (5-10 minutes), offering drivers convenience comparable to a conventional Initial Combustion Engine Vehicle (ICEV). Most notably, FCEV engines generate superior torque compared to ICEVs, leading to enhanced acceleration. This combination of eco-friendliness and power makes FCEVs an attractive alternative to ICEVs and BEVs (Saritas et al., 2019).

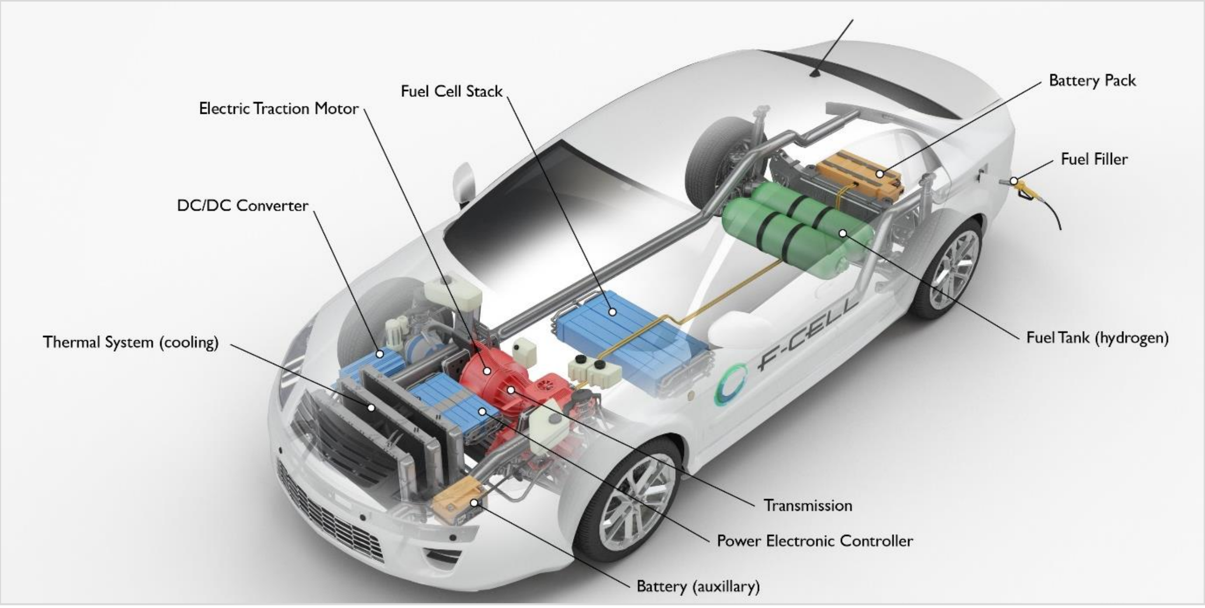


Figure 6. The diagram presenting a hydrogen-powered FCEV construction. Source: U.S. Department of Energy's Vehicle Technologies Office (2022).

The FCEV construction, presented in Figure 6, can be dissected into several integral components. The *low-voltage auxiliary battery*, which powers vehicle accessories and initiates the car's operation before engaging the traction battery, coexists with the *high-voltage battery* pack responsible for storing regenerative braking energy and providing supplemental power to the electric traction motor. Power transformation for vehicle accessories and *auxiliary battery* recharge is facilitated by the *DC/DC converter* that moderates high-voltage DC power from the *traction battery* to lower voltages. The electric traction motor, powered by the fuel cell and the traction battery pack, propels the vehicle's wheels, with certain vehicles utilizing motor generators for both drive and regeneration functions. Energy production in FCEVs occurs within the fuel cell stack, a cluster of individual membrane electrodes that utilize hydrogen and oxygen. Hydrogen is stored onboard in the fuel tank until required by the fuel cell and is replenished via a fuel filler that connects the vehicle to a fuel dispenser nozzle. The management of the electrical energy flow from the fuel cell and traction battery is controlled by the *power electronics controller*, which adjusts the electric traction motor's speed and the torque it yields. Finally, the *thermal system* ensures the optimum operating temperature range for the fuel cell, electric motor, power electronics, and other components. In contrast, the *electric transmission* is responsible for transferring mechanical power from the electric traction motor to the wheels, enabling vehicle propulsion.

Overview of the main differences between FCEVs and BEVs

FCEVs and BEVs represent two distinctive approaches to electrifying automotive transport, each with unique operational characteristics. A key differentiator lies in their energy sourcing and storage: BEVs draw their energy exclusively from the electrical grid, storing it in large battery packs. FCEVs generate electricity onboard using hydrogen-powered fuel cells. This fundamental distinction leads to various operational disparities. FCEVs can be refueled rapidly, akin to conventional ICEVs, like gasoline or diesel cars, and typically have a more extended range. At the same time, BEVs require longer charging periods but currently benefit from a more extensive charging infrastructure. Moreover, FCEVs offer superior performance in colder climates, as their efficiency is less affected by temperature than that of BEVs. However, the production, transport, and storage of hydrogen for FCEVs present significant challenges nowadays, whereas the electricity for BEVs can be more readily sourced from the existing power grid. Despite these differences, both technologies represent a *coopetitive* role in transitioning to sustainable low-carbon transportation. Nevertheless, commercialization of FCEVs is yet to attain its full potential due to a myriad of challenges, including the high cost of fuel cell stack production and maintenance, the paucity of hydrogen supply and refueling facilities, reliability issues, slow cold start, safety concerns, and immature onboard energy management systems (Luo et al., 2021).

The Total Cost of Ownership (TCO) provides a comprehensive measure for comparing FCEVs and BEVs, encompassing both vehicle capital expenses (CAPEX) and operational expenses (OPEX). **CAPEX** considerations include the upfront vehicle price, the potential resale value of batteries and fuel cells, the residual value of the vehicle at the end of its life, and any financial impacts from grants or incentives. On the other hand, **OPEX** considers ongoing operational costs such as the price of hydrogen fuel for FCEVs and electricity for BEVs, regular maintenance, replacement of components, taxes, insurance, and parking fees. These factors combine to form the TCO, providing a more holistic assessment of the long-term financial implications of both electric vehicle types. Such comprehensive evaluations must consider particular FCEV or BEV models in the context of selected countries or even narrowed to individual jurisdictions since, for instance, the value of financial incentives and grants or fuel prices can be differentiated across individual self-governing administrative units. Based on the already conducted research, it can be stated that BEVs currently represent a lower TCO than FCEVs across most segments of on-road vehicles. An example of the comparison of the TCO of heavy-duty vehicles fuelled by hydrogen, electricity, and diesel can be found in research conducted by C. Rout et al. (2022). In 2021, BEVs showed the lowest TCO under base case conditions in the UK. This suggests that BEV technology offers cost advantages over clean, fossil-fuel-based hydrogen vehicles and diesel, particularly when paired with renewable energy sources. Nonetheless, FCEVs, including buses, trucks, tippers, and forklifts using hydrogen generated onsite using only renewable energy sources, showed a lower TCO than diesel-powered ICEVs. Moreover, the study suggested that FCEVs could become cost-competitive in terms of TCO with diesel-powered ICEVs and BEVs if they used clean hydrogen generated using only renewable energy sources as fuel, with conditions like reduced fuel prices and purchase grants favoring the TCO of hydrogen fuels over ICEVs and BEVs. Both significant purchase grants and low hydrogen fuel prices could substantially reduce the TCO of FCEVs for heavy-duty vehicles. However, electricity remained a cheaper option for most vehicles unless sourced from a rapid charger. Notably, under high purchase grants and a 20% fuel price reduction, some FCEVs outperformed BEVs in terms of TCO, indicating that under favorable conditions, FCEVs could present the most cost-effective option for heavy-duty vehicles.

Another study example was presented by G. Morrison et al. (2018), who used a model developed by the US DOE, *Autonomie*, as a simulation tool for advanced TCO modeling for light-duty FCEVs and BEVs in the USA. Their results provided evidence that in 2020, BEVs held a notable cost advantage over FCEVs. However, this is projected to dwindle by 2030 due to anticipated sharp cost reductions in FCEVs, driven by increasing deployments and associated technology learning. By 2030, the Light-Duty Vehicles (LDVs) market is expected to bifurcate, with FCEVs and BEVs each dominating distinct sub-segments. As FCEVs continue to decrease in cost, they are projected to become the lower-cost option in most light-duty vehicle sub-segments. The study identified specific light-duty vehicle sub-segments as more suited to one powertrain over the other: larger vehicles, such as passenger vans and SUVs, showed a relative cost advantage for FCEVs, while smaller classes like mini-compacts, compacts, and midsize sedans were economically more viable for BEVs.

2.2.2. The characteristics of the FCEV market model

A market is a term that refers to a space or mechanism wherein buyers (representing the demand side) and sellers (representing the supply side) interact and share information to exchange goods, services, or resources. This interaction, governed by supply and demand forces within framework conditions, establishes the price and quantity of the goods or services traded. Markets can exist in various forms, including physical locations, digital platforms, or even abstract concepts in the case of markets for specific financial or intangible goods. The markets can be distinguished by their geographical locations, including local, regional, national, international, or global. Among these typologies, it is worth noting that markets can be distinguished considering their internal structure, such as perfect competition, oligopoly market, monopoly market, and monopolistic competition. In a narrow sense, the FCEV market (a fraction of the broader automotive industry) can be described as a space or mechanism where buyers interact and share information with FCEV sellers to establish the price and quantity of the FCEVs traded. Using the ***product approach***, one can distinguish the market segments for the individual categories of FCEVs, considering their sizes and weight classes[22]. This segmentation commonly distinguishes *Light-Duty Vehicles* (LDVs), *Medium-Duty Vehicles* (MDVs), and *Heavy-Duty Vehicles* (HDVs) segments as they differ significantly. Moreover, such segmentation is crucial to identifying the categories of market participants and understanding unique interactions between them (such as competition between FCEV sellers). Appropriate division of individual market segments is also significant for recognizing FCEV prices and the non-price factors impacting the *demand* (such as changes in prices of complementary and substitutionary goods, as well as incomes and preferences of consumers) or *supply* (such as production costs, price of production factors, technology advancements, state interventions in the form of fiscal incentives or subsidies, as well as suppliers expectations). The FCEV market can also be distinguished using the ***spatial approach***, which describes the market based on geographical limitations. Contemporary FCEV markets, due to limited infrastructure, can be mostly recognized on the national level or, in the case of countries like the United States, regionally (since the distribution of hydrogen refueling stations is limited to individual states like California).

---

[22] Unique factors primarily drive the differences in weight class divisions across various countries. First of all, it is worth noting that vehicles' weight and size directly influence on-road infrastructure's design and capacity. Countries with more robust infrastructure may allow larger and heavier vehicles, while those with less developed or older infrastructure may restrict vehicle size and weight to prevent damage and ensure road longevity. Secondly, each country has specific traffic safety concerns based on its unique road conditions, driving habits, and accident data. These factors often guide the regulations on vehicle weight and size to ensure the safe cohabitation of various types of vehicles on the roads. Next, it is worth underlining that countries with stringent environmental regulations may have more restrictive weight classes to limit emissions, encourage fuel efficiency, and promote the use of greener transportation alternatives. Moreover, the specific requirements of a country's transportation market also play a role. For instance, a country with a significant goods transportation industry might have different weight class divisions compared to a country where passenger vehicles dominate. Lastly, each country's legal and regulatory context can also influence the classification of vehicles. For instance, certain weight classes may be linked to specific licensing requirements, taxation policies, or vehicle inspection regimes.

The internal interactions between the participants and stakeholders shape the FCEV market. Figure 7 presents an overview of the FCEV market model that includes its participants (in the inner circle) and the main categories of stakeholders.

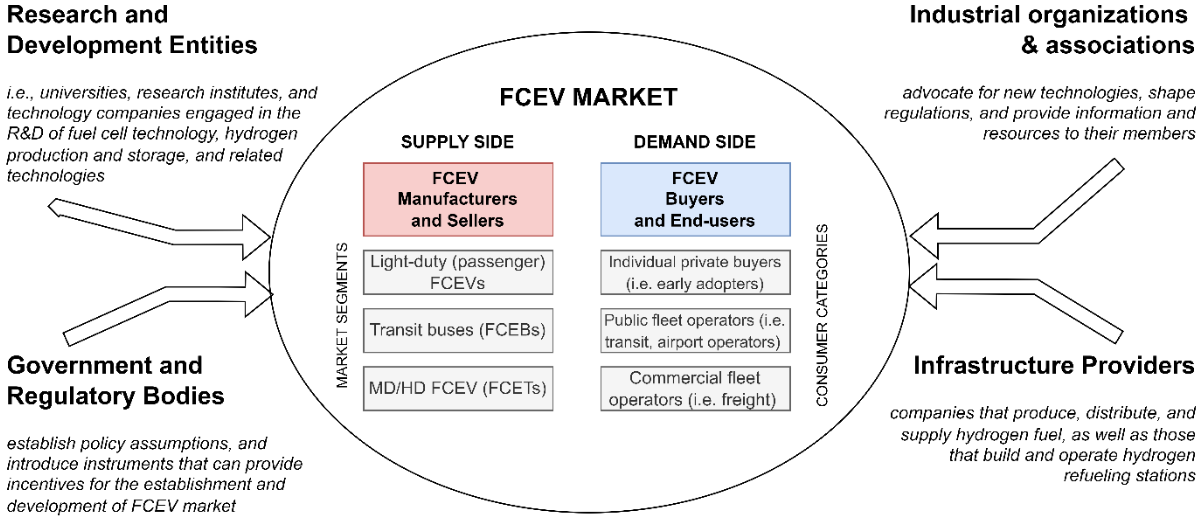


Figure 7. The model of FCEV market participants and stakeholders. Source: Own elaboration.

The FCEV market demand side is shaped by three distinct consumer groups: individual private buyers and early adopters, public fleet operators, and commercial fleet operators, each with unique motivations and requirements. The ***individual private buyers and early adopters*** are environmentally conscious consumers and technology enthusiasts driven by personal values, environmental considerations, and the desire to utilize advanced technology. Their demand, mainly focused on the LDV segment, tends to be influenced by factors such as vehicle performance, availability of refueling infrastructure, upfront vehicle costs, and incentives for FCEV vehicle ownership. Interestingly, as the study shows, early LD-FCEV adopters' decision-making process consists of (1) assessing the feasibility and utility of FCEVs and infrastructure and (2) comparing FCEVs to other zero-emission vehicles (mainly BEVs). Among the main justifications for FCEV rejection, early adopters mentioned insufficient refueling stations near their homes, workplaces, or usual travel routes. However, vehicle range was not a significant issue for most study subjects, suggesting that an extended range was as necessary as tax incentives and potential savings on fuel and maintenance compared to other vehicles (Lopez Jaramillo et al., 2019). The following group of consumers, ***public fleet operators***, are usually government or municipal entities that aim to reduce carbon emissions, support new technology, and meet public sustainability commitments. They may have different purchasing criteria like lifecycle costs, vehicle reliability, and public image benefits. Policy directives, budget constraints, and the need for reliable refueling infrastructure strongly influence their demand. In this context, FCEV public transit fleets' development requires leveraging the consistent, long-term aggregate demand and financial support to develop hydrogen supply and refueling infrastructure projects and aligning these projects to aid broader systemic evolution (A. Y. Ku et al., 2021). The last group of consumers, ***commercial fleet operators***, are entities that prioritize operational efficiency, total cost of ownership, and the ability to meet sustainability targets set by the company or regulatory bodies. Their decisions are primarily driven by factors such as vehicle range, refueling time, maintenance costs, and the potential for fuel savings (Bae et al., 2022; Li et al., 2022).

The FCEV market supply side is structured around three primary segments, each catering to different vehicle classes and uses: light-duty, FCEB, and medium- and heavy-duty FCETs. The ***light-duty segment*** includes passenger cars, SUVs, and small vans predominantly used for personal transportation or small-scale commercial activities. Manufacturers in this segment are typically traditional, well-established, and recognized automotive companies such as Toyota, Hyundai, and Honda, and new entrants focusing on integrating fuel cell technology into smaller, personal-use vehicles. The production volumes in this segment tend to be higher, but the individual unit cost and profit margins are usually lower than the other segments. The ***fuel cell electric bus (FCEB) segment*** includes larger commercial vehicles such as delivery vans and buses. These vehicles are often used for tasks that require more cargo capacity and range than light-duty vehicles but less than heavy-duty ones. The supply in this segment comes from a mix of traditional automotive manufacturers, specialized commercial vehicle producers, and new market entrants focusing on clean hydrogen technologies. Lastly, the ***heavy-duty FCET segment*** comprises large vehicles like buses, heavy-duty trucks, and other specialized commercial vehicles. Given the high-energy requirements and extended range of these vehicles, the integration of fuel cell technology presents a significant opportunity. The suppliers in this segment are often specialized commercial vehicle manufacturers, sometimes in partnership with fuel cell technology companies. In each of these segments, FCEV suppliers must not only develop vehicles that meet the performance and cost expectations of their customers but also collaborate with infrastructure providers to ensure the availability of hydrogen refueling options. The supply-side structure, therefore, extends beyond vehicle manufacturing to include a broader ecosystem of technology providers, infrastructure developers, and service providers.

The FCEV market stakeholders

The academic and research entities are not directly related to the FCEV market functioning. However, they represent a vital group of stakeholders gathering institutions that contribute to advancing FCEV technology and its applications through research and development. They perform fundamental and applied research, often funded by public or private entities, in fields like materials science, engineering, and environmental science. These entities are crucial in understanding and improving fuel cell efficiency, durability, and cost-effectiveness. They also provide critical insights into the environmental impacts of FCEVs and the policy instruments necessary for their widespread adoption. Additionally, these institutions often collaborate with industry players to facilitate knowledge transfer and accelerate the practical implementation of their findings.

Governments and regulatory bodies are critical in the FCEV market establishment and development as another category of stakeholders. These entities establish and enforce regulations concerning vehicle emissions, safety, and efficiency. They also provide policy direction, incentives, and subsidies to stimulate the adoption of FCEVs and fund research and infrastructure development related to hydrogen fuel cell technology. Furthermore, they can influence the market by setting targets for zero-emission vehicles and reducing fossil fuel dependence. Regulatory bodies are also responsible for standards development, which guides the manufacturing, operation, and maintenance of FCEVs. The role of these bodies is crucial in shaping a sustainable and supportive environment for the growth of the FCEV market.

Industrial organizations and associations play a substantial role by acting as intermediaries between businesses, government agencies, and the public, fostering collaborations and communication. Industrial organizations, comprising manufacturers and suppliers of FCEVs and their components, work towards technology advancements, cost reduction, and production scale-up. They often invest in research and development for more efficient fuel cell technology and infrastructure. Associations, on the other hand, promote the interests of their members, advocate for supportive policies, and work to raise awareness and acceptance of FCEVs. They often publish industry standards, conduct market research, organize conferences and trade shows, and provide education and training. Their contribution is pivotal in creating a cohesive and supportive ecosystem that accelerates the adoption and growth of the FCEV market.

Since hydrogen fuel is the most critical complementary good for the FCEVs, the last identified group of FCEV market stakeholders, ***infrastructure providers,*** incorporates hydrogen fuel suppliers and refueling infrastructure station operators. These entities are responsible for establishing, operating, and maintaining the infrastructure that produces, stores, and delivers hydrogen fuel to FCEVs alongside the entire hydrogen economy value chain. This group comprises entities engaged in hydrogen production, often through methods such as SMR or electrolysis, and entities that construct and manage refueling stations. They are at the forefront of addressing challenges related to the availability, affordability, and convenience of hydrogen fuel. Their operations involve the physical construction and maintenance of infrastructure and continuous technological improvement to enhance safety, efficiency, and environmental sustainability. Their role is crucial in the widespread adoption of FCEVs, as a reliable and accessible hydrogen infrastructure is a prerequisite for FCEV deployment at scale.

2.2.3. The barriers to the establishment and development of the FCEV market

Following the overview of the characteristics of the FCEVs, the market model, and the characteristics of its participants and stakeholders, this subchapter delves into the intricate dynamics influencing the establishment and development of the FCEV market based on contemporary research. The focus is on identifying the crucial barriers currently shaping its operations. Even though FCEVs are attracting significant attention due to their potential for zero tailpipe emissions and comparable driving ranges to conventional internal combustion engine vehicles, the transition towards large-scale market adoption of FCEVs is laden with many barriers, including technological hurdles, the need for large-scale infrastructure development, high initial costs, regulatory concerns, and public acceptance issues, among others. The contemporary studies identified and examined various categories of barriers, which mainly revolved around the FCEV market supply and demand side, infrastructural concerns, political and legal barriers, and last but not least, sustainable and low-cost hydrogen fuel supply (Bratt, 2022; Itaoka et al., 2017; Staffell et al., 2019; Trencher & Edianto, 2021; Trencher & Wesseling, 2022).

FCEV market supply-side barriers represent a category of determinants that influence the production and supply of FCEVs. A significant barrier is the limited number of automakers currently producing FCEVs, which results in low economies of scale in vehicle or component production. This limited production scale contributes to high manufacturing costs, making

FCEVs less price-competitive with conventional ICEVs or even other types of electric vehicles like BEVs. This high cost of production extends to the critical components of FCEVs, such as fuel cells and hydrogen storage systems (internal tanks), which are technologically complex and expensive to manufacture. Furthermore, the environmental impacts caused by manufacturing FCEVs and their components can also pose a challenge. The production processes for FCEVs and their key components often involve substantial energy use. They can generate significant greenhouse gas emissions, which contradict the ultimate aim of these vehicles, i.e., reducing environmental impacts. Hence, these barriers pose considerable challenges to expanding the FCEV market on the supply side.

By following these deliberations, it should be noted that the FCEV market is shaped by **demand-side barriers**. A principal issue is psychological barriers that impede the demand for these vehicles, such as aversion to high purchase costs or *range anxiety*, the fear that a vehicle has insufficient range to reach its destination or next refueling station. Compounding this is the low public awareness or acceptance of hydrogen drivetrains, which limits potential demand. Negative perceptions about the environmental benefits of FCEVs also affect their market uptake. Despite their potential for zero-emission driving, misconceptions regarding the environmental impacts of hydrogen production and the electricity used for recharging can negatively influence consumers' attitudes toward FCEVs. Furthermore, FCEVs' low visibility and public awareness compared to more conventional vehicle options inhibit their market penetration. Weak overall demand for these vehicles, resulting from these factors, further compounds the challenge.

A significant infrastructural hurdle for the FCEV market development pertains to refueling stations as a category of **infrastructural barriers**. Their inadequacy to support wide-scale vehicle diffusion is a considerable challenge. There are high construction and operational costs associated with these stations, which can deter investment in their establishment. As a result, the profitability of these refueling stations can be low, particularly in the early stages of FCEV market development when the number of FCEVs on the road is still relatively small. Furthermore, the availability and capacity of the refueling network play a crucial role in the market acceptance of FCEVs. In areas where such infrastructure is sparse or non-existent, consumers may be hesitant to purchase an FCEV due to concerns about refueling convenience and reliability. Additionally, poor reliability of stations and nozzles can further discourage potential users.

The **hydrogen fuel supply** represents another critical challenge in the establishment and development of the FCEV market. The high cost of hydrogen fuel, primarily due to production, transportation, and storage costs, stands as a significant deterrent for potential users. Furthermore, the availability of clean or low-carbon hydrogen is currently limited. This scarcity hampers the widespread adoption of FCEVs, as it negates one of their key selling points - their potential to be a truly *zero-emission* alternative to fossil fuel vehicles. Additionally, existing infrastructure for hydrogen production is predominantly configured for hydrogen produced from fossil fuels, contributing to CO2 emissions. This misalignment raises concerns about the environmental impact and sustainability of hydrogen as a FCEV fuel source.

Legal and political barriers can severely impact the progression of the FCEV market. Laws and regulations that inadvertently increase costs or hinder investments in market creation can be substantial barriers, stifling the growth and innovation necessary for the market to mature. In many regions, the lack of standardized protocols and regulations around technology configurations, such as refueling interfaces, can also lead to uncertainty, affecting manufacturers and consumers. Institutional restrictions or policies can further dampen the adoption and advancement of FCEVs. Lastly, a lack of consistent and robust government support in terms of favorable policy, subsidies, and commitment to infrastructure development can deter investments and slow market development.

This overview of the main categories of FCEV market development barriers calls for a comprehensive and aligned green industrial policy approach from states and international organizations, setting clear guidelines and providing vital support to overcome these barriers and facilitate a conducive environment for the FCEV market to thrive. The impacts of long-term contracts and government incentives on the FCEV market growth within a hydrogen supplier and automaker framework were studied by P. Toktaş-Palut (2023). It can be stated that, indeed, state interventions are crucial for FCEV market growth, and the policy priorities should change following the maturity of the FCEV market.

As the contribution to the ongoing debate on the barriers to the FCEV market development, it can be stated that economy-wide deployment of FCEVs faces comparable trilemma as the entire energy sector in the energy transition process. The author proposes to frame these considerations as an ***FCEV deployment trilemma*** using the analytical framework of the *energy trilemma*. In the *FCEV deployment trilemma*, ***Sustainability*** pertains to the environmental impact of FCEVs, including supplying hydrogen fuel, the vehicle production process, and the lifecycle emissions. It emphasizes the transition to clean hydrogen and the importance of creating a net-zero emission transportation sector. ***Functionality*** focuses on the technical and operational performance of refueling infrastructure as well as the wide accessibility and reliability of the stations. ***Cost-competitiveness*** addresses the financial feasibility of FCEVs, including the purchase price of the vehicles, the cost of hydrogen fuel, and other costs that constitute the total cost of ownership. The FCEV deployment trilemma incorporates three significant contemporary challenges that synthesize the discussed barriers.

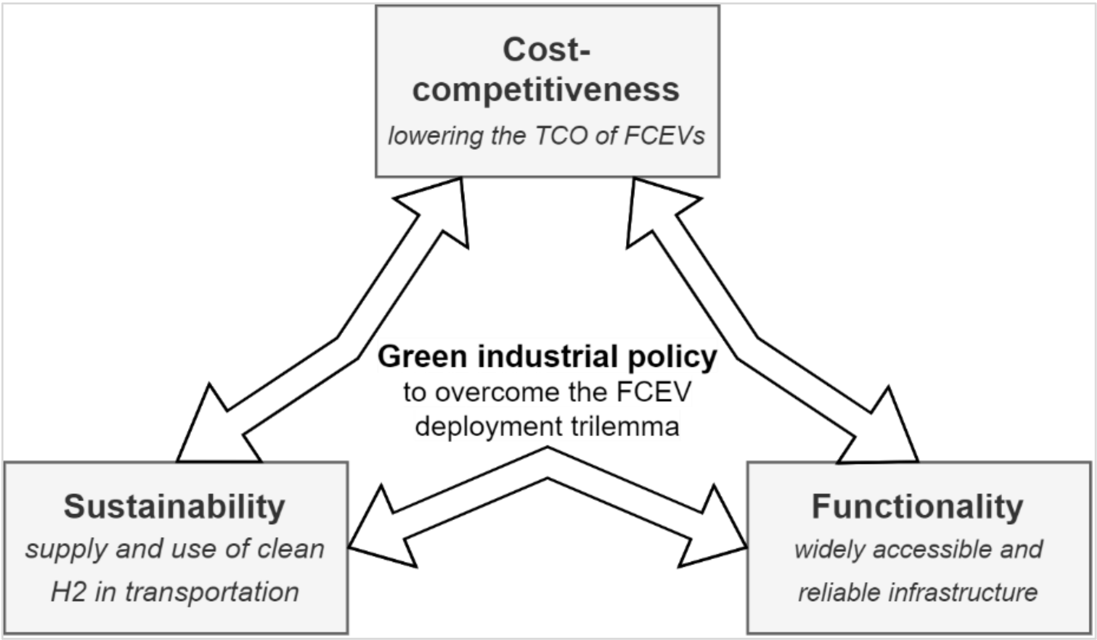


Figure 8. FCEV market development trilemma. Source: Own elaboration.

The FCEV deployment trilemma, demonstrated in Figure 8, presents three interconnected and mutually dependent objectives, each presenting distinct challenges and trade-offs. Integrating sustainability, functionality, and cost-competitiveness is critical in successfully deploying FCEVs and market development. However, emphasizing one aspect may inevitably compromise the others due to technological, logistical, and economic constraints.

(1) Aiming for cost-competitive FCEVs coupled with the high functionality of refueling stations potentially jeopardizes the sustainability objective. Given the current state of the hydrogen economy, clean hydrogen is not abundantly available. Thus, sourcing hydrogen from conventional fossil fuel-based methods is an immediate solution, but it would negatively impact environmental sustainability due to the high carbon emissions associated with such methods.

(2) Striving for a widely accessible, reliable hydrogen refueling infrastructure while maintaining the commitment to use only clean hydrogen can undermine the cost-competitiveness of FCEVs. Presently, the production of clean hydrogen and its transportation over long distances - necessitated by an insufficiently developed value chain - incurs substantial costs. Consequently, the financial viability of FCEVs could be compromised, posing barriers to widespread adoption.

(3) Ensuring the cost-competitiveness of FCEVs while insisting on the use of clean hydrogen for transport could limit the scope for a functional, widely accessible infrastructure. An option like onsite hydrogen production, which could potentially solve this issue, is constrained by the intermittent availability of renewable energy sources and geographical limitations, making it an infeasible solution for every location. Moreover, even short-distance transportation of clean hydrogen can add significantly to the fuel cost and the total cost of ownership, thereby influencing the market dynamics adversely.

Therefore, the proposed FCEV deployment trilemma reflects the complex interplay between the three crucial dimensions of sustainability, functionality, and cost-competitiveness. The challenge lies in finding a balanced approach that optimizes each without disproportionately compromising the others. A direct instrumental response to this trilemma can be a green industrial policy, with its ability to shape and direct the market towards desired objectives. It has the potential to act on all three fronts, sustainability, functionality, and cost-competitiveness, to optimize the FCEV market development. Regarding ***sustainability***, green industrial policy can stimulate the production and adoption of clean hydrogen through various instruments. These might include investment in R&D for efficient and sustainable hydrogen production techniques, regulation to phase out carbon-intensive hydrogen production (like carbon pricing), or incentivizing practices that capture and store or reuse carbon emissions during hydrogen production. By creating a market preference for clean hydrogen, such a policy could accelerate the shift away from fossil fuel-based hydrogen. Concerning ***functionality***, policy plays a crucial role in ensuring a widespread, reliable hydrogen refueling infrastructure. It can guide strategic planning and investment in infrastructure development, covering the entire value chain, from production facilities to transportation networks to refueling stations. Furthermore, green industrial policy can encourage research and technological innovation to optimize hydrogen storage and distribution, leading to more efficient and reliable hydrogen delivery systems. Lastly, green industrial policy has the potential to improve the ***cost-***

competitiveness of FCEVs and clean hydrogen. It can do this by providing financial incentives, like subsidies or tax breaks, to both manufacturers and consumers of FCEVs. In addition, the policy can stimulate competition within the market, encouraging manufacturers to innovate and find cost reductions, thereby driving down prices and fostering economies of scale. Overall, the green industrial policy serves as a potential catalyst in balancing the trilemma by fostering an environment conducive to the growth and development of the FCEV market. It aligns the interplay of sustainability, functionality, and cost-competitiveness to create a market scenario where FCEVs can be a preferred solution for decarbonizing transport.

2.2.4. The establishment and development of the FCEV market from the perspective of the economics of sustainable development

Based on the already presented characteristics and determinants of establishing and developing an FCEV market from the model perspective, it can be stated that there is significant potential for this market development to comply with the normative postulates of the economics of sustainable development. According to the primary paradigm of this theory postulates that *sustainability is a broadly understood balance of social, economic, and environmental development* (Poskrobko, 2012, 2013). First, the author will aim to define the potential contributions of FCEV market development to the main postulates.

Strong sustainability emphasizes the irreplaceability of natural capital and urges us to maintain it over time. The FCEV market development can contribute to the preservation of natural capital since hydrogen, as a fuel, can be produced from various sources, including water, without depleting natural resources like fossil fuels. In addition, clean hydrogen produced from biomass and waste can generate negative CO2 emissions in the entire lifecycle and offer higher energy efficiency at lower operational costs as compared to clean hydrogen from water-splitting electrolysis, which stands as a chance to decarbonize transportation to a greater extent, promote a circular economy, and reduce environmental degradation (Megia et al., 2021). Since FCEVs emit only water vapor, deployment of those vehicles can, therefore, eliminate harmful tailpipe emissions and directly increase air quality, especially in highly populated urban areas and along transit corridors (Mac Kinnon et al., 2016). Furthermore, FCEV market development (under current green industrial policies promoting clean hydrogen production) will enforce higher use of renewable energy sources, balancing their operations and optimal consumption, which can help maintain natural capital for future generations (Maggio et al., 2019).

The **pluralist approach** in the context of the economics of sustainable development acknowledges the validity and relevance of both neoclassical economic and environmental economics theories and perspectives, recognizing that none of them can adequately address every sustainable development issue. In the context of neoclassical and environmental economics, the FCEV market development can be seen as embodying this pluralist approach in several ways. From a neoclassical perspective, which emphasizes market mechanisms and rational decision-making, the growth of the FCEV market can be understood as a response to changing market conditions. For instance, technological advances and policy incentives have reduced the costs of FCEVs and increased their competitiveness compared to conventional ICE vehicles. Consumer demand for environmentally friendly transportation options has also supported FCEV market growth. Neoclassical economics also emphasizes efficiency, and FCEVs, with their high energy efficiency compared to ICEV, align well with this perspective. On the other hand, environmental economics emphasizes the importance of accounting for the external costs of economic activities, such as pollution, which are not typically reflected in market prices. FCEVs contribute to this perspective by reducing the external costs associated with transportation, such as air pollution and greenhouse gas emissions. Green industrial policies promoting FCEVs, such as subsidies or carbon pricing, can be seen as attempts to internalize these externalities, a key focus of environmental economics. Therefore, the development of the FCEV market can be seen as embracing a pluralist approach by addressing both the market mechanisms emphasized by neoclassical economics and the environmental externalities highlighted by environmental economics. The growth of this market demonstrates how different economic perspectives can be integrated to promote sustainable development.

However, since the economics of sustainable development distance itself from neoclassical and environmental economics as the consequent evolution of their postulates, the FCEV market development also **challenges the postulates of consumer sovereignty and the substitutability of resources**. In neoclassical economic theory, consumer sovereignty suggests that consumers dictate what goods and services are produced based on their preferences and purchasing decisions. However, the shift towards FCEVs can be seen as challenging this notion. State interventions such as subsidies for FCEVs, regulations limiting CO_2 emissions, and investment in hydrogen refueling infrastructure are playing crucial roles in shaping the market, independent of, and sometimes ahead of, consumer preferences expressed in demand. Thus, these policies influence and potentially limit consumer choice, suggesting that consumer sovereignty is not absolute. Simultaneously, the postulate of substitutability implies that any natural resource can be replaced by another, often artificial, resource without loss of utility. However, FCEVs underscore the limitations of this assumption. For instance, while hydrogen can replace fossil fuels as an energy carrier in vehicles, the process of creating hydrogen often requires water. This resource is not unlimited and cannot be substituted. Additionally, the value of clean air, which FCEVs help to preserve by reducing emissions, cannot be replaced by any other resource. Thus, the development of the FCEV market highlights the importance of sustainable resource use and the preservation of non-substitutable resources, such as clean water. These considerations indicate that the transition to a *clean* hydrogen economy, represented in part by the growth of the FCEV market, requires rethinking some traditional economic principles to address sustainable development challenges effectively.

The development of the FCEV market corresponds with and considers the **accomplishments of research on the concept of sustainable development** in several ways. First of all, the attempts to establish and develop this market emphasize the need for **environmental sustainability**, including already mentioned aspects, such as reducing harmful CO_2 emissions and preserving the environment.

Secondly, it supports **economic sustainability** by, for instance, creating jobs. As a study shows (Bezdek, 2019), the establishment and development of the FCEV market may catalyze significant employment opportunities, accommodating a broad range of skills and experiences while also filling the vacuum left by restructuring in other fossil-fuel-based industries. By requiring associate's degrees, on-the-job training, and trade certifications, this market will provide diverse opportunities for the reallocation of the workforce within and across sectors. The diverse skills and professions involved in the FCEV market-related industries render these sectors' prospects for job creation across different regions globally attractive. The ability to form innovative specialized clusters based on various industry segments further augments the ease of overall on-road vehicular market penetration, particularly if regions can highlight their strengths in areas such as high-tech, research, education, manufacturing, IT, and energy. It is worth mentioning that academia and educational institutions at all levels will play a significant role in shaping the required competencies of the workforce. Besides job creation, the development of this market will also spur FCEV-related economic activity in manufacturing, infrastructure development, maintenance, and research and development.

Doing so may contribute to the economic dimension of sustainable development, which advocates for sustained economic growth and the equitable distribution of economic benefits.

Thirdly, the FCEV market development may foster **social sustainability**. By reducing air pollution, FCEVs contribute to better public health outcomes, an essential aspect of social sustainability. Additionally, the role of FCEV market development in achieving SDGs is worth mentioning. According to SGD 7 – *Affordable and clean energy* – the development of this market may stimulate the diffusion of clean hydrogen and fuel cell technologies, translating to an increase in the share of renewable energy in the global energy mix (SDG 7.2) and contributing to the improvement in energy efficiency. Unfortunately, as long as these technologies represent a niche fraction of energy and transportation sectors, they not significantly impact universal access to affordable and reliable energy services. From 1990 until 2022, the FCEV market has not reached the necessary maturity level to make clean hydrogen a widely available energy carrier (SGD 7.1). In contrast, even in the 2020s, the gradually progressing FCEV market development can contribute to achieving SDG 11.2 thanks to the increasing significance of public transit relying on FCEVs. Based on the example of hydrogen-powered fuel cell electric buses (FCEBs), the overall development of this market may provide access to safe, affordable, accessible, and sustainable transport systems (A. Y. Ku et al., 2021).

Another vital aspect of **social sustainability** is the necessity of setting up local hydrogen communities. A hydrogen community can be perceived as a type of *net-zero-energy community* that can greatly reduce energy needs through efficiency gains such as the balance of energy for vehicles, thermal, and electrical energy within the community using renewable energy sources and electricity and hydrogen as energy carriers. Moreover, these communities are collectively organized around the needs and expectations of citizens (Carlisle et al., 2009). According to Y. He et al (2021) hydrogen community can be described and designed as an integrated system that incorporates, i.e., low-rise houses, rooftop photovoltaic panels, hydrogen vehicles, a hydrogen refueling station, an electric micro-grid and utility power grid, and hydrogen pipelines that distribute the fuel locally. The establishment and local functioning of those communities (studied based on the cases in California in the United States) provided evidence that communities play a crucial role in early-stage deployment and acceptance of burgeoning hydrogen technologies among local municipal and rural communities. The remote and local development of hydrogen infrastructure stands as a pivotal step towards commercializing fuel cell vehicles and transitioning towards a hydrogen economy.

It can be assumed that hydrogen communities can therefore become an incentive to increase the environmental awareness of the citizens contributing to promoting postulates of ***Homo Sustinens***. In this context, it is also worth stating that the development of the FCEV market might be accelerated thanks to spurring the attitudes that constitute the *Homo Sustinens* model. By nature, FCEVs offer a more sustainable mode of transportation than traditional fossil fuel vehicles. The increasing demand and market development of FCEVs indicates a societal shift towards sustainable choices, reflecting the preference of *Homo Sustinens* for sustainable solutions. The FCEV market growth requires long-term thinking, considering immediate economic gains and long-term environmental impacts. This aligns with the assumptions of *Homo Sustinens*, who emphasize the importance of long-term sustainability over short-term profits. Furthermore, FCEV adoption requires ***shared responsibility*** from consumers, businesses, and policymakers, reflecting *Homo Sustinens'* emphasis on *collective responsibility* and *cooperation* for sustainable outcomes. The FCEV market could also promote social equity, as clean air and a stable climate are shared benefits and common welfares that improve the quality of life for all, aligning with *Homo Sustinens'* focus on equity and fair resource allocation. The development of FCEVs also recognizes the *interconnectedness* of various domains of sustainability - environmental, social, and economic. The interplay between these elements in successfully deploying FCEVs reflects the *Homo Sustinens* assumption that economic activities, social equity, and environmental conservation are interconnected and interdependent. Therefore it can be stated that *Homo Sustinens*, as a normative model of economic agents, may significantly contribute to the establishment and development of the FCEV market.

The FCEV market development heavily relies upon and, at the same time, stimulates **technological development and innovation growth** within numerous industries, including automotive and petrochemical industries, aligning with the sustainable development goal of promoting innovation and sustainable industrialization. Therefore, FCEV market development can contribute to achieving SDG 9 - building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. In this context, this market can directly or indirectly contribute to actions in the areas of specific goals. For instance, the FCEV market may stimulate the development of innovative, reliable, sustainable, and resilient refueling infrastructure, including regional and transnational infrastructure (SGD 9.1). The study shows that such an infrastructure should be coupled with onsite storage and production from renewable energy sources, such as wind and solar power

(Tabandeh et al., 2022). In addition to that, it is worth noting that such a refueling infrastructure will most likely be an upgrade of already existing fossil-fuel-based infrastructure, leading to retrofitting the petrochemical industry to make it sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes (9.4).

To achieve such ambitious objectives, the FCEV market development necessitates a **global responsibility and coordination** at all governance levels in adopting new policy instruments aligned with the strategies for the transition to a hydrogen economy. First, the successful deployment of FCEVs and market development depends on the availability of hydrogen refueling infrastructure, which demands concerted effort and investment at both national and local levels. This infrastructure must be built in a coordinated way with locations based on potential demand and existing traffic flows (including transnational flows of goods and people). Global coordination is necessary to establish standards for hydrogen production, storage, and transport, as well as for the design and safety of FCEVs and their components. Standardization and further certification can reduce costs, increase safety, secure the proper labeling of clean hydrogen, and ensure interoperability of vehicles and infrastructure across borders. Addressing technical challenges related to FCEVs and hydrogen requires international collaboration in research and development. By working together, countries can pool resources, share knowledge, and avoid duplication of effort. FCEVs and hydrogen are part of global supply chains, and the growth of these industries can have significant economic implications. Policymakers must coordinate their approaches to avoid trade disputes and ensure fair competition in international trade. Next, it is worth mentioning that to build a skilled workforce for the hydrogen economy, governments, educational institutions, and industries need to collaborate on the development of relevant education and training programs. Lastly, to promote FCEV market development, governments at all levels need to adopt and harmonize incentives such as tax credits, grants, and loans, as well as regulations that require or encourage the use of hydrogen-powered fuel cell electric vehicles. Thus, the transition to a hydrogen economy, with FCEVs at its core, is a complex task requiring coordination at all governance levels and across countries to align policies, build infrastructure, conduct joint research, develop industry, educate workers, and incentivize adoption.

The final consideration regarding the postulates of the economics of sustainable development is related to a **long-term perspective**. FCEVs represent a long-term solution to transportation-related environmental challenges, embodying sustainable development focused on future generations' needs. First, it is necessary to mention that building a hydrogen infrastructure for fuelling FCEVs is a long-term investment. This includes setting up production facilities for hydrogen, storage facilities, and widespread refueling stations. These infrastructure developments require considerable time and capital to establish. Furthermore, despite the advances in FCEV technology, further research and development are necessary to increase the efficiency and durability of fuel cells, reduce costs, and improve hydrogen storage and distribution. These advancements require a long-term commitment in the form of, i.e., extensive subsidization offered by governments at all levels in the long term. Another aspect of FCEV market development relates to the evolution of regulatory frameworks in individual countries and international organizations. Regulations and standards that guide the safe production, storage, transport, and end-use of hydrogen, as well as the design and operation of FCEVs, need to evolve over time as technology and market dynamics change. Besides, the evolution of the regulatory framework must be aligned to changes within other substitutional technologies like BEV. Another aspect of FEV market development is consumer acceptance of FCEVs, which will likely be gradual. Consumers (both private and institutional) need time to become familiar with the new technology, and factors like vehicle cost, availability of models, and access to refueling stations will affect the adoption rate. Building the already mentioned workforce needed for the entire hydrogen economy value chain, and naturally including the FCEV market, involves developing education and training programs, which is a long-term endeavor. Alongside the structural changes regarding the relocation of the workforce, the structural changes may occur as a result of transitioning to a hydrogen economy, in which FCEVs play a major part, standing as a fundamental shift that will take many years and will impact the structure of individual sectors and the entire economy. Lastly, the potential benefits of FCEVs in terms of reduced greenhouse gas emissions and improved air quality will accrue over the long term. This also applies to using renewable or low-carbon methods to produce hydrogen. To conclude, FCEV market development requires long-term thinking, as the economics of sustainable development suggests, to navigate this complex process effectively and realize the potential benefits. Considering those mentioned above, it is now worth continuing the deliberations related to the FCEV market establishment and development with the case study of the US state of California, which represents one of the most developed FCEV markets globally.

3. THE FCEV MARKET IN THE US STATE OF CALIFORNIA

Noteworthy, California, in recent decades, became a nationwide pioneering state in adopting and advancing zero-emission vehicle technologies within the on-road transportation sector. The third chapter of this dissertation provides an overview of the FCEV market in the US state of California alongside the policies that have aimed at shaping its establishment and development. First, it briefly presents the characteristics of the US political and economic system, followed by the legal administrative division and responsibilities of federal, state, and local governments. Secondly, the author demonstrates the assumptions, objectives, and instruments of green industrial policy enacted at the federal and state government levels in California to establish and develop the FCEV market in that state. The following subchapter focuses on the specific characteristics of the FCEV market in California. It offers an examination of the establishment and development phases of this market. Additionally, it provides an analysis of the structure of the FCEV market, its stakeholders, and the main factors influencing its development identified by the author. Through this comprehensive exploration, this chapter elucidates the unique evolution of the FCEV market in California and highlights the potentially influential factors that have led to its current status. Finally, this chapter provides the contextual legal and political framework for the empirical studies, the results of which are presented in the final chapter.

3.1. The green industrial policy for the establishment and development of the FCEV market in the US state of California - state and federal dimensions

3.1.1. The emergence and characteristics of the US political and economic system

The United States of America was established on *federalism*, which is a mode of political organization of a state that traces its roots to the nation's founding in the 18th century. The US political system is a *constitutional federal republic* based on the US Constitution, adopted in 1787 with subsequent amendments. In the 19th and 20th centuries, *federalism*, which merges various political units under a joint central authority while preserving regional self-governance, gained widespread acceptance. This trend was somewhat paradoxical as these centuries also saw the rise of nationalism, emphasizing the establishment of independent nation-states centered on shared ethnic identity. The nation-state represents a singular ethnic community's political organization, demarcating and legitimizing its distinct identity. In contrast, federations often unify political entities with diverse ethnic bases, emphasizing cooperation and shared governance over homogeneity. While both models are theoretically in tension, with the nation-state prioritizing ethnocultural singularity and federations endorsing multi-ethnic integration, their concurrent acceptance in the 19th and 20th centuries reflects the complex realities of political organization. They cater to different aspects of the political spectrum - where nation-states satisfy the need for cultural homogeneity and self-identification, federations answer the call for broader cooperation and co-existence among diverse entities (Riker, 2018). *Federalism* in the United States of America is founded on a separation of powers among three branches of government: the *legislative branch (Article I),* the *executive branch (Article II),* and the *judicial branch (Article III)*. The US Congress, consisting of the Senate and the House of Representatives, forms the *legislative branch* holding the power to establish legislative regulations. The *executive branch*, led by the President, implements and enforces laws. With the Supreme Court at its pinnacle, the *judicial branch* interprets these laws. This separation ensures a system of *Checks and Balances*[23], where each branch has measures of influence over the others and can limit their powers, thus preventing abuses and maintaining democratic governance.

The division of responsibilities and powers between the national government and subnational entities is central to the American political structure and is enshrined in the US Constitution (Karmis & Norman, 2016). However, it is worth emphasizing that the Constitution does not explicitly determine *federalism* as the nation's political system. According to E. Chemerinsky (2011, p. 115), *A fundamental principle of American government is that Congress may act only if there is express or implied authority in the Constitution, whereas states may act unless the Constitution prohibits the action*[24]. To provide a transparent and consistent overview of the division of the competencies within the federal, state, and local governance levels, the following description will first present the prerogatives followed by examples of the competencies related to the FCEV market development.

---

[23] The Checks and Balances system imbues each governmental branch with unique authorities to restrain the other branches, thereby ensuring a prevention of the concentration of power in any single branch. To illustrate, the legislative body, Congress, possesses the prerogative to legislate laws, which, however, can be counteracted by the President through their *veto* power. In addition, the Supreme Court holds the capacity to invalidate these laws, if deemed unconstitutional. The bicameral Congress, comprising the Senate and the House of Representatives, has the capability to countermand a Presidential *veto*. This power, however, can only be exercised by securing a two-thirds majority vote in both houses. This complex system of inter-branch counteractions and mutual control allows for a dynamic equilibrium of power, thus preserving the democratic fabric of the nation.

[24] Which in fact is an interpretation of the Tenth Amendment to the U.S. Constitution’s that states: *The powers not delegated to the United States by the Constitution, nor prohibited by it to the States, are reserved to the States respectively, or to the people.*

The federal government level

At the federal government level, the government's competencies are specifically enumerated in *Article I, Section 8* of the US Constitution, and primarily involve national or international issues. This includes foreign policy, national defense, interstate commerce, postal service, promotion of science and research, immigration, tribal, and monetary policy. The federal government also sets minimum civil rights and environmental protection standards. Based on these competencies, the federal government can establish nationwide standards and policies that affect the FCEV market, such as fuel efficiency requirements, emission standards, and minimum safety regulations. Federal agencies like the Department of Energy, the Department of Transportation, and the Environmental Protection Agency may play crucial roles in funding research and development, endorsing new technologies, and enforcing environmental regulations across individual states. Federal agencies can also impose federal tax credits and offer financial incentives through subsidies that may stimulate the market by reducing costs for manufacturers, fuel providers, infrastructure operators, and end-use consumers. However, it is worth explaining that the federal government has limited opportunities to define and shape the nationwide growth of the FCEV market since most competencies are assigned to the states.

The state government level

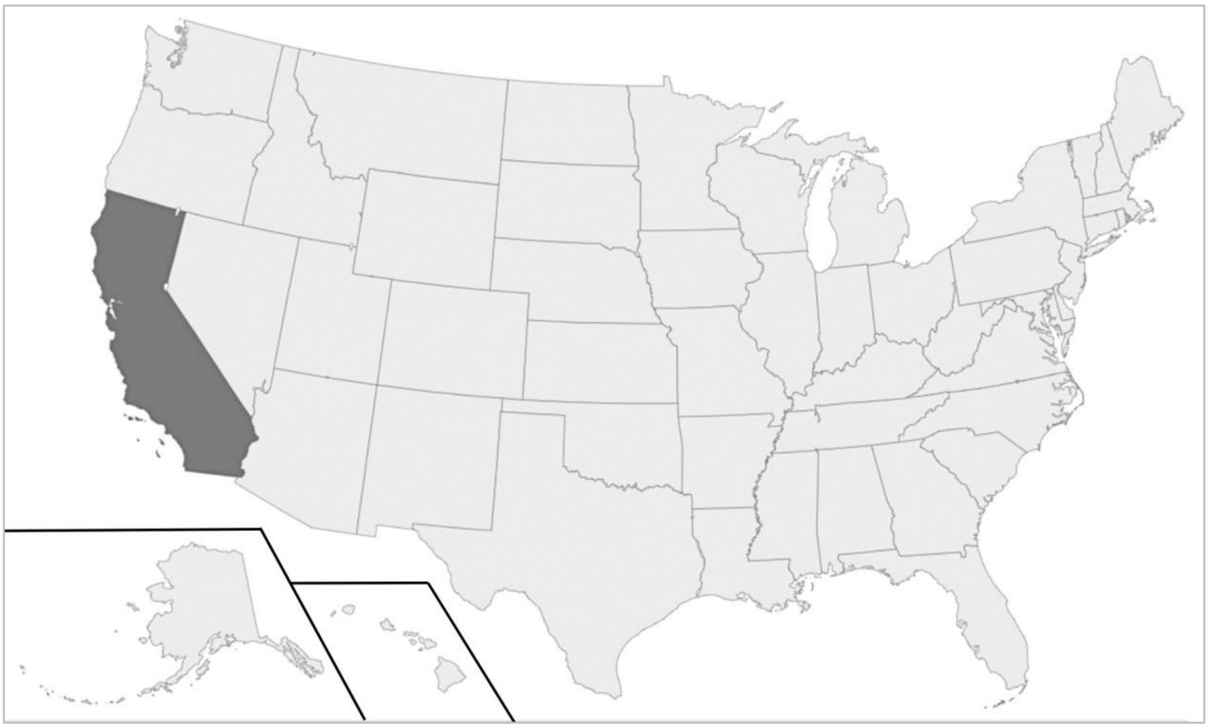


Figure 9. The political map of the USA with highlighted state of California. Source: Own elaboration.

The independence of US states and their right to shape the extent of competencies and involvement in individual policies is granted by The 10th Amendment of the US Constitution, which provides powers to the state governments not explicitly given to the federal government. Each state also has its own constitution, outlining its powers and responsibilities. These duties include but are not limited to education, public safety, and welfare programs. The individual US states maintain separate governments with powers distinct from the federal government. However, when state law conflicts with federal law, federal law prevails according to the Supremacy Clause of the US Constitution. In other words, the autonomy within areas such as industrial, environmental, or social policy allows individual states to set objectives and pursue actions to achieve them. In establishing and developing FCEV, it can be assumed that at the state level, the governments have significant influence over local transportation policies and infrastructure development, both critical for FCEV market development. States can implement incentives for FCEV purchase, establish regulations promoting FCEV usage, and oversee the development of hydrogen refueling infrastructure subsidized by state funds. The state of California, for instance, has been a pioneer in setting ambitious targets for zero-emission vehicles and creating supportive regulatory environments coupled with measurement and standard requirements for hydrogen production, transportation, storage, and usage.

The local level

Below the state level, local governments (including counties, municipalities, townships, and special districts) are generally governed by laws and regulations enacted at the state level. Their responsibilities usually include zoning, police, and fire protection, public utilities, and certain aspects of education. Local authorities, on the other hand, can further stimulate FCEV adoption through their control over zoning, building codes and standards, commissioning and fire marshall inspections of the refueling stations, and last but not least, pursuing local transportation policies. They can offer additional incentives such as preferential parking or usage of High-Occupancy Vehicle (HOV) lanes for FCEV owners. The exemplification of the division of the state into counties[25] is demonstrated in Figure 10.

---

[25] California State Association of Counties, https://www.counties.org/general-information/california-county-map (accessed on August 1, 2023).

Figure 10. The political map of the US state of California with the division into counties. Source: California State Association of Counties, https://www.counties.org/general-information/california-county-map (accessed on August 1, 2023).

This division and distinction of competencies ensure that each level of government can address issues within its jurisdiction, fostering a more responsive governance system. However, it also entails a complex system of coordination and negotiation among different levels of government, often leading to debates about the appropriate balance of power and authority between federal, state, and local entities. Several examples of the shared competencies between the federal and state governments include levying taxes, administering courts, developing transportation infrastructure (especially across the state's borders), or chartering banks and corporations (Chmielewski, 2023). Since the individual states may differ regarding their policy assumptions, objectives, and instruments, it is crucial to evaluate the policies of the selected states considering the legal and political framework established at the federal government level. Among 50 US states, California represents a unique example of the FCEV market, which has matured since the end of the 20th century. Before a detailed examination of this market's policy assumptions, objectives, and instruments, as well as its analysis, it is fundamental to demonstrate an overview of selected indicators that distinguish this state from the other US states in a studied period.

The US economic system is primarily capitalist, characterized by private ownership of production means, market competition, and the pursuit of profit. However, it is more accurately described as a *mixed economy*, with both private sector (business) and public sector (government) involvement. While businesses operate largely without government control, the government plays a significant role in providing public services (like education and infrastructure), regulating economic activities for fairness and safety, implementing policies to counteract economic downturns, and managing inflation through monetary and fiscal policy. The US economy has been notable for its innovativeness, particularly in high-technology industries. These characteristics have helped the US become one of the largest and most influential developed economies globally, making it a critical player in international political and economic relations. At the same time, the US system faces challenges, including economic inequality, political polarization, and debates over the appropriate balance between free markets and state intervention. These issues continue to shape the evolution of the US political and economic system.

3.1.2. Evolution of federal green industrial policy for the establishment and development of the FCEV market

Considering the limited prerogatives of the US federal government in the area under study, especially in establishing policy instruments that could be directly aimed at developing the FCEV markets on a state level, the review will consider the most significant pieces of legislation. The presented legal acts (Table 5) have become the legal framework conditions for individual states or guide the adoption of state-specific regulations.

Year	Name of the policy act	Key provisions and types of green industrial policy instruments
1970	**The Clean Air Act**	• *Regulations and standards*: introduced the air pollution standards from stationary and mobile sources based on the *National Ambient Air Quality Standards* established by the US EPA.
1970	**The National Environmental Policy Act**	• As a policy act, it guided federal agencies to act according to the established environmental objectives.
1975	**The Energy Policy and Conservation Act**	• *Regulations and standards*: introduced strict fuel economy requirements for automakers (the CAFE standards). • *Fiscal instruments*: i.e., enacted federal financial assistance for state-level energy conservation programs. • *Information policy*: i.e., deployed the energy conservation program for appliances, which established efficiency standards and labeling systems.
1978	**The Public Utilities Regulatory Policies Act** (as part of the *National Energy Act*)	• *Regulations and standards*: mandated utilities to purchase power at preferential rates that spurred RES deployment. • *Market-based instruments:* Established a competitive market for small power producers by offering favorable rates and grid access for RES and cogeneration facilities. • *Information policy:* provided transparency in rates and promoted demand-side management programs.
1992	**The Energy Policy Act**	• *Regulations and standards*: established the first Federal fleet requirements for purchasing alternative fuel vehicles, including hydrogen-powered FCEVs. • *Research and development*: initiating R&D programs to finance innovative hydrogen and fuel cell technologies used within the transportation sector, i.e., *The FreedomCAR and Fuel Partnership*.
2005	**The Energy Policy Act** (the amendment)	• *Fiscal incentives:* the IRS recognized, defined, and provided hydrogen fuel with separate federal tax codes. • *Research and development*: increased R&D funding and promoted FCEV demonstration projects run by US DOE. • *Regulations and standards*: established some of the first safety codes and standards for refueling stations.
2007	**The Energy Independence and Security Act**	• *Regulations and standards*: mandated a Renewable Fuel Standard. • *Market-based instruments:* allocated funding for the US DOE's *Loan Programs Office* to support clean energy projects, including FCEVs.
2009	**The American Recovery and Reinvestment Act**	• *Research and development*: allocated funding for R&D and deployment of, among others, stationary hydrogen-powered fuel cell technologies.
2021	**The Infrastructure Investment and Jobs Act**	• *Research and development*: allocated funding for R&D of ZEVs, including FCEVs and refueling infrastructure. • *Subsidies:* introduced deployment and demonstration grants for FCEVs and hydrogen refueling stations.
2021	**The Regional Clean Hydrogen Hubs**	• *Subsidies:* allocated funds to establish six to ten regional clean hydrogen hubs across the United States.
2022	**The Inflation Reduction Act**	• *Fiscal instruments:* established the Hydrogen Production Tax Credits.

Table 5. The overview of the selected federal legislative acts (with a year of adoption) and provisions and types of green industrial policy instruments. Source: Own elaboration.

One of the first pieces of legislation was passed as **The Clean Air Act**[26] in 1970, with significant amendments in 1977 and 1990. It can be considered one of the most significant pieces of environmental legislation in the US (Popp, 2003; Portney, 1990). The Clean Air Act has granted the Environmental Protection Agency (EPA) the authority to regulate air pollution from stationary and mobile sources. Amendments in 1990 introduced new regulatory programs for acid rain control, toxic air emissions, ozone depletion, and automobile exhaust emissions (Bryner, 1995). In 1970, the US Congress also passed **The National Environmental Policy Act**[27] (NEPA), which included the *US Declaration of National Environmental Policy*. NEPA required federal agencies to consider environmental impacts in their decision-making and planning processes. This has been crucial in shaping transportation and energy policies. However, NEPA has been a policy act (not a regulatory one), guiding federal agencies to adopt specific review procedures. An example of such regulations can be found in the environmental impact assessment procedures established by the US President's Council of Environmental Quality (Caldwell, 1998).

In 1975, as a federal response to the 1973-74 oil embargo[28], US Congress passed **The Energy Policy and Conservation Act (EPCA)**[29], which led, among others, to the establishment of the Strategic Petroleum Reserve (to increase resilience to energy dependency) and the Energy Conservation Program for Consumer Products, representing a crucial step toward broader energy efficiency and conservation efforts by introducing the labeling system. EPCA also authorized financial support for state-level energy conservation programs. States could draft their own plans, which, once approved, would be eligible for federal financial assistance. Moreover, the EPCA was broadened with **The Corporate Average Fuel Economy (CAFE) Standards**. Initially, CAFE standards, administrated by the US Department of Transportation, aimed to improve the average fuel economy of cars and light trucks produced for sale in the US. Over time, these standards have improved vehicle fuel efficiency and encouraged the development of alternative fuel vehicles (National Research Council, 2002). At the end

---

[26] The Clean Air Act (42 U.S. Code, §7401 et seq., status of 1970, with the amendments in 1990) allowed the U.S. EPA to establish the *National Ambient Air Quality Standards* (NAAQS) to regulate emissions of hazardous air pollutants (GHGs). It enforced every U.S. states to enact NAAQS on the state level adjusting it to the state characteristics alongside the *State Implementation Plans* (SIPs) by 1975.

[27] 42 U.S. Code §4321 et seq., status of 1970.

[28] In the midst of the 1973 conflict between Arab nations and Israel, the Arab constituents of the Organization of Petroleum Exporting Countries (OPEC) executed an embargo targeted at the United States. This action was a direct response to the American decision to furnish the Israeli defense forces with supplies and was intended to secure an advantageous position in the subsequent peace negotiations after the war.

[29] The Energy Policy and Conservation Act (Public Law 94–163, 89 Stat. 871, status of 1975) was amended by the Energy Independence and Security Act (42 U.S. Code, ch. 152, §17001 et seq., status of 2007).

of the 1970s, **The Public Utilities Regulatory Policies Act**[30] (PURPA) of 1978 was adopted, which required utility providers to buy power from independent producers if it costs less than the utility's own generation, allowing increasing interest and deployment in renewable and low-emission energy sources[31]. While PURPA set federal standards, it also recognized the role of state regulatory authorities. States were responsible for implementing many of PURPA's provisions, allowing for flexibility in adjusting to local conditions.

The abovementioned legislation set a fundamental framework for further development of low- and zero-emission vehicles. Considering the established time span of this dissertation (1990-2022), 1992 marked the year of adoption of **The Energy Policy Act**, the first policy that established federal fleet requirements for acquiring alternative fuel vehicles, including hydrogen-powered FCEVs. It encouraged the use of these vehicles by federal agencies[32]. These requirements paved the way for further initiatives aimed at the broad deployment of these vehicles. However, at the beginning of the 1990s, numerous low- and zero-emission vehicle constructions across all weight classes and functions were characterized by low technology readiness. For this reason, the federal government has been initiating research and development programs to finance innovative hydrogen and fuel cell technologies used within the transportation sector and beyond (alongside low- and zero-emission vehicle constructions). Examples of this approach can be found in **The FreedomCAR and Fuel Partnership** (2003), a partnership between the US Department of Energy (DOE), some of the largest auto manufacturers, and energy companies to collaborate on research and development for fuel cell technology[33]. Furthermore, **The Energy Policy Act of 2005** (which amended the act of 1992 and PURPA) instructed the Secretary of Energy to oversee a research and development initiative focused on technologies linked to the production, purification, distribution, storage,

---

[30] 16 U.S. Code ch. 46 § 2601 et seq., status of 1978.

[31] Utility providers were required to purchase power from *qualifying facilities* (QFs) at the *avoided cost* rate, which is the cost the utility providers would have incurred if it generated the power itself or purchased it from another source. This provision gave small renewable energy producers a market for their power. PURPA created two types of QFs: *Small Power Production Facilities* (typically renewable energy sources like solar, wind, geothermal) and *Cogeneration Facilities* (which produce both electricity and another form of useful thermal energy). Utilities were required to offer non-discriminatory interconnection services to QFs, ensuring they had access to the grid. It encouraged utilities to consider implementing rates that would vary according to the time of day or the season to reflect the actual costs of producing electricity at different times. This was aimed at promoting more efficient electricity use by consumers.

[32] Under Section 303 of the Energy Policy Act of 1992, it was stipulated that Federal agencies must ensure a minimum of 75% of their light-duty vehicle (LDV) procurements by 1999 were comprised of alternative fuel vehicles (AFVs) if the agency possessed more than 20 vehicles and operated in a Metropolitan Statistical Area (MSA) or Consolidated Metropolitan Statistical Area (CMSA).

[33] The consortium involved U.S. DOE, BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation, Shell Hydrogen LLC, and the United States Council for Automotive Research (USCAR) formed by Daimler-Chrysler Corporation, Ford Motor Company, and General Motors Corporation (U.S. DOE, 2006).

and usage of hydrogen energy and fuel cells, as well as associated infrastructure. This act involved collaboration with other federal entities and private sector partners. Following this act, in 2005, the Internal Revenue Service (IRS) recognized, defined, and provided hydrogen and other alternative fuels with separate tax codes[34]. 2007 marked the year of the adoption of **The Energy Independence and Security Act**, which mandated a Renewable Fuel Standard (RFS), including biogas used in hydrogen production. The act also authorized the US DOE to research and develop fuel cell technologies, including hydrogen-powered fuel cells. It allocated funding for the US DOE's Loan Programs Office to support clean energy projects, including FCEVs. Shortly after this act, **The American Recovery and Reinvestment Act** of 2009 (ARRA) was enacted, providing $2 billion in funding for research, development, and deployment of advanced technologies that included fuel cell technologies mainly for stationary purposes such as energy storage and recovery (US DOE, 2011).

The sustainable and low-cost production of hydrogen was much of a concern of federal agencies expressed in some of the already mentioned research and development programs. To intensify this effort, The US Department of Energy established the Energy Earth Shots Initiative to expedite the emergence of plentiful, economical, and reliable clean energy solutions by 2030. This initiative formed a critical pillar of the Biden-Harris Administration's strategic approach to the climate crisis and supported the federal target of attaining net-zero carbon emissions by 2050. As of 2022, it assumed catalyzation of economic growth and job creation in the clean energy sector by offering dedicated research and development funds and grants for developing hydrogen production infrastructure. The initiative was inaugurated by the **US DOE Hydrogen and Fuel Cell Technologies Office** with the launch of the **Hydrogen Shot** on June 7, 2021. The Hydrogen Shot has set a bold objective of decreasing the cost of clean hydrogen by a staggering 80%, thereby bringing it down to $1 per 1 kilogram within one decade, also identified as *1-1-1 Hydrogen Shot.* Noteworthy, the initiative is poised to substantially contribute to the broader *Energy Earth Shots Initiative* and increase the role of a low-carbon hydrogen economy nationwide and internationally, making US enterprises and the economy competitive in this domain.

---

[34] 26 U.S. Code §6426.

Furthermore, in **The Infrastructure Investment and Jobs Act of 2021**[35] (Public Law 117-58), henceforth referred to as the Bipartisan Infrastructure Law, there was a continuation of the authorization pertaining to the national onroad transportation legislation, accompanied by an allocation of $550 billion dedicated to newly-established infrastructure projects. This legislation emphasized the promotion of diverse alternative fuel solutions, including hydrogen-powered fuel cells, via an array of green industrial policy instruments such as grants, analytical studies, technological standards, financial lending, R&D initiatives, and fleet capital allocation, among others. Notably, it underscored the amplification of investments in hydrogen station network development targeting an array of FCEVs spanning light to heavy-duty market segments.

It is important to emphasize that in 2022, the US DOE demonstrated a complementary initiative, **The Regional Clean Hydrogen Hubs**[36], also known as **H2Hubs**. It allocated up to $7 billion to establish six to ten regional clean hydrogen hubs across the United States to facilitate clean energy investments, generate quality jobs, and enhance energy security in communities nationwide. The next crucial policy act, which strengthened the Hydrogen Shot initiative and allowed a post-COVID-19 and post-2022 energy crisis recovery, was the **Inflation Reduction Act of 2022**[37], which established the **Hydrogen Production Tax Credit**[38]. This policy provides a financial incentive of up to 3 USD per kilogram for hydrogen production projects demonstrating a lifecycle greenhouse gas emissions intensity of less than 0.45 kilograms of carbon dioxide equivalent per kilogram of hydrogen produced (kg CO_2e/kg H2). Lastly, in September 2022, US DOE, in cooperation with numerous federal agencies, presented the draft of the **US National Clean Hydrogen Strategy and Roadmap**. This document investigated the potential of clean hydrogen to facilitate the nation's decarbonization objectives across various economic sectors, including transportation. The strategy offered an overview of the current state of hydrogen production, transportation, storage, and utilization in the country and outlined a strategic approach to realize widespread production and usage of clean hydrogen with detailed projections for 2030, 2040, and 2050. This strategy was adopted and presented as the federal framework for the future development of a low-emission hydrogen economy (US DOE, 2023).

---

[35] Public Law 117-58.
[36] 42 U.S. Code, §16161a.
[37] U.S. Public Law no. 117-169, status of 08.16.2022.
[38] 26 U.S. Code, §45V et seq.

The federal government has been presenting a gradual consideration and incorporation of hydrogen and fuel cell technologies within the legislative framework by introducing the mentioned acts and a limited number of policy incentives. It can be stated that by 2022, the federal government's contribution to the establishment and development of the nationwide FCEV market was limited to, still fundamental, regulations that included GHG emissions, fuel efficiency, and public fleet requirements, which influenced both the supply and demand side of the market. Simultaneously, federal agencies such as DOE and DOT[39] have offered substantial R&D and infrastructure funds through grants and public-private partnerships to refine and advance the hydrogen and fuel cell technologies alongside the low-carbon hydrogen economy value chain. Furthermore, the federal government has provided partial funding through grants[40] and tax credits for developing hydrogen refueling infrastructure[41]. A vital example of this is the **H2USA Public-Private Partnership** launched in 2013 by the Department of Energy, which was accompanied by the public announcements made by the leading FCEV manufacturers[42] about their plans to commercialize these types of vehicles in 2015-2017 (US DOE, 2012). H2USA was a collaboration platform aimed at accelerating the deployment of hydrogen infrastructure, which had an evident effect in California with minimal examples in other states. Undoubtedly, the federal government made the FCEVs visible thanks to partially incorporating these vehicles in public fleets and funding the demonstration projects. Through these multi-dimensional efforts, the US federal government has contributed to establishing and developing the FCEV market by setting the framework conditions for the individual states. Nevertheless, the following deliberations will focus on the state of California, which presented a unique involvement in shaping the FCEV market establishment and development.

---

[39] For instance, DOT established the *Truck Emissions Reduction Study and Grant at Port Facilities* to test, evaluate, and deploy projects that reduce port-related emissions from idling trucks up to 80% of eligible project cost (23 U.S. Code, §151 and Public Law 117-58). Another example is the *Bus and Bus Facilities Grants program.* The initiative involves replacing, refurbishing, and procuring buses and vans along with related equipment. It also includes the construction of corresponding bus facilities. A special emphasis is placed on low-emission or zero-emission vehicles and facilities (49 U.S. Code §5312 and §5339 and Public Law 117-58).

[40] *The Charging and Fueling Infrastructure Discretionary Grant Program* (CFI Program, Public Law 117-58 and 23 U.S. Code, §151), implemented by the Federal Highway Administration (FHWA) under the U.S. Department of Transportation (DOT), provides funds for the deployment of public electric vehicle charging stations and alternative fuel infrastructure, including hydrogen, both in urban and rural communities and along designated Alternative Fuel Corridors (AFC) program (also jointly established by FHWA and DOT under the Fixing America’s Surface Transportation (FAST) Act of 2015 to build a network of highways throughout the U.S.A. that will support vehicles running on alternative fuels).

[41] 26 U.S. Code, §30C, §30D, and §38 and Public Law 117-169 - Alternative Fuel Infrastructure Tax Credit were established from 2022 and offered a tax credit of 30% of the cost, not to exceed $30,000.

[42] The initial H2USA initiative included Toyota, Hyundai, General Motors, Honda, Mercedes/Daimler (U.S. DOE, 2012).

3.1.3. *Evolution of state green industrial policy for the establishment and development of the FCEV market in California*

To begin with, it is crucial to underline that the green industrial policy for establishing and developing the FCEV market at the state level in California has a longstanding tradition dating back to 1990. However, the formulation of their assumptions, objectives, and instruments is the consequence of the pro-environmental orientation of the state industrial policies in the context of the transportation sector that, noteworthy, could be traced back in this state back to the 1960s. Since that time, legal regulations and policies have been proposed and enacted through various methods, including Assembly Bills (AB)[43], Senate Bills (SB)[44], and Executive Orders (EO)[45] established by different institutions[46]. The selected policy acts adopted before 1990 are presented in Table 6.

Year	Name of the policy act	Key provisions
1967	*The Mulford-Carrell Air Resources Act*	Established California Air Resources Board with respective prerogatives.
1968	*The Federal Clean Air Act*	Granted California the authority to enforce independent state vehicle emissions standards.
1970	*The California Environmental Quality Act*	The first coherent state policy act that introduced the environmental conservation agenda and control procedures.
1974	*The Warren-Alquist State Energy Resources Conservation and Development Act*	Established California Energy Commission with respective prerogatives.
1978	*The Public Utilities Regulatory Policies Act*	Accelerated transition toward renewable energy sources usage.
1987	*The California Exhaust Emission Standards And Test Procedures*	Established the standards and procedures for 1988-2000 Model Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles.

Table 6. The selected policy acts adopted before 1990. Source: Own elaboration.

---

[43] Assembly Bill (AB): An Assembly Bill is a piece of proposed legislation that originates in the California State Assembly, the lower house of the bicameral California State Legislature. An AB must pass through several stages, including committee review, floor debates, and voting in both the Assembly and the Senate. If it is passed by both houses, it is sent to the Governor for signature. Once signed by the Governor, it becomes state law.

[44] Senate Bill is similar to an Assembly Bill, but it originates in the California State Senate, the upper house of the California State Legislature. The process for review, debate, and voting is similar to that of an Assembly Bill. Once passed by both houses and signed by the Governor, a Senate Bill becomes state law.

[45] Executive Order (EO): An Executive Order is a directive issued by the Governor of California that manages operations of the state government. The legal or constitutional authority for executive orders is derived from the state constitution or statutory delegation from the state legislature. An Executive Order does not need to pass through the legislative process but can be challenged in court if its legality or constitutionality is questioned. Executive Orders often address administrative and operational issues, but they can also be used to take action on policy matters, including environmental policy.

[46] While all three can lead to new laws or directives, they differ primarily in their origination and the process through which they are enacted or issued. Assembly Bills and Senate Bills follow the legislative process, originating in their respective houses and requiring passage by both houses and the Governor's signature. In contrast, Executive Orders come directly from the Governor and do not require legislative approval, but their scope and authority can be subject to legal limitations.

Undoubtedly, the federal government contributed to the efforts made at the state level, but since the beginning, California has represented more extensive environmental protection and conservation efforts. It can be stated that a foundation of this substantially pro-environmental orientation in California's state legislation was the **Mulford-Carrell Air Resources Act**[47], signed into law in **1967**. This act established the **California Air Resources Board**, the state agency responsible for air quality management and control, and precisely, the reduction of carbon emissions. The year after the establishment of CARB, the **Federal Clean Air Act of 1968** acknowledged California's progressive efforts in environmental regulation. Furthermore, it granted California the unique authority to enforce its own vehicle emissions standards, which were more rigorous than those at the federal level. One of the primary reasons for California's autonomy in the form of a **federal waiver** was recognizing California's severe air quality problems and its efforts to address them. Since then, other US states have adopted the federal or California standards[48]. This waiver has been a crucial tool for California in driving its independent pro-environmental policy[49].

By utilizing this authority, CARB swiftly adopted the nation's pioneering standards for nitroxide emissions from motor vehicles merely four years after this legislative endorsement. This initiative by CARB served as an incentive for developing catalytic converters, a significant innovation that drastically enhanced the capacity to mitigate smog-forming automobile emissions (CARB, 2020). Furthermore, in 1970, California enacted **The California Environmental Quality Act**[50] (CEQA), pivotal in enforcing environmental protection within the state. Firstly, CEQA requires state and local agencies to identify the environmental impacts of their actions and commercial projects before granting them

---

[47] The Mulford-Carrell Air Resources Act (California Health & Safety Code, §39000 et seq.), signed by Governor Ronald Reagan on August 30, 1967 formed the California Air Resources Board as the convergence of the Bureau of Air Sanitation and the California Motor Vehicle Pollution Control Board, thus emphasizing a unified approach to air quality regulation across the state. The Federal Air Quality Act of 1967, concurrently enacted, further fortified California's mandate to impose air quality standards that exceeded federal benchmarks in response to the state's unique topographical, climatic, and demographic challenges.

[48] By 2019, the following 13 U.S. states have adopted California's Low-Emission Vehicle (LEV) standards for criteria pollutants and greenhouse gases (GHG), as well as the Zero-Emission Vehicle (ZEV) regulations:
New York, Massachusetts, Vermont, Maine, Pennsylvania, Connecticut, Rhode Island, Washington, Oregon, New Jersey, Maryland, Delaware, Colorado. This adoption falls under Section 177 of the Clean Air Act (42 U.S. Code, §7507) (CARB, 2019).

[49] However, it's important to note that while California has considerable autonomy, its policies still exist within a broader Federal legal framework conditions and can be subject to federal review or challenge. For example, there have been times when the federal government has threatened to revoke California's waiver under the Clean Air Act, leading to legal disputes (Osofsky, 2010).

[50] The CEQA (California Public Resources Code §21000–21189 et seq.) was enacted shortly after the The National Environmental Policy Act (NEPA) adopted at the federal level which established the President's Council on Environmental Quality (CEQ).

approval or financing in the form of grants. Secondly, CEQA enforces the facilitation of public participation in project decision-making. By offering a platform for community members to voice their concerns and insights, potential project impacts can be effectively addressed. This inclusive process allows individuals to contribute towards developing project alternatives and mitigation strategies, thereby playing a pivotal role in minimizing adverse project outcomes and enhancing the overall sustainability of the initiative.

The establishment of CARB and the introduction of CEQA were followed by Jerry Brown's first term as governor from 1975 to 1983, which was instrumental in pushing California's independent pro-environmental policies. His administration enacted strict energy-efficiency policies, leading California to have some of the lowest *per capita* energy use figures in the United States. Furthermore, in response to the escalating energy crisis of the early 1970s and the unsustainable surge in energy demand, **The Warren-Alquist State Energy Resources Conservation and Development Act**[51] of **1974** instituted the **California Energy Commission (CEC)**. This establishment was aimed at addressing these emergent energy-related challenges within the state. The commission's mandate included the promotion of energy efficiency and conservation, as well as the certification of thermal power plants. The act allowed the commission to set energy efficiency standards for appliances and new buildings, significantly reducing California's energy consumption. In **1974**, California also enacted legislation to regulate automotive smog emissions, a particularly significant problem in Los Angeles that required strict fuel efficiency measures[52]. This legislation was a pioneering initiative, preceding similar federal regulations. **The Public Utilities Regulatory Policies Act of 1978** (PURPA) was a federal law responding to the energy crisis, but it significantly impacted California's energy policy. PURPA required utility providers to buy power from independent producers if it cost less than the utility's own generation. This allowed the cogeneration of energy and the incorporation of RES in California’s energy mix (Righter, 1996).

---

[51] The Warren-Alquist State Energy Resources Conservation and Development Act was enacted as a California Public Resources Code Section 25000 et seq.

[52] An example of this regulation is an adoption of the smog check requirement of American automobiles manufactured on or after 1966. This requirement was further developed into a standardized state-wide Smog Check I (1984) under the legal framework of the California Senate Bill 33 (Presley, Chapter 892, Statutes of 1982) led by California Bureau of Automotive Repair. This program was in the course of next decades further significantly developed through Smog Check II (1997) and adjusted to meet modern vehicular technologies and more strict emission requirements under Assembly Bill 2289 (status of 2010).

Noteworthy, CARB adopted **The California Exhaust Emission Standards And Test Procedures for 1988-2000 Model Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles**[53] in 1987, which became the most rigorous tailpipe emission standards in the United States at that time. These examples from the 1960s, 1970s, and 1980s illustrate how California has long been a nationwide leader in the independent pro-environmental green industrial policy structuring and regulating the transportation sector. Many of these policies have shaped the environmental landscape in California and paved the way for a contemporary approach to various industries, including establishing and developing the FCEV market.

The selected green industrial policy acts and instruments adopted between 1990 and 2022

The timeline of adoption of individual legislative acts, the introduction of policy instruments, as well as the adoption of the FCEV-market-oriented strategies, is presented in Figure 11 and further discussed in the subsequent paragraphs to demonstrate the complex legal and policy determinants that shaped the establishment and development of the matured green industrial policy that targeted the FCEV market establishment and development in this US state between 1990-2022.

---

[53] California Code of Regulations, title 13 §1960.1.

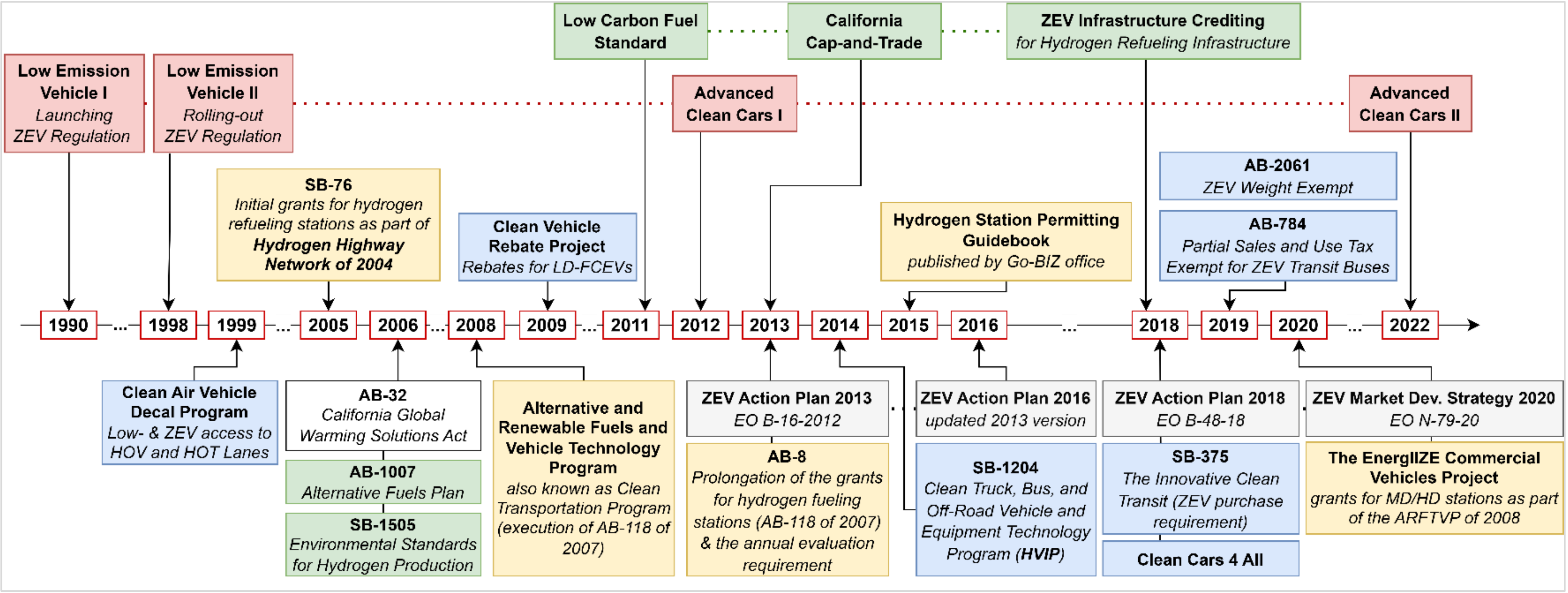


Figure 11. The evolution of policies for establishing and developing the FCEV market in California in 1990-2022 with selected policy acts adopted before 1990. Colours represent the strategic policy objectives (green - sustainable and low-cost supply of hydrogen, yellow - developing accessible and reliable refuelling infrastructure, red - increase in market supply for FCEVs, blue - increase in market demand for FCEVs), policy acts (white), and strategies (grey). Source: Own elaboration.

Within the scope of this dissertation, California introduced various green industrial policy acts and implemented numerous instruments, as demonstrated in Figure 11. After a review of those acts and market development strategies, the author identified four strategic policy objectives that the state legislators and industrial policy-makers addressed:

I. sustainable and low-cost supply of hydrogen,

II. developing accessible and reliable refueling infrastructure,

III. increase in market supply for FCEVs,

IV. increase in market demand for FCEVs.

Considering the abovementioned four strategic policy objectives, it is possible to identify 11 policy instruments (Table 7) that have been introduced and will be further deliberated in this review.

Strategic policy objectives	**Type of green industrial policy instrument**	**Green industrial policy instruments**
I. Develop sustainable, low-cost hydrogen fuel supplies	Regulations and standards	Hydrogen Fuel Specifications; Measurements and Standards
	Tradeable permits	LCFS; ZEV Infrastructure Crediting (HRI)
II. Develop accessible, reliable refueling infrastructure	Regulations and standards	CEQA Review Exempt, Fuelling Station Building Standards & Safety Codes
	Subsidies	Hydrogen Fuelling Infrastructure Grants
	Information policies	ZEV Infrastructure Support & Hydrogen Fuelling Station Evaluation Reports
III. Increase the market supply of FCEVs	Regulations and standards	Sales Requirement for ZEV manufacturers (as % of sale – ACC II)
	Tradeable permits	Tradable ZEV credits for manufacturers (ZEV Regulation / ACC I)
IV. Increase the market demand for FCEVs	Regulations and standards	ZEV Purchase Requirements for transit buses, airport shuttles & other public fleets
	Taxes and charges	Tax credits and exempts, i.e., ZEV Transit Bus Tax Exempt
	Subsidies	CVRP Rebates & HVIP Vouchers
	Information policies	Access to HOV & HOT Lanes and ZEV Weight Exemption

Table 7. Presentation of 11 green industrial policy instruments included in this study that California introduced in 1990–2022 to help establish and develop the FCEV market.

I. *Green industrial policy instruments for the sustainable and low-cost supply of hydrogen fuel*

Since the 1990s, the CEC and the CARB have delineated ambitious goals to enhance air quality and curtail petroleum reliance, including slashing petroleum fuel consumption to 15% below 2003 levels by 2020 and reducing greenhouse gas emissions to 80% below 1990 levels by 2050. These objectives implied an increased consumption of alternative fuels, with clean hydrogen for FCEVs and biofuels for ICEVs central to the strategy. However, the augmentation of these fuels, specifically hydrogen, necessitated adjustments in the regulations and codes of standards that dictate the retailing of transportation fuels in California. This expansion also demanded significant development of California's hydrogen refueling infrastructure to support increased numbers of fuel cell vehicles. Since the 1990s, under the aegis of the California Department of Food and Agriculture's Division of Measurement Standards (DMS) and funded by the CEC, two pivotal tasks were delineated: (1) evaluating methods for hydrogen fuel quality testing and (2) creating necessary standards and regulations for retail hydrogen fuel dispensers in California. As DMS underscored, high-purity hydrogen is imperative due to the sensitive nature of fuel cell catalysts.

Additionally, SB 76 mandated the Department of Food and Agriculture, with CARB's concurrence, to define, by 2008, specifications for hydrogen fuels for use in internal combustion engines and fuel cells in motor vehicles. The bill also set environmental goals for funded activities to be achieved by 2010, which included (1) a statewide 30% reduction in greenhouse gas emissions, (2) deriving 33% of hydrogen for vehicles from RES, and last but not least, (3) ensuring no increase in smog-forming emissions. SB 76 further required CARB to provide biannual reports on its implementation efforts, including attaining the aforementioned environmental goals[54]. The following **Senate Bill 1505**[55] mandated the CARB to create and implement specific regulations to ensure the production and use of hydrogen for transportation, leading to a decrease in greenhouse gas emissions, criteria air pollutants, and toxic air contaminants. SB 1505 emphasized the commitment to support the FCEV market development as one of the critical means for achieving these emission reduction targets. By ensuring the clean production and use of hydrogen fuel, the bill

---

[54] A status report on transportation-related hydrogen activities in other states, the siting of hydrogen fueling stations, the impact of Hydrogen Highway activities on affected communities and neighborhoods, and the development of hydrogen-related business activity in California was mandated to be delivered by the end of 2006.

[55] Senate Bill 1505 (Lowenthal, *Hydrogen fuel*, status of 2006).

supported the broader adoption and development of the FCEV market in California. These efforts, coupled with the already-mentioned Assembly Bill 1007, were part of broad statewide efforts to mitigate climate change expressed through the enactment of Assembly Bill 32 – **The California Global Warming Solutions Act of 2006**. AB 32 legally mandated a significant reduction in greenhouse gas emissions[56], effectively positioning the state toward a sustainable, low-carbon future. AB 32 was the first initiative in the United States to adopt a comprehensive, long-term strategy to tackle climate change[57].

The **measurement and standards requirements for hydrogen used as a fuel in transportation** were outlined in SAE International's Surface Vehicle Standard J2719 in 2011 and adopted by California's Department of Food and Agriculture[58]. However, these standards were accompanied by robust, validated test methods and metrological requirements set by the DMS of the California Department of Food and Agriculture to regulate compliance.

Before 2007, no direct specifications or tolerances for these dispensers were developed, disincentivizing manufacturers from investing in their development. To rectify this, the CEC funded the development of testing and certification protocols for hydrogen dispensers. Subsequently, three metrological standards were developed and incorporated into the Hydrogen Field Standard, a mobile device used for testing dispensers at retail stations throughout California. (Ferris et al., 2020). More importantly, in 2006, SB 1505 imposed on state agencies to *require that, on a statewide basis, no less than 33.3% of the hydrogen produced for, or dispensed by, fueling stations that receive state funds be made from eligible renewable energy resources as defined in subdivision* (SB 1505, sec. 3, par. 43869, p. 2B). The requirement determined the post-2007 policy instruments and was in force until the end of 2022 contributing to the sustainable supply of hydrogen fuel used in transportation sectors.

---

[56] Assembly Bill 32 included the major GHGs, such as carbon dioxide (CO2) and methane (CH4), as well as the groups of GHGs that are being emitted into the atmosphere, including nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3, added to AB 32 in the following years).

[57] AB 32 obligated California state agencies, including CARB, to establish plans to roll back its GHG emissions to the levels of 1990 by 2020, which signifies an approximate reduction of 15 percent compared to the emissions projected under a "business as usual" scenario. This stringent regulation propelled the state to innovate and adopt cleaner technologies, including FCEVs, to achieve the stated reduction targets (CARB, 2023c).

[58] Quality standards for hydrogen fuel were published in 2011 as SAE International’s Surface Vehicle Standard J2719 - Hydrogen Fuel Quality for Fuel Cell Vehicles. SAE J2719 has been adopted by reference by the Department of Food and Agriculture in California Code of Regulations Title 4, Division 9, Chapter 6, Article 8, Section 4181.

To increase a sustainable and low-cost hydrogen supply, the CARB initiated in 2011 **The Low Carbon Fuel Standard (LCFS),** a significant policy instrument designed to reduce the emission intensity of the fuels used in transportation. By setting specific emission-intensity benchmarks, the LCFS encourages the use of low-carbon transportation fuels and stimulates their production. The standard reflects each fuel's total lifecycle of greenhouse gas emissions, including the direct tailpipe emissions from their use and life-cycle emissions associated with their production and transportation. It is crucial to emphasize that LCFS works on a market-based credit-deficit system. Fuels with lower carbon emission intensity than the benchmark generate credits, while those with higher carbon intensity generate deficits. Companies supplying transportation fuels must either generate or acquire enough LCFS credits to offset any deficits their fuels might create, thereby adhering to the carbon intensity standards set for each compliance period. This market-based system incentivizes the production and use of low-carbon-intensity fuels and discourages the use of higher-carbon-intensity fuels[59].

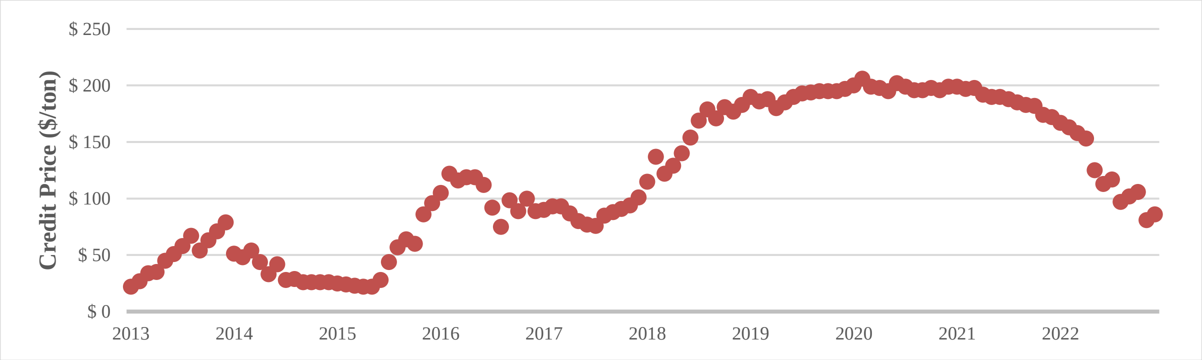


Figure 12. Monthly average LCFS credit price reported by CARB (2013-2022). Source: Own elaboration based on CARB Database available at the dedicated website: https://ww2.arb.ca.gov/. (Accessed: August 1, 2023).

The 2018 Low Carbon Fuel Standard amendments introduced a provision for ZEV infrastructure. This provision allowed hydrogen refueling and charging station operators to generate additional LCFS credits for the deployment of certain types of ZEV infrastructure, specifically Hydrogen Refueling Infrastructure (HRI) and Direct Current (DC) Fast Charging Infrastructure (FCI). In essence, since 2018, eligible hydrogen refueling stations or DC fast chargers have been capable of generating infrastructure credits in addition to the LCFS credits they receive for dispensing low-carbon fuel. The amount of these additional HRI or FCI credits is based, among other factors, on the capacity of the station or charger, subtracting the quantity

---

[59] Moreover, California is not working in isolation. The Pacific Coast Collaborative, consisting of California, Oregon, Washington, and British Columbia, is a regional effort to align strategies and policies to reduce GHGs and encourage clean energy use. This collaboration seeks to create a West Coast market for low-carbon fuels, providing a stronger impetus for their production and use.

of dispensed fuel. The more unused capacity, the more credits these facilities can generate[60]. By creating a mechanism to reward the deployment of ZEV infrastructure, the LCFS aims to stimulate the growth of ZEVs in California. It will reduce the carbon intensity of the transportation fuel pool, helping the state achieve its ambitious greenhouse gas reduction targets (CARB, 2021b). It is worth emphasizing that before 2018, LCFS was awarding all types of low-carbon emission-intensity fuel, keeping the **technology-neutral approach**, the so-called agnostic approach, toward low-carbon fuel. The 2018 amendments determined the additional support given to hydrogen and battery-powered vehicles, somehow determining the policy orientation and the scope of refueling infrastructure development strategy in California, narrowing it to BEVs and FCEVs.

II. Green industrial policy instruments for the development of an accessible and reliable refueling infrastructure

As of 2004, hydrogen-powered FCEVs were not a significantly important alternative to the BEVs, gradually increasing their visibility within the on-road transportation sector. The crucial change occurred thanks to the recognition of FCEVs' potential demonstrated through a sequence of bills that guided the state agencies in the context of refueling infrastructure development and further research and development activities. In 2004, California's Governor, Arnold Schwarzenegger, instituted EO S-7-04, marking a significant step in advancing the state's FCEV market. This order envisioned California's interstate freeways as a **Hydrogen Highway Network**. It mandated that the California Environmental Protection Agency and all other related government agencies collaborate with stakeholders to plan and establish a network of hydrogen fueling stations. The objective was to ensure access to hydrogen fuel for every Californian by 2010, with a significant proportion originating from low-carbon, renewable sources. This vision was further delineated in the California Hydrogen Highway Plan issued by the California Environmental Protection Agency in 2005. The Executive Order was boosted in 2005 when **Senate Bill 76** was enacted as part of the state budget, providing $6.5 million to fund the Hydrogen Highway initiative. These funds, made available from January 1, 2006, were purposed to (1) establish up to three publicly accessible hydrogen fueling demonstration stations, (2) lease up to 12 hydrogen-powered vehicles,

---

[60] The complete HRI Credit Calculation formula as well as the requirements related to reporting and can be https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/guidance/zev_infra_crediting_overview.pdf

and purchase up to two hydrogen-powered shuttle buses for use at airports or universities, and lastly (3) employ staff for two years to support the effort.

The state of California recognized the need to develop the refueling infrastructure as a crucial part of policy for establishing and developing the FCEV market. Furthermore, the increasing number of refueling stations was coupled with acknowledging their accessibility and reliability as the crucial determinants of their performance. The review of the policy instruments that are implemented in this domain should be started with **subsidies**. The subsidies are provided in the form of competitive grants solicitation within a framework of **The Alternative and Renewable Fuels and Vehicle Technology Program** (ARFVTP), also known as **The Clean Transportation Program**[61]. It was a first-of-its-kind initiative that was established in California in 2008. ARFVTP is the primary funding source for the refueling station development[62]. Furthermore, another available funding is the **EnergIIZE** (Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles) program, which represents the first statewide commercial vehicle fleet infrastructure incentive program for eligible applicants[63]. It is funded by the CEC under the Clean Transportation Program and implemented by CALSTART. The program covers up to 50% of eligible equipment and software costs and does not exceed a USD 3 million project cap (in some exceptional cases, the cover amount can reach 75% and a USD 4 million project cap). The eligible software includes compressors, liquid and gaseous pumps, piping and pipelines, dispensers, hose and nozzles, high-pressure storage, onsite production, and chillers. Specific non-hydrogen-related

---

[61] The ARFVTP program was enforced by adopting Assembly Bill 118 (Núñez, *Alternative fuels and vehicle technologies: funding programs*, status of 2007), and was prolonged through January 1, 2024 by Assembly Bill 8 (Perea, *Alternative fuel and vehicle technologies: funding programs*, status of 2013).

[62] The ARFVTP program was designed to foster the development and adoption of advanced technologies and alternative fuels in the four key areas that include (1) Fueling and Charging Infrastructure - The ARFVTP aims to expedite the development of conveniently located fueling and charging stations for low- and zero-emission vehicles, which is seen as essential for facilitating the widespread adoption of these vehicles, (2) ZEV Adoption and Advancement - Another goal is to accelerate the advancement and adoption of alternative fuel and advanced technology vehicles. It includes passenger cars and medium- and heavy-duty low-emission or zero-emission vehicles, (3) In-State Production of Renewable Fuel - The program also aims to increase in-state production of alternative, low-carbon renewable fuels. It helps reduce GHG emissions and can have economic benefits by promoting local industries. (4) Manufacturing and Workforce Training - Finally, the program supports the manufacturing sector related to clean transportation and fuels, and it fosters workforce training to meet the needs of this growing market, as it is essential to ensure sufficient skilled workers are available to support the transition to a cleaner transportation sector.

[63] To be eligible, commercial fleet users or station owners must meet three criteria – (1) projects must be intended for deployment of hydrogen refueling equipment for the MD/HD FCET, (2) the refueling station must be capable of dispensing 350 or 700 bar and be certified by respective institutions such as the National Fire Protection Association, and lastly (3) eligible for the largest incentive funding cap across other funding lanes within EnergIIZE program, which means that an applier must demonstrate eligibility regarding decarbonization of the fleet in detailed technical aspects.

equipment can also be covered, including switchgear, electrical panel upgrades, wiring and conduit equipment, and pump meters. So do other financing programs, the application process is conducted virtually via a dedicated platform[64]. Interestingly, the CEC presents the list of approved vendors that provide the equipment alongside the list of preferred vendors, limiting the number of companies by half[65]. These state programs can be enhanced by the federal funds allocated by the dedicated agency, such as US DOE or DOT (discussed previously).

Once the potential operator of a refueling station receives a subsidy awarded by a federal or state agency, establishing a refueling station requires meeting **station building standards and safety codes** adopted in California on the state and local levels. First of all, there are crucial permitting aspects, such as zoning, architectural review, the CEQA review, as well as local fire department approval, and utility power connections of these facilities. Based on state and local permitting regulations, the hydrogen refueling stations are awarded exempt or accelerated administrative procedures, which speed up these procedures, decrease transaction costs, and reduce uncertainty. Besides, the California Governor's Office of Business and Economic Development (GO-Biz) offers consultations on constructing and commissioning procedures, including a review of necessary documents (Vacin & Eckerle, 2020).

Finally, California utilizes information instruments, an example of which is the CARB’s annual presented reports on the *Evaluation of Fuel Cell Electric Vehicle Deployment*[66]. Based on AB 8, CARB is required to perform an analysis to evaluate and report findings to the CEC on *the need for additional publicly available hydrogen-fueling stations for the subsequent three years in terms of the quantity of fuel needed for the actual and projected number of hydrogen-fueled vehicles, geographic areas where fuel will be needed, and station coverage*[67]. These publicly available reports offer a detailed evaluation of the infrastructure and FCEV market analysis, which can be very informative for public and private entities operating in this market or representing some stakeholders. Besides, CARB developed the **California Hydrogen Infrastructure Tool** (CHIT) as part of the ZEV Infrastructure Support mechanism. It is a tool designed within ArcGIS that leverages Geographical Information System technology. It is used to evaluate the spatial discrepancies between the

---

[64] The detailed information about the EnergIIZE program can be found on dedicated website (www.energiize.org).
[65] As of December 2022, the list of the preferred vendors in the context of hydrogen technologies was limited to: Air Products and Chemicals Inc., Black & Veatch - dba Overland Construction Inc., EnTech Solutions, FuelCell Energy, GHD Services Inc., In-Charge Energy Inc., Integrated Cryogenic Solutions LLC, Johnson-Peltier Inc., TLM Petro Labor Force Inc., Trillium USA Company LLC.
[66] California Health and Safety Code 43018.9.
[67] Assembly Bill 8 (Perea, Statutes of 2013, Chapter 401).

coverage and capacity of existing and planned stations and the potential early adopter market for FCEVs (CARB, 2016).

III. Green industrial policy instruments for the increase in market supply for FCEVs

It is worth emphasizing that in the 1980s, CARB began considering policies that eventually led to the **Zero Emission Vehicle (ZEV) mandate** established in **1990** under the **Low-Emission Vehicle Program I**. It was the first-of-its-kind policy in the world, pushing car manufacturers to develop electric and hybrid vehicles. The ZEV mandate applied to major automakers selling vehicles in California. Under the program, each automaker had to ensure that a certain percentage of the vehicles they sell are ZEVs or LEVs, or they can meet their obligations partially through the sale of transitional zero emission vehicles (TZEVs), like plug-in hybrid electric vehicles. It is worth emphasizing that the ZEV mandate is a credit-based regulation. Each vehicle type offered for sale earns a certain amount of tradable credits based on its zero-emission range and type. For instance, under **LEV I**, a battery electric vehicle (BEV) would earn more ZEV credits than a plug-in hybrid electric vehicle (PHEV) due to the BEV's greater zero-emission range. Automakers could bank their excess ZEV credits for use in future years and trade ZEV credits with other automakers. This created a market for ZEV credits and gave manufacturers flexibility in meeting their requirements. Each automaker's compliance was assessed annually. If a manufacturer did not meet its ZEV credit requirement in a given year, it must have made up the deficit in the following year. If a manufacturer remained out of compliance, it might have caused financial penalties. This mechanism has remained almost unchanged since the introduction of **LEV II**[68]and the **LEV III** regulations as part of the **Advanced Clean Cars Program**. These LEV III regulations set increasingly strict emission standards for criteria pollutants and greenhouse gases for new passenger vehicles through the 2025 model year. In 2022, the CARB endorsed the **Advanced Clean Cars II** regulations and prolonged the ZEV mandate. These comprehensive regulations imposed a new mechanism – **a percentage share of ZEVs offered for sale** for the model years between 2026 and 2035.

---

[68] The LEV II regulations were subsequent advancements on the LEV I, continuing the reduction of criteria pollutant emissions from new light- and medium-duty vehicles, beginning with the 2004 model year. In a groundbreaking move, CARB sanctioned the Pavley bill in 2004 (AB 1007), necessitating auto manufacturers to curb greenhouse gas emissions from new vehicles for models between 2009 and 2016. After the United States Environmental Protection Agency adopted federal greenhouse gas standards that maintained the benefits of the Pavley regulations, they were adjusted to equate compliance with the federal standards to compliance with California's standards for the 2012 through 2016 model years. This became known as the "deemed to comply" option.

It is crucial to underline that based on these regulations, by 2035, it is envisaged that all new passenger cars, trucks, and SUVs sold in California will be zero-emissions vehicles. The Advanced Clean Cars II regulations not only built on the state's expanding ZEV market and tightened motor vehicle emission control norms but also enhanced them to achieve stricter tailpipe emissions standards and accelerate the transition to 100% ZEVs[69]. The foundation of LEV I and the ZEV mandate has been instrumental in developing the contemporary policy landscape, where strategies for establishing and developing markets for ZEVs, including FCEVs, are being implemented. For this reason, **1990** was acknowledged as the beginning of this doctoral research's time scope.

IV. Green industrial policy instruments for the increase in market demand for FCEVs

Undoubtedly, the instruments aimed at increasing the FCEV market demand are crucial to overcoming barriers associated with the development of this market. First, several California legislatures established **purchase requirements** for ZEVs, including FCEVs, in various public and private fleets. These typically involve setting purchase requirements for ZEV targets (as California sustains the *technology-neutral* policy approach) for institutional buyers (such as transit agencies, airports, and port operators).

Regarding the transit agencies, **The Innovative Clean Transit** (ICT) regulation[70], adopted by the CARB in 2018, required all public transit agencies to gradually transition to 100% zero-emission bus (ZEB) fleets. The regulation set a timeline for when transit agencies need to start using ZEBs, intending to have a whole ZEB fleet by 2040. CARB's ICT regulation also applies to privately and publicly owned airport shuttles. By 2035, all airport shuttle buses must be zero-emission. This includes hotel shuttle services, parking lots, and rental car companies. Lastly, under Assembly Bill 739, state agencies must buy more ZEVs when adding to or replacing their fleets. By 2025, at least 50% of the light-duty vehicles purchased by state agencies must be zero-emission. In addition, at least 15% of newly purchased buses, trucks, and off-road vehicles must be zero-emission by 2025 and at least 30% by 2030. FCEVs can help to meet these requirements, particularly in applications where their range and refueling speed are advantages. These purchase requirements are key instruments

---

[69] The Advanced Clean Cars II and setting the target in 2035 was enforced by the Governor Newsom's Executive Order N-79-20.

[70] The ICT regulation was aligned to the state legislation expressed in the California Sustainable Communities and Climate Protection Act (Steinberg, Senate Bill 375, Chapter 728, statutes of 2008), and Clean Energy and Pollution Reduction Act (De Leon, Senate Bill 350, Chapter 547, Statutes of 2015).

to promote the deployment of ZEVs, including FCEVs, and help California meet its climate and air quality goals established by previously discussed pieces of legislation. They also help to stimulate the market for these vehicles, driving technological improvements and cost reductions. Noteworthy, since 2019, California has offered limited state **sales and use tax exemptions** when public agencies purchase a zero-emission bus and are eligible for the Low Emission Truck and Bus Purchase Vouchers[71].

The next crucial group of incentives is the **subsidies** offered under different funding programs. First of all, the potential users of light-duty vehicles can apply for subsidies, called *LD-ZEV Rebates*, from $1,000 to $7,500 for the purchase or lease of new, eligible ZEVs, including FCEVs under the CVRP program[72] administered since its foundation in 2008 by The Center for Sustainable Energy on behalf of CARB, as of 2022, three commercially available models are only eligible for the rebate[73]. Another subsidy program also covers the light-duty vehicle segment - *Clean Cars 4 All* – proposed by CARB and funded by the California Climate Investments[74]. The initiative aimed to offer financial incentives to lower-income Californians in five air districts (Bay Area, San Diego, South Coast, San Joaquin, and Sacramento). Since 2019, the program has encouraged these individuals to retire their older, high-emission vehicles and replace them with zero- or near-zero-emission alternatives. The following segment of the FCEV market covered by the subsidy program is the transit FCEB segment. The buses can be replaced using the subsidies under the ARFVTP program, especially in the context of school buses, which have a separate budget for such replacements[75]. However, the central subsidy program that stimulates the demand for FCEV is The Hybrid and **Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)**, which was established in 2014[76]. The HVIP vouchers cover only two types of ZEV trucks and buses, including battery- and fuel-cell electric vehicles. The vouchers are granted by the California Environmental Protection Agency and solicited by the CARB. The value of the voucher depends on the class and function of the

---

[71] Zero Emission Transit Buses Tax Exemptions allow wavering 3.9375% sales and use taxes based on the California Revenue and Taxation Code 6377.

[72] California Health and Safety Code 44274 and 44258.

[73] This list includes Honda Clarity Fuel Cell, Hyundai Nexo, Toyota Mirai Fuel Cell Vehicle. As of 2022, the value of the CVRP Rabate for all three models was $4,500. More detailed information can be found on the CRVP website: https://cleanvehiclerebate.org/en

[74] Clean Cars 4All was established based on Assembly Bill 630 (Cooper, Vehicles: retirement and replacement, statutes of 2017, Article 3: Clean Cars 4 All Program).

[75] In 2012 Senate Bill 110 allocated a sum of up to $75 million to the program, sourced from the California Clean Energy Jobs Act (Proposition 39).

[76] The HVIP was enacted by SB 1204 (Lara, ch. 452, Statutes of 2014) with a specific requirement expressed in Appendix B to the California Health & Safety Code Section 39719.2(c) and (d).

vehicles. As of 2022, there were 152 ZEVs, including 6 FCEVs (Class 8)[77], and at least 147 vouchers were granted through this program totaling $37 184 000 (accounting for less than 1% of all funding) (California HVIP/CARB, 2023). Lastly, local programs are established by individual counties and municipalities. For instance, the San Joaquin Valley Air Pollution Control District established ***Drive Clean! Rebate Program***. The program offers rebates to residents and businesses within the Valley who purchase or lease new, clean-air light-duty vehicles. To qualify for a rebate, the vehicle must be purchased or leased from the approved list of eligible vehicles, which covers the same models as CVRP regarding LD-FCEV. As of 2022, the program offers up to $3,000 additional funding depending on the resident's income and other program requirements[78].

In 1999, CARB established a Clean Air Vehicle (CAV) Decal program in cooperation with the California Department of Motor Vehicles [79]. It allowed the low- and zero-emission vehicles, including hydrogen-powered FCEVs, to freely enter the **High Occupancy Vehicle** (HOV) lanes on the highways, even if the driver is solely in the vehicle[80]. This program aimed to encourage the purchase of these vehicles by offering a meaningful incentive in the form of single-occupant use of carpool lanes thanks to stickers placed on the vehicles. The type and colors of the stickers have varied over the years, as has the program, which has significantly evolved since its adoption by gradually increasing the standards and lowering the tailpipe emission levels of the vehicles allowed to use the HOVs solely occupied by the driver.

To stimulate demand for FCEVs, especially in the context of medium- and heavy-duty FCET segments, California since 2019 has offered the **ZEV Weight Exemption**[81] because, under

---

[77] The models were as follows: New Flyer Xcelsior XHE40 FCEB, New Flyer Xcelsior XHE60 FCEB, Nikola TRE FCEV Truck, Hyundai XCIENT FCEV Truck, Hyzon Motors HyHD8 FCEV Truck (with a ICEV conversion option). All vouchers, except of conversation were established at $240,000. The up-to-date information can be found at the HVIP Program website: https://californiahvip.org/ (Access: August 1, 2023).

[78] The program details can be found at: https://www.valleyair.org/drivecleaninthesanjoaquin/ (Access: August 1, 2023).

[79] The program was origninaly enacted based on the Assembly Bill 71 (Cunneen, High-occupancy vehicle lanes: low-emission vehicles, status of 1999). As of 2022, CAV decal stickers are issued by the California's DMV to qualifying vehicles pursuant to last California Vehicle Code §5205.5 and §21655.9 following the Assembly Bill 544 (Bloom, Vehicles: high-occupancy vehicle lanes, status of 2017).

[80] HOV lanes are reserved traffic lanes on highways designed to encourage carpooling and more efficient use of roadway capacity. Thanks to the CAV Decal program, HOVs have aleardy become an incentive that promotes the low- and zeroemission vehicles. However, they are typically used by vehicles carrying two or more passengers, including the driver. The primary goal of HOV lanes is to decrease traffic congestion and reduce emissions by promoting shared transportation and low- and zero-emission vehciels.

[81] Assembly Bill 2061 (Ting, Transportation electrification: electric vehicle charging infrastructure, Statutes of 2014), within the confines of federal law as stipulated by the Fixing America's Surface Transportation Act, permits the operation of near-zero-emission or zero-emission vehicles. These vehicles are defined according to

US federal law, there are weight limits for vehicles on interstate highways and some other roads. These limits are intended to prevent damage to roads and bridges. However, zero-emission vehicles, including FCEVs, often weigh more than their conventional counterparts because of the weight of the batteries or hydrogen storage systems. California offers a weight exemption for these vehicles to address this issue and encourage the deployment of ZEVs. The exemption allows ZEVs to exceed the weight limits by up to 2,000 pounds (~907 kg). This policy aims to level the playing field by allowing zero-emission trucks and buses to carry the same payload as comparable diesel-powered vehicles. The ZEV weight exemption is an example of the supportive policies that California has implemented to accelerate the transition to a clean, low-carbon transportation system. Addressing the unique challenges associated with zero-emission vehicles helps make these vehicles more competitive and attractive to fleet operators.

---

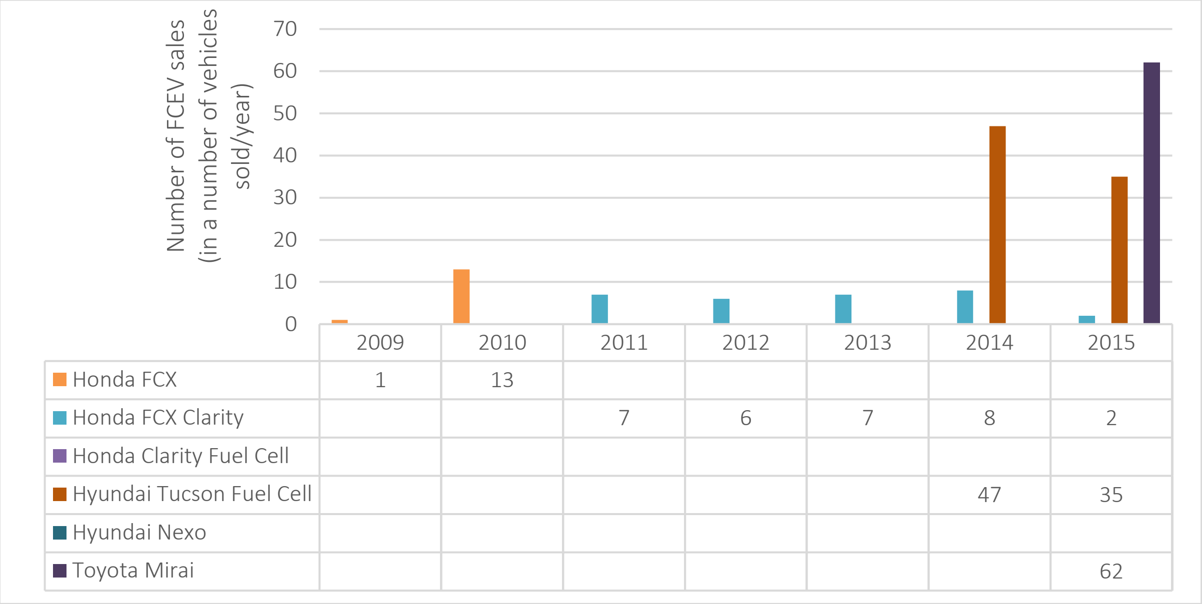
subdivisions (c) and (d) of Section 44258 of the Health and Safety Code (https://dot.ca.gov/) (Accessed: August 1, 2023).

3.2. Characteristics of the FCEV market in the state of California

For the last decade, the US state of California has been one of the leading FCEV markets globally. Several key characteristics of the FCEV market in the state include an early adoption and pioneering global position, rapidly expanding hydrogen refueling infrastructure and the concentration of numerous large transnational companies and start-ups developing hydrogen and fuel cell technologies. In addition, it is worth emphasizing the expansion of all classes of vehicles beyond the passenger light-duty FCEV segment, high public awareness and social acceptance, and significant RES share in the state's energy-mix. All of these selected determinants were complemented by the independent green industrial policy implemented by the California state government. The following subchapter overviews the FCEV market in this state to provide a background for the empirical studies, the results of which are presented in the fourth chapter. The preliminary analysis of the establishment and development of the FCEV market in California has distinguished unequal development of the individual market segments, so at first, the author focuses on the three following market segments, namely: light-duty (passenger) FCEVs (LD-FCEVs), fuel cell electric buses (FCEBs), and medium- and heavy-duty FCEVs (FCETs). Secondly, the author demonstrates the advancements of the hydrogen refueling infrastructure, which provides one of the most essential complementary goods to the FCEV – hydrogen fuel. Lastly, the author briefly presents the characteristics of the relevant FCEV market stakeholders who share diverse interests and contributions to its development.

3.2.1. The establishment and development of the LD-FCEV market segment in the state of California

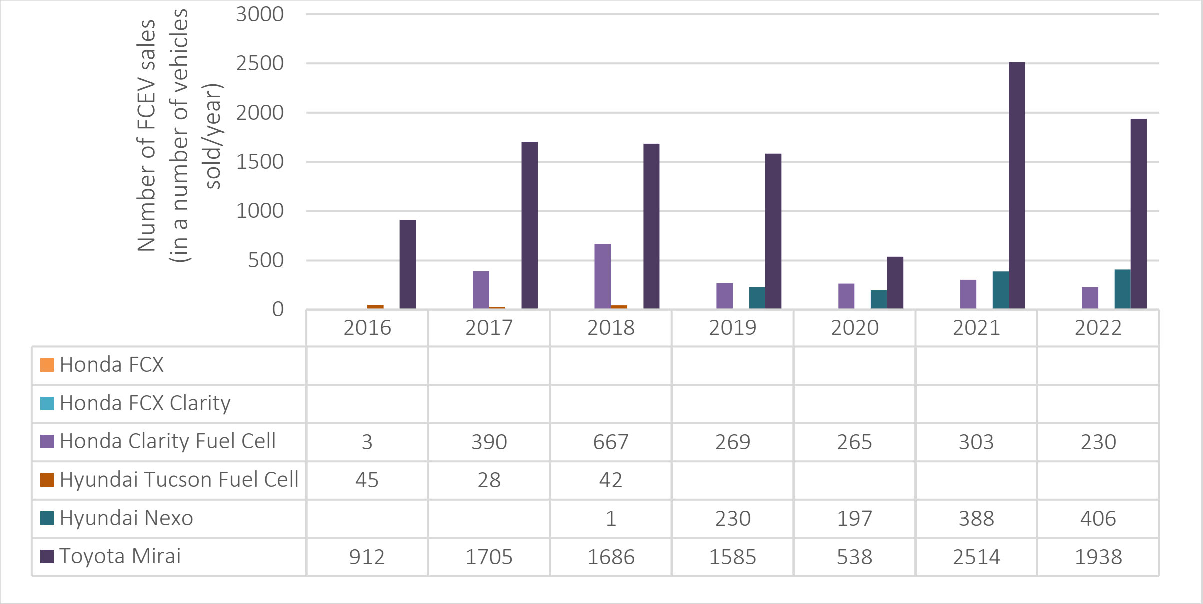
Development of FCEVs, as a highly advanced type of vehicle construction, at an early stage was concentrated on light-duty (passenger) vehicles because they represented a more manageable scale for refining the fuel cell technology and driving down the manufacturing costs thanks to the expected economies of scale and demand from early-adopters (who has already presented interest in BEVs). Addressing challenges like fuel cell durability, hydrogen storage, and system integration in smaller vehicles was more accessible than in buses or trucks. Besides, as it should be noted, manufacturers hoped to generate public interest and acceptance of hydrogen-powered fuel cell technology by targeting light-duty passenger vehicles. The light-duty passenger segment was also selected due to strict carbon emission standards from personal vehicles in California and other jurisdictions, as many other states and countries were introducing their restrictions. In addition to that, it is essential to acknowledge that establishing a hydrogen fueling infrastructure has been perceived by OEMs as one of the critical barriers for the FCEV market development, so starting with light-duty passenger vehicles allowed for more focused and gradual development of this infrastructure, typically beginning in urban or densely populated areas where these vehicles might be considered by the early-adopters willing to pay a premium for new, zero-emission technology in contrast to the bus or MD/HD vehicles fleet operators. Lastly, FCEVs offered a more extended range and faster refueling as compared to early BEVs, which was a selling point for personal light-duty vehicle users who might have experienced range anxiety or lack of convenient access to electric charging stations (Trencher, 2020).



	2009	2010	2011	2012	2013	2014	2015
Honda FCX	1	13					
Honda FCX Clarity			7	6	7	8	2
Honda Clarity Fuel Cell							
Hyundai Tucson Fuel Cell						47	35
Hyundai Nexo							
Toyota Mirai							62

Figure 13. The annual LD-FCEV sales between 2009 and 2015 (in a number of vehicles sold per year). Source: (CEC, 2023).

The establishment of the LD-FCEV market segment in the state of California can be traced back to 2009, marked by the sale and registration of the first LD-FCEV, the Honda FCX (CEC, 2023). This event initiated a gradual increase in light-duty passenger FCEV sales in California, as detailed in Figure 13, covering the period from 2009 to 2015. The early development of this niche market was led by Original Equipment Manufacturers such as Honda, with their FCX and FCX Clarity models. The market gained further traction with Hyundai's introduction of the Tucson Fuel Cell. A significant advancement occurred in 2015 with Toyota’s entry into the market with its first-generation Mirai, significantly contributing to the growth of the FCEV market in California, as indicated in Figure 14.



	2016	2017	2018	2019	2020	2021	2022
■ Honda FCX							
■ Honda FCX Clarity							
■ Honda Clarity Fuel Cell	3	390	667	269	265	303	230
■ Hyundai Tucson Fuel Cell	45	28	42				
■ Hyundai Nexo			1	230	197	388	406
■ Toyota Mirai	912	1705	1686	1585	538	2514	1938

Figure 14. The annual LD-FCEV sales between 2016 and 2022 (in a number of vehicles sold per year). Source: (CEC, 2023).

By 2022, the LD-FCEV market segment in the state of California was dominated by three models offered by three individual OEMs: Toyota, Honda, and Hyundai. At the end of 2022, the manufacturers’ suggested retail price range for those vehicles started with Honda (~34,415 USD), followed by Toyota Mirai (~49,500 USD), and finally, Hyundai Nexo (~60,135 USD) (Hydrogen Fuel Cell Partnership, 2022). The light-duty passenger FCEV segment in the state of California is the most dominant among other segments, translating to the increasing total FCEV registrations. Figure 18 presents the dynamic change in the registered number of LD-FCEVs at the end of each year, starting from 2010 until 2022 (with a dynamic growth that occurred in a post-2015 period).

Figure 15. Overview of the light-duty passenger vehicles available at the end of 2022 in the state of California. Top vehicle: Toyota Mirai; Middle vehicle: Honda Clarity Fuel Cell.; Bottom vehicle: Hyundai Nexo. Source: Hydrogen and Fuel Cell Partnership, https://h2fcp.org/ (Accessed on: August 1, 2023).

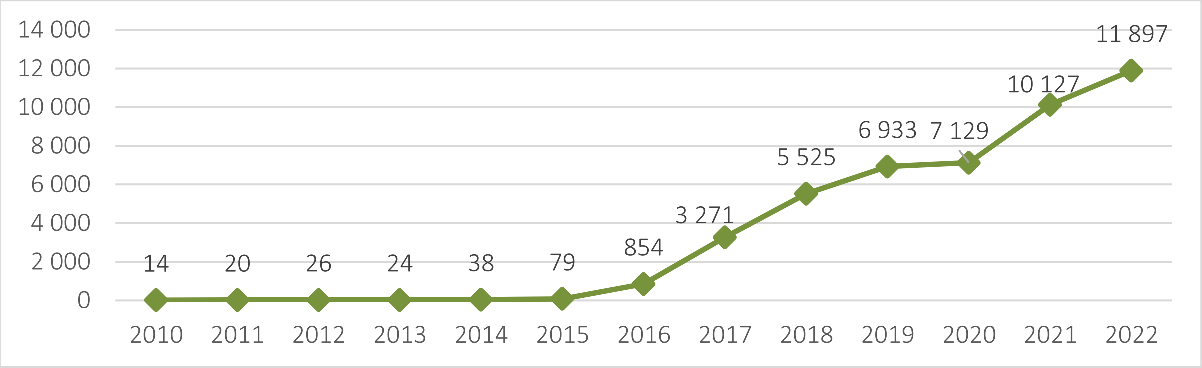


Figure 18. Total number of registered LD-FCEV in California at the end of a year between 2010 and 2022 (in a number of registered vehicles in a specific year). Source: Own elaboration based on: (CEC, 2023).

It can be observed that the breakthrough occurred at the turn of 2015 and 2016 when the number of LD-FCEV registrations increased to 854 (while the Toyota Mirai was introduced and reached 62 purchased models in 2015, followed by 912 models in 2016, accounting for 94% of LD-FCEV market segment share). Furthermore, it is worth studying the spatial distribution of the LD-FCEV registrations at the county level, which can provide overall information on how this market was organized geographically. Starting with Figure 16, it can be observed that the first 14 LD-FCEV registrations were located in the Los Angeles and Orange counties. In comparison, the 79 LD-FCEV registrations expanded to the neighboring Riverside County five years later. By then, the LD-FCEV market segment was limited to Southern California, with some particular locations facing higher registration numbers.

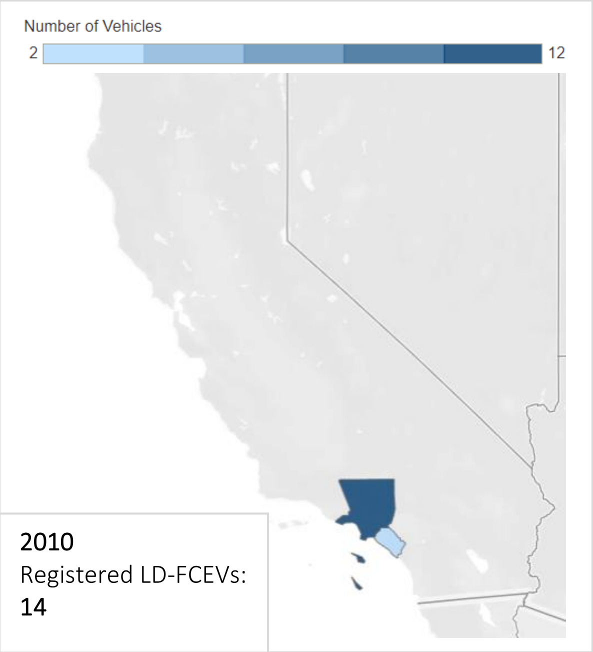


Figure 16. Spatial concentration of the registered FCEVs in the end of 2010 with a breakdown to counties in the U.S. state of California. Source: CEC, 2023.

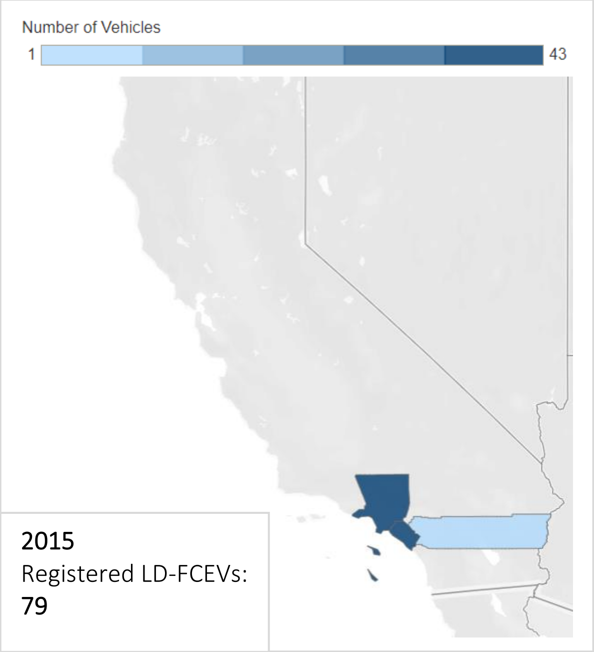


Figure 17. Spatial concentration of the registered FCEVs in the end of 2015 with a breakdown to counties in the U.S. state of California. Source: CEC, 2023.

An example of this phenomenon is the Torrence district in the City of Los Angeles near Port of Long Beach (postal ZIP code: 90501), facing 12 registrations in 2015 (since the port authorities were one of the first adopters of LD-FCEVs in the commercial fleets). The further roll-out of the LD-FCEV market segment is presented in Figure 19, which demonstrates the registration in 2020. At that time, the LD-FCEV registrations spurred across the entire state, reaching the Bay Area (San Francisco, San Mateo, Alameda, and Santa Clara counties). Still, the market concentration stayed at the same stage, with Los Angeles and Orange counties having the highest number of LD-FCEV registrations. Interestingly, while looking at the registration breakdown of the individual postal ZIP codes, it can be noticed that the Torrence district and the district neighboring the University of California Irvine faced the highest concentration of these types of vehicles.

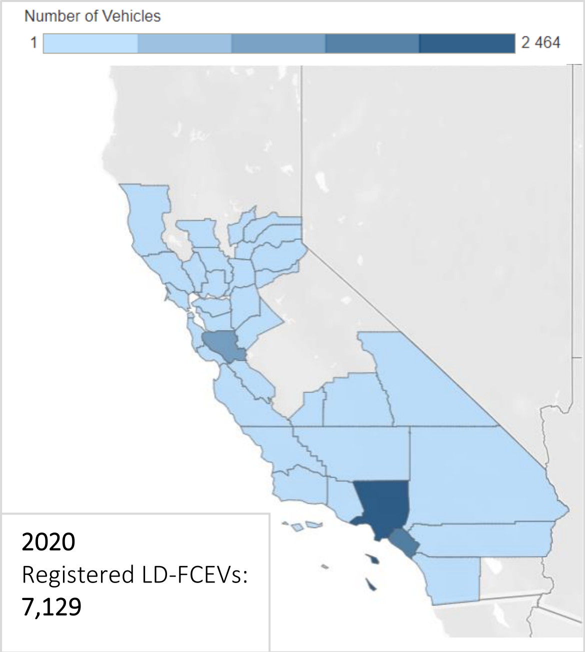


Figure 19. Spatial concentration of the registered FCEVs in the end of 2020 with a breakdown to counties in the U.S. state of California.
Source: CEC, 2023.

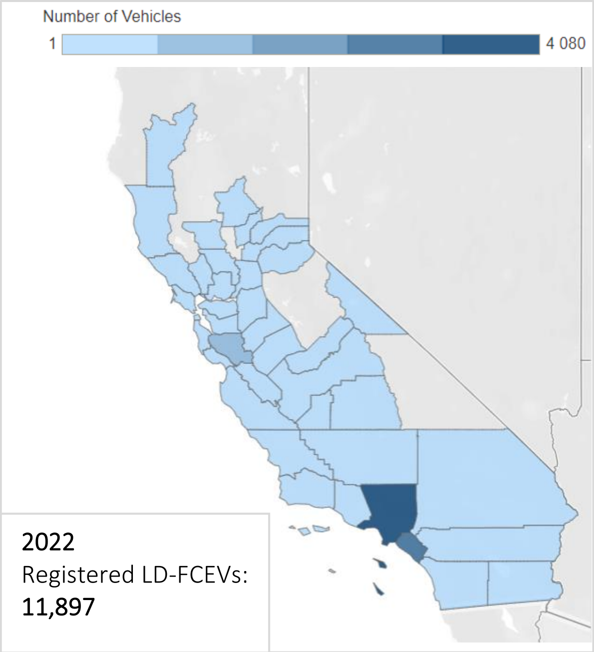


Figure 20. Spatial concentration of the registered FCEVs in the end of 2022 with a breakdown to counties in the U.S. state of California.
Source: CEC, 2023.

Lastly, the overview of the LD-FCEV registrations by counties in 2022 (Figure 20) provides evidence that this market segment has developed spatially since these vehicles were registered in most of California's counties (except for those remote areas with significantly low population density). It is worth noting that the 11,897 (primarily located in Southern California) represented 0.04% of all light-duty vehicles registered in California (while 763,557 BEVs accounted for 2.61%). However, making further assumptions based on the spatial distribution of LD-FCEV registration at the county level in 2022 could be biased since some counties (like San Bernardino) cover vast areas of the state. Therefore, the author, to provide the highest possible precision based on available data from CEC (2023), presented in Figure 21 the distribution of the FCEV registrations at the lowest possible analytical level – the ZIP code level.

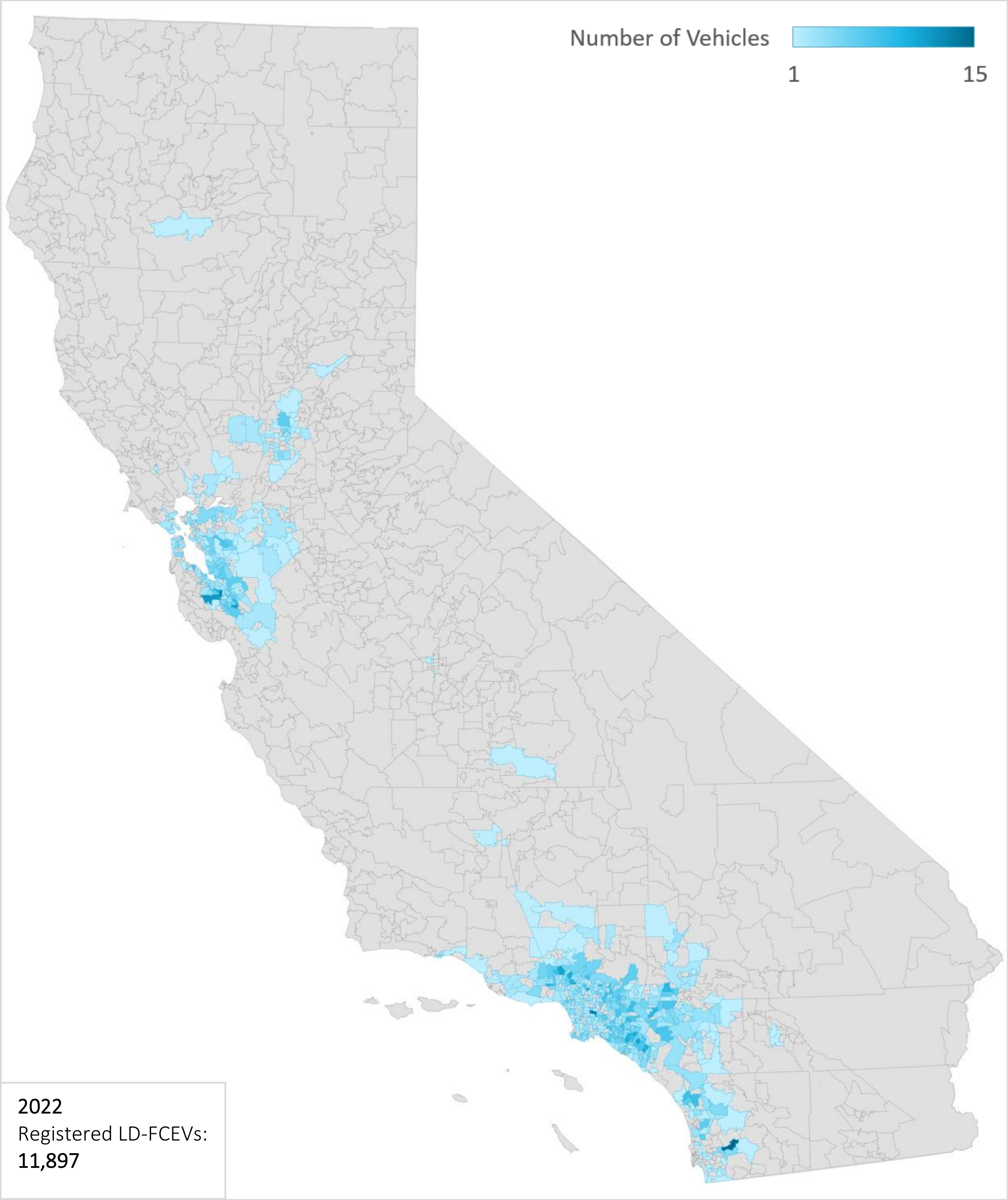


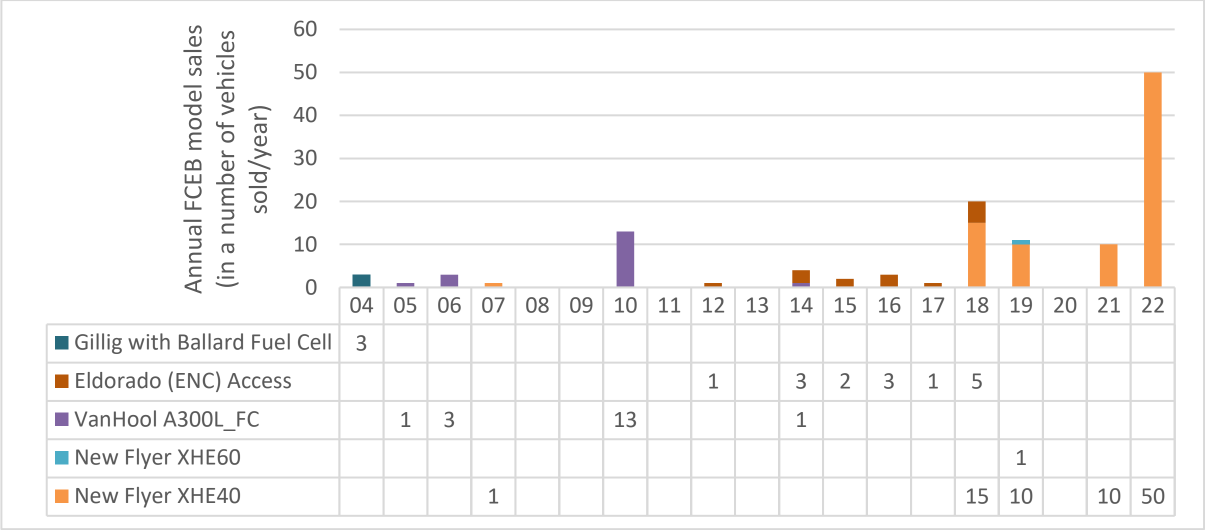
Figure 21. Spatial distribution of registered LD-FCEVs in 2022 with a breakdown to individual ZIP codes. Source: Own elaboration based on CEC, 2023.

The LD-FCEV spatial distribution of registered LD-FCEVs (status of 2022), with a breakdown to individual ZIP codes, clearly demonstrates that this market segment is concentrated in two regions: Bay Area (North California) and Greater Los Angeles (Southern California) as indicated in Figure 21.

It can be stated that the light-duty passenger FCEV market segment in California is an emerging yet dynamic segment primarily driven by environmental concerns, technological advancements, and supportive regulatory frameworks. Concentrated in urban areas with hydrogen refueling infrastructure, particularly in Southern California, the market caters to a demographic of environmentally conscious, higher-income individuals who value innovation and zero-emission vehicles. Despite being in its growth stage and facing high barriers to entry due to the need for advanced technology and infrastructure, the market is experiencing increasing adoption among early adopters and institutional consumers. Three key suppliers (Toyota, Hyundai, and Honda) dominate the highly competitive landscape of an oligopoly market structure, focusing on technological innovation and customer service. Their efforts to increase the dynamics of the market segment growth are visible, i.e., in joint marketing activities that offer pre-paid hydrogen fuel cards worth 15,000 USD for up to three years of usage, considerably decreasing the OPEX of these vehicles. Pricing strategies often reflect the vehicles' zero-emission value proposition, extended ranges, and short refueling times. However, purchasing decisions are sensitive to incentives like CVRP Rebates and subsidies for institutional fleets. Interestingly, at the end of 2022, the cumulative share of all CVRP Rebates granted to public and business entities accounted for 301 rebates, in contrast to 12,378 rebates granted to private individuals. Therefore, it can be stated that highly scattered private agents with low negotiation power have dominated the demand side of the LD-FCEV market segment (especially since 2015) (CVRP, 2023). However, thanks to green industrial policy instruments, the demand for this type of light-duty vehicle is expected to increase in the coming years.

3.2.2. The establishment and development of the FCEB market segment in the state of California

The initial LD-FCEV commercialization and market segment development laid the foundation for the further development of the other segments, including hydrogen-powered FCEBs. The first evidence of deployment of this type of bus was observed in SunLine Transit Agency in 2002. At that time, the FCEBs were not commercially available. Hence, the agency collaborated with the US DOE and ThunderPower LLC to deploy the conceptual FCEB model and test its operationality compared with the conventional ICEV (diesel) buses (NREL, 2002).

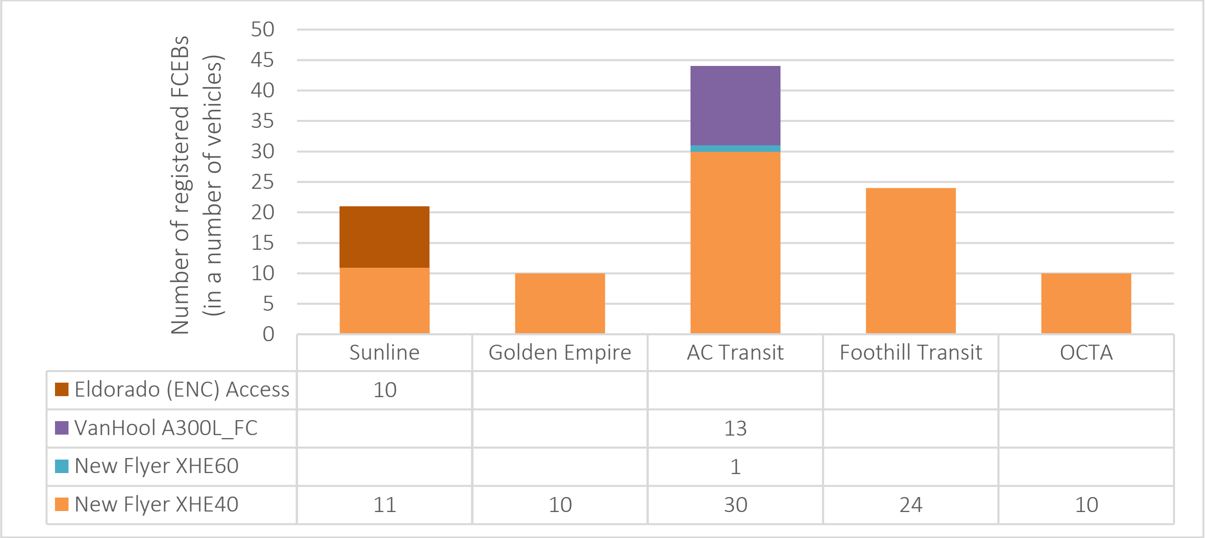


	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
🟦 Gillig with Ballard Fuel Cell	3																		
🟫 Eldorado (ENC) Access									1		3	2	3	1	5				
🟪 VanHool A300L_FC		1	3				13				1								
🟦 New Flyer XHE60																1			
🟧 New Flyer XHE40				1											15	10		10	50

Figure 22. The annual FCEB sales per model and OEM (in a number of vehicles sold per year). Source: Own elaboration based on (Eudy et al., 2007, 2008, 2009, 2010, 2011, 2012, 2014, 2015, 2016; Eudy & Gikakis, 2012; Eudy & Post, 2017, 2018).

After the successful tests, the following transit agencies continued the demonstration projects, including SamTrans (The Santa Clara Valley Transportation Authority), which deployed the first Gillig's FCEB in 2004 (NREL, 2005), AC Transit (The Alameda-Contra Costa Transit District), which deployed three VanHool A330 Fuel Cell models in 2006 (NREL, 2006).

As presented in Figure 22, the FCEB market segment size was stagnant until 2018, when New Flyer introduced a modernized XHE40 model, and the state of California introduced the Innovative Clean Transit rule, mandating all transit agencies to transition to a complete zero-emission bus fleets gradually by 2028. However, it is essential to emphasize that this segment has a significantly less extensive role in the overall FCEV market roll-out. Nevertheless, as of the end of 2022, there were 110 registered FCEBs, including 86 from New Flyer (Figure 23).



	Sunline	Golden Empire	AC Transit	Foothill Transit	OCTA
🟫 Eldorado (ENC) Access	10				
🟪 VanHool A300L_FC			13		
🟦 New Flyer XHE60			1		
🟧 New Flyer XHE40	11	10	30	24	10

Figure 23. The structure of FCEB fleet with the breakdown by individual models at the end of 2022 (in a number of vehicles). Source: Own elaboration based on Annual Bus Inventory Report published by CARB (2023b).

At the end of 2022, there were two leading OEMs, including the already mentioned New Flyer (with the Xcelsior XHE40 model) and El Dorado National (with the Access model). However, between 2019 and 2022, only New Flyer was selling the FCEBs, making it the monopolist agent that was included in the HVIP incentive program catalog. Transit agencies purchasing New Flyer's FCEBs can receive a 240,000 USD voucher (direct subsidy) per HXE40 and HXE60 models.

Figure 25. The New Flyer Xcelsior XHE40 FCEB deployed by SunLine Transit Agency. Source: Own resources from the author's study visit in the Sunline Depot in Thousands Palms, CA (January 14, 2023).

It is crucial to underline that due to the complexity of transit bus procurements, which includes assessing needs, budgeting, specification development, proposal evaluations and negotiations, and quality assurance checks to ensure the acquisition of buses that meet the demands, the purchase price is not fixed, but set individually (the example of a customized New Flyer HXE40 is presented in Figure 25). Moreover, it also depends on the quantity of purchased FCEBs and the individual specifications of transit agencies, which can vary widely. However, according to the National Renewable Energy Laboratory (NREL), the CAPEX of FCEB purchases has declined significantly over the last two decades (Figure 24). The decline in FCEB capital costs translated to the broader deployment of these vehicles within the transit agency fleets in California. Moreover, some agencies, like AC Transit, share the deployment results in annually published *Zero-Emission Transit Bus Technology Analysis* reports.

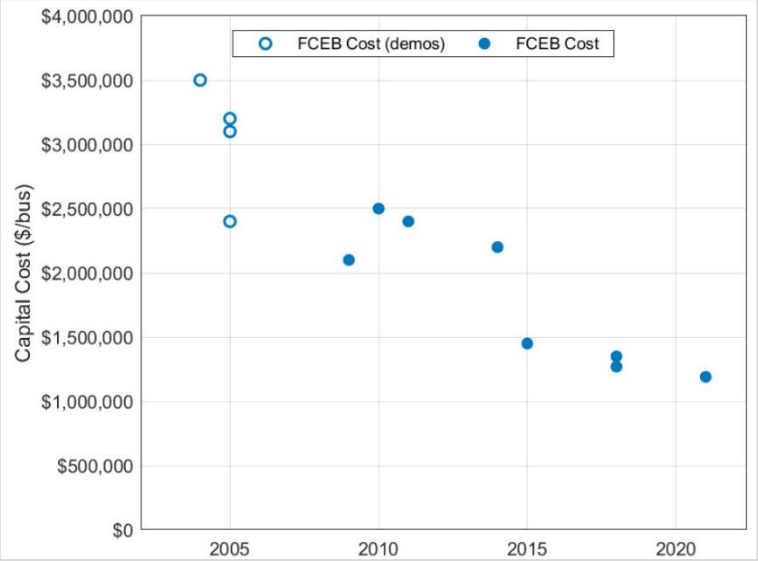


Figure 24. The FCEB capital costs for FCEV demonstration projects (demos) in 2004 and 2005, and later on market basis (in USD/bus). Source (NREL, 2023).

These publications are a source of in-depth insights into the long-term research project (known as the *5-by-5 study*), conducted in cooperation with Stanford University, which aims to provide a comparative qualitative and quantitative operational and financial evaluation of legacy (2010) FCEBs and modern (2018-2022) FCEBs as compared to conventional diesel, diesel-hybrid, and battery-electric buses. This insightful study has already provided strong empirical evidence that in the case of AC Transit, the FCEBs are the most cost-effective zero-emission type of bus construction (despite the high initial capital costs of 1,156,044 USD per New Flyer Bus XHE40 in 2019) (AC Transit, 2022).

Since the number of FCEB models, all fueled with fuel cells Ballard Power Systems[82], currently available on the market is limited to transit buses, the potential consumers constitute a cohort of transit agencies registered and operating in California. According to the Federal Transit Administration, which requires the agencies to report their operations annually, 234 agencies operated in this state at the end of 2022. Among them, the Los Angeles County Metropolitan Transportation Authority had the highest rate of vehicles operating at maximum service – 1,727, while AC Transit was fifth – 399, OCTA was ninth – 214, and Sunline was twelve – 88 (FTA, 2023).

In summary, this market segment can be described as a duopoly (or monopoly if New Flyer is considered the sole OEM and seller). The consumers have moderate price negotiation power, as they can still individually or collectively procure these vehicles. In the author's opinion, the potential of new entrants is meager since it requires complex multilateral cooperation between the fuel cell and hydrogen storage tank manufacturers and the bus constructors.

However, the pressing need for transit bus fleet decarbonization will translate to an increasing demand for FCEBs, which can incentivize new entrants. At the end of 2022, there were no hydrogen-powered buses other than those fuelled by fuel cells, like the hydrogen-powered ICEV. In other words, the FCEBs have no direct substitutes offering comparable range, fuelling times, or fleet operational effectiveness. In the coming years, it can be expected that the FCEB market segment will develop and attract more consumers and sellers, and so will the LD-FCEV market segment.

---

[82] Ballard Power Systems is a global provider of innovative clean energy and fuel cell solutions. Their proton exchange membrane (PEM) fuel cells are used in various FCEVs, including buses, commercial trucks, and passenger cars, playing a crucial role in the supply chain of this emerging market.

3.2.3. The establishment and development of the MD/HD FCET market segment in the state of California

The first demonstration projects of medium- and heavy-duty FCEVs – also recognized as Fuel Cell Electric Trucks (FCETs) – started in California in 2016 with a *ZECT II* project (6 Kenworth's concept trucks), followed by *Project Portal* in 2017 (2 Toyota's concept trucks), and *Shore-to-Shore* project in 2019 (10 concept trucks developed in cooperation with Toyota and Kenworth) (CHBC, 2023). Simultaneously, other OEMs – Hyzon Motors, Nikola Motor Company, and Hyundai – were developing their FCET models. Eventually, starting in 2021, three FCET models were available in California on a market basis (demonstrated in Figure 26).

Figure 26. Overview of the fuel cell electric trucks available at the end of 2022 in the state of California under the HVIP Program. Top vehicle: Hyzon Motors HyHD8 FCET; Middle vehicle: Nikola TRE FCET; Bottom vehicle: Hyundai XCIENT FCET. Source: Hydrogen and Fuel Cell Partnership, https://h2fcp.org/ (Accessed on: August 1, 2023).

It is worth emphasizing that the FCET market segment was established in 2021. Still, until the end of 2022, neither CEC nor CARB has tracked the FCET registrations. For this reason, to estimate the sales of these vehicles, the author studied the HVIP voucher database. HVIP vouchers, as indicated in the previous subchapter, are offered as a direct subsidy from the state government to purchase medium- and heavy-duty zero-emission vehicles, including FCETs. It is crucial to underline that according to CEC, 60% of all MD/HD ZEVs in California were purchased with HVIP vouchers (California HVIP/CARB, 2023). The author broadened this dataset with a consideration of 30 Hyundai XCIENT FCETs purchased as part of the NorCal ZERO project co-funded by the Alameda County Transportation Commission, Bay Area Air Quality Management District, CARB, and CEC (CTE, 2023).

Figure 27 demonstrates the share of individual models in the cumulative FCET sales in 2021-2022 to estimate the market shares of individual OEMs. As a company primarily focused on developing fuel cell and battery electric trucks, Nikola Motor Company dominated the market with their TRE FCET. It was followed by Hyundai XCIENT FCETs (which, interestingly, includes two side-by-side Hyundai Nexo fuel cell modulus) and Hyzon Motors HyHD8 FCET.

Within the FCET market segment, three sellers were offering their products (demonstrated in Figure 27). Within this market segment, it is possible to identify individual entities representing major institutional consumers – ports. Port of Los Angeles (Long Beach) and Port of San Diego are significant FCET early adopters under the pressing state requirement to reduce emissions from drayage trucks, yard tractors, and other heavy equipment. Both ports actively explore and test FCEV solutions, contributing to the demand for such vehicles and associated fueling infrastructure. As the author could not access detailed retail price information for each FCET directly, the author reviewed the leading analysis conducted by National Renewable Energy Laboratory (Hunter et al., 2021), Argonne National Laboratory (Burnham et al., 2021; Islam et al., 2020), and the International Council on Clean Transportation (Sharpe & Basma, 2022), which can be a source of information about the retail price for each type of Class 8 FCET (the heaviest MD/HD FCET that all three models belong to). The detailed overview of the FCET retail prices suggests that their range is between $312,700 and $386,000, significantly depending on the **nominal power of the fuel cell stack** (as the most expensive component of the vehicle) and the **range** (estimated based on the standard fuel consumption and a capacity of the fuel tank). All three models are customizable depending on the buyers' preferences so that the final retail price can vary. In this context, it is worth reminding that the state of California offers a $240,000 subsidy under the HVIP Program, decreasing the final purchase cost considerably.

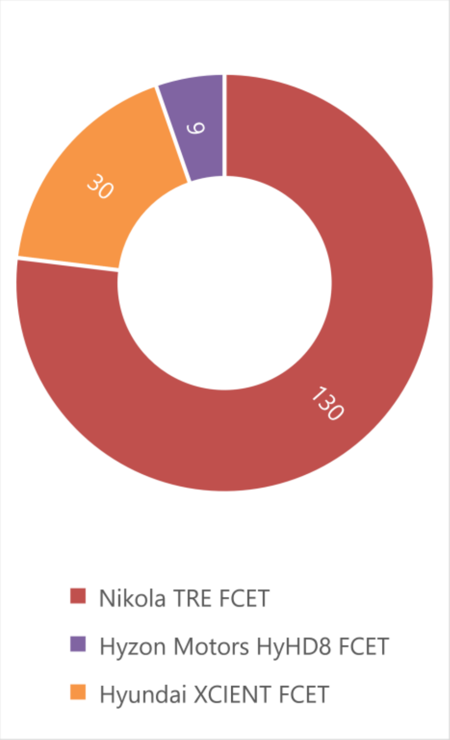


Figure 27. The structure of FCET sales with the breakdown by individual models in 2021-2022 in the US state of California. Source: Own elaboration based on HVIP voucher database (California HVIP, 2023) and Center for transportation studies (CTE, 2023).

In summary, the FCET market segment in California is characterized by a dynamic interplay of technological innovation that allowed the deployment of hydrogen-powered fuel cell electric trucks, state regulations, such as Innovative Clean Fleets, and evolving market demands among agents such as ports. Primarily targeting logistics and transport businesses, this niche yet growing market is driven by three suppliers: Nikola Motor Company, Hyundai, and Hyzon Motors. This segment's customers (mainly corporate or institutional buyers) have relatively high negotiating power. The market, though currently limited in sales volume, is experiencing a high growth rate, primarily influenced by stringent state regulations to decrease the carbon intensity of heavy-duty vehicles. The demographic segmentation is largely irrelevant as the market caters to business entities, but it's geographically concentrated in industrial hubs and areas with strict emissions regulations. Competitively, the segment has a few key players dominating the market, with high barriers to entry due to technological complexity and significant capital requirements. In the context of battery-electric trucks, product differentiation is primarily based on zero-emission capabilities, shorter refueling times, and more extended ranges (up to 500 miles), translating to more efficient duty cycles. Distribution channels are currently limited but are expanding with the growing demand, involving direct sales and specialized dealers. In terms of pricing, the segment exhibits value-based strategies, reflecting long-term savings and zero-carbon emission benefits, with relatively inelastic price sensitivity. Technologically, the segment is rapidly evolving, with continuous advancements in fuel cell technology. This technological aspect is critical for performance, cost, and overall market dynamics.

3.2.4. The hydrogen refueling station operators and other stakeholders of FCEV market development in the state of California

The overview of the FCEV market stakeholders must be primarily focused on the refueling station operators since the expansion of hydrogen refueling infrastructure and the sustainable and low-cost supply of hydrogen fuel are fundamental for the FCEV market growth across all three market segments. Historically, it can be observed that the infrastructure expansion started at the beginning of the 2010s, enforced by the state's efforts to expand the refueling stations network (Figure 28).

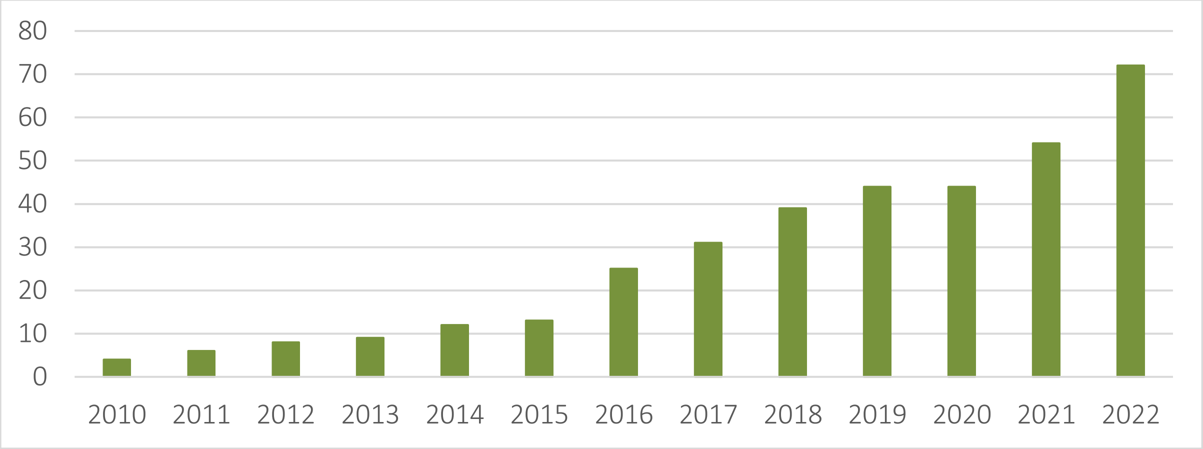


Figure 28. The number of hydrogen refueling stations operating at the end of a year in the US state of California (2010-2022). Source: Own elaboration based on CARB's Annual Reports (CARB, 2015, 2018, 2021a, 2023a).

Based on the review of annually presented CARB hydrogen infrastructure evaluation reports, it can be stated that the location of hydrogen refueling stations in California is primarily concentrated in metropolitan and suburban areas, where the demand for FCEVs is relatively high. California is the only state where hydrogen refueling stations are placed compared to other US states. Hydrogen refueling stations are predominantly located in regions such as the San Francisco Bay Area, Los Angeles, Orange County, Santa Clara, Alameda, and San Diego, with a few stations scattered along connecting highways. Hydrogen refueling stations in California are typically placed strategically in highly populated areas, along major transportation corridors, and close to residential areas where FCEV owners live or work. It is to ensure accessibility and convenience for FCEV drivers. The locations have the necessary infrastructure to refuel hydrogen vehicles safely and efficiently, including storage tanks, compressors, and dispensers. Many hydrogen refueling stations are co-located with traditional gasoline stations to leverage existing fueling infrastructure and locations familiar to drivers.

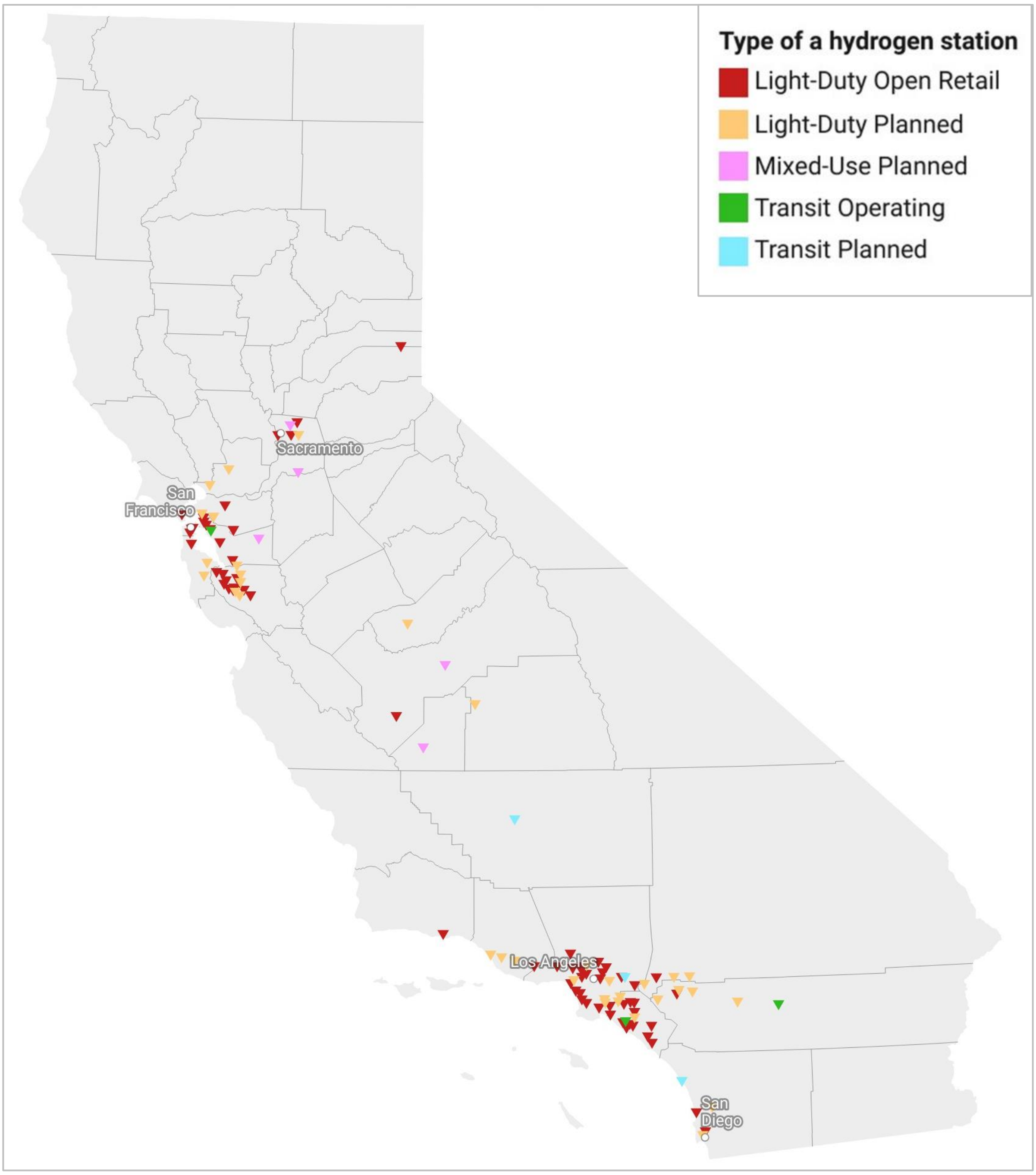


Figure 29. Hydrogen refueling stations locations at the end of 2022, with a breakdown to counties in the US state of California. Source: Own elaboration based on: CEC, 2023.

Besides, some stations are located near industrial hydrogen sources or use onsite electrolysis to generate hydrogen, reducing transportation and storage costs. The stations' locations are part of a larger network expansion plan, which aims to ensure coverage throughout the state to support a growing FCEV fleet. However, there still exists a significant need to increase the capacity of the existing stations, which can be noticed after studying California's GIS-Based Hydrogen Network Analysis Tool (CHIT) provided by CARB (Figure 30).

Hydrogen refueling infrastructure in California is primarily supported by a consortium of companies, each contributing uniquely to the ecosystem. Three companies, Shell, Iwatani Corp., and True Zero (First Element Fuel Inc.), primarily operate the hydrogen refueling stations. True Zero leads the charge, having built and operated over half of the state's hydrogen stations for fuel cell electric vehicles (FCEVs), thereby playing a pivotal role in advancing the FCEV market in California. Similarly, Iwatani Corp. has a significant presence, offering a range of services at its stations, from hydrogen production to retail.

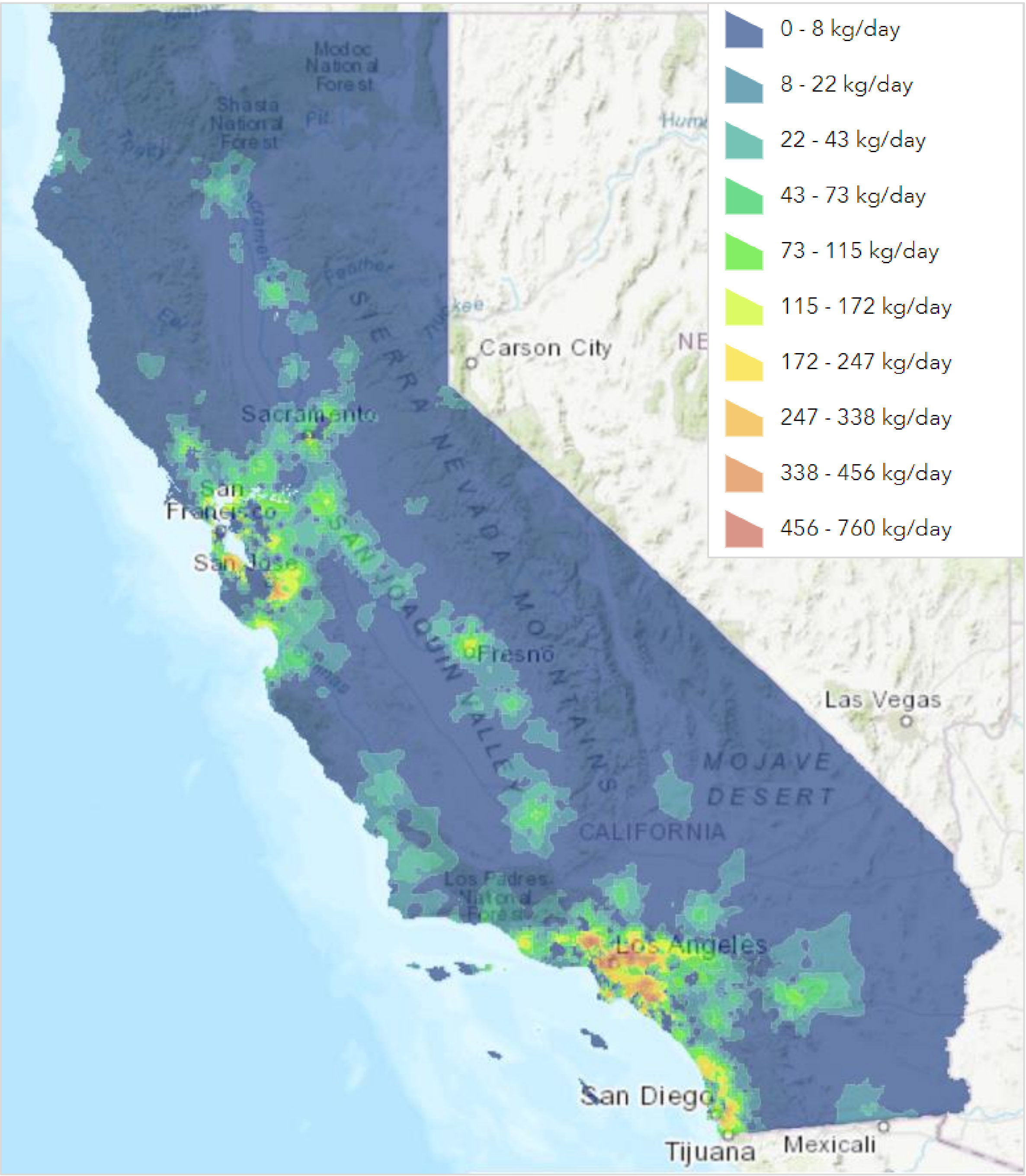


Figure 30. Local hydrogen refueling capacity needed (kg/day). Source: (CARB, 2016).

In addition, several other companies contribute to the hydrogen supply chain and retail services. SGH2 Energy, for instance, champions clean hydrogen production through an innovative process that gasifies recycled mixed paper waste. This produces hydrogen and reduces carbon emissions, contributing to a sustainable hydrogen supply chain based on biomass. Linde Gases, a leading industrial gas company, supplies hydrogen and actively participates in developing hydrogen fueling infrastructure. Likewise, Air Products and Chemicals holds a substantial position in the hydrogen market with its extensive supply network, providing both liquid and gaseous hydrogen for various applications, including FCEV fueling. SoCalGas, the nation's largest natural gas distribution utility, is diversifying into renewable hydrogen and investing in hydrogen infrastructure, thereby supporting California’s clean energy aspirations. Nel Hydrogen contributes as a global supplier of hydrogen production equipment, facilitating hydrogen availability for various uses, including FCEV fueling. With its long-standing investments in hydrogen energy, Air Liquide offers solutions encompassing hydrogen production, distribution, and station operation.

Additionally, Plug Power emerges as a key player by providing hydrogen fuel cell systems that serve as alternatives to conventional batteries in electrically powered equipment and vehicles. San Diego Gas & Electric, a regulated public utility, also participates in initiatives to develop and deploy hydrogen as a clean energy source. Collectively, these suppliers and operators are indispensable in ensuring the availability and accessibility of hydrogen fuel, a crucial factor in promoting the use and adoption of FCEVs. Their concerted efforts are fundamental in establishing a robust and efficient hydrogen infrastructure, addressing the escalating demand for FCEVs. To meet the demand for hydrogen fuel, several transit agencies developed an interesting business model where the hydrogen refueling station is located at their depot, simultaneously operationally serving FCEBs from their fleet and commercially serving light-duty FCEVs and FCETs. An example of such an approach can be found in the SunLine depot in Thousand Palms in Coachella Valley (Figure 31). Undoubtedly, such an approach can turn transit agencies into hydrogen fuel suppliers, as these companies not only operate the stations but also possess and develop clean hydrogen generation installations (mainly using water electrolysis).

Figure 31. The multiuse hydrogen refueling station shared between FCEB and LD-FCEV developed by SunLine Transit Agency. Source: Own resources from the author's study visit in the Sunline Depot in Thousands Palms, CA (January 14, 2023).

California's FCEV market is interconnected with a network of other various stakeholders. Each entity is, to some extent, critical in developing and deploying FCEVs in the market due to its niche character. Besides the hydrogen suppliers and refueling station operators, the other stakeholders of the FCEV market in California can be grouped into (1) academic and research entities, (2) government and state regulatory bodies, (3) industrial organizations and associations, and hydrogen infrastructure providers.

Academic and research entities

These institutions are vital in conducting in-depth multidimensional research and development projects from the beginning of the studied period. An example of this effort is the research conducted at the University of California, Davis. This university has conducted extensive research on hydrogen technologies and fuel cell vehicles for over two decades, initiated by pioneers like Prof. Dan Sperling and Prof. Mark Delucchi. In 2002, Toyota delivered the first market-ready LD-FCEV in the United States to the UC Davis Institute of Transportation Studies (UC Davis, 2002). It was followed by the establishment of *The Hydrogen Pathways Program* by Prof. Joan Ogden in 2003 as an academic response to the announced Governor's plans for the Hydrogen Highway initiative. It has significantly contributed to this field with a team of leading Ph.D. researchers and graduate students. Later, this program expanded into the *Sustainable Transportation Energy Pathways* (STEPS) program in 2007, maintaining a robust focus on hydrogen technologies and FCEVs. The primary research areas included technical assessment and system-level modeling with a notable hydrogen refueling station operating between 2004-2009. Ogden's team's studies, which continued until her retirement in 2018, were innovative for focusing on expanding hydrogen refueling stations and their strategic placement using a clustering approach. They also performed techno-economic assessments on various aspects of hydrogen production and storage. Ogden's contributions were also recognized through her role in several high-level committees (J. M. Ogden, 1999a, 1999b; J. Ogden & Nicholas, 2011; Yang & Ogden, 2007).

The role of other academic institutions, for instance, associated with the Universities of California, Stanford University, or the University of Southern California, is undisputed, especially in the context of preliminary demonstration projects and initial attempts to design and test the onsite refueling stations included in the *Hydrogen Highway* initiative and various projects funded through the CEC's Alternative and Renewable Fuel and Vehicle Technology Program.. Examples of these institutions may include (1) UC San Diego Strategic Energy Initiatives, which conduct research on alternative energy sources, including hydrogen and fuel cells. Simultaneously, they aim to advance the technology and improve its viability in the transport sector. (2) Transportation Sustainability Research Center at UC Berkeley, which investigates sustainable transportation solutions. It provides critical research and policy analysis related to FCEVs, contributing to the understanding and development of the market. (3) The Strategic Energy Analysis Center at the National Renewable Energy Laboratory (NREL) conducts extensive research on clean energy technologies, including FCEVs. Its work on cost analysis, market dynamics, and technical potential significantly shapes the FCEV market. (4) As indicated before, the Institute of Transportation Studies at UC Davis focuses on researching sustainable transportation solutions. It provides valuable insights into transportation behaviors, policies, and technologies, including FCEVs, contributing to the market's overall development. (5) The National Fuel Cell Research Center at UC Irvine advances fuel cell technology, contributing to the FCEV market. The center's research helps improve FCEVs' performance, durability, and affordability. In conclusion, these stakeholders contribute to the FCEV industry's technical development and market dynamics. Their research efforts, technological advancements, and strategic initiatives help drive the market forward, fostering the adoption and growth of FCEVs in California.

Governmental and regulatory bodies

As indicated in the previous subchapter, the governmental and regulatory bodies at the state and federal levels are responsible for setting regulations, providing funding, and driving the sector's strategic direction. Based on the conducted review of the competencies and responsibilities, the author presents the selected bodies that may contribute to the FCEV market development in California. First, the California Energy Commission oversees programs that have allocated funding for developing hydrogen fueling stations across the state, providing a vital foundation for the FCEV market. As presented, the California Air Resources Board is responsible for California air quality and emission regulations. Through initiatives like, i.e., the Advanced Clean Cars II (ACC II) regulation, CARB sets ambitious targets for zero-emission vehicle (ZEV) adoption, including FCEVs, thereby driving demand in the market. The Governor's Office of Business & Economic Development (GO-Biz) facilitates economic development in California and promotes zero-emission technologies. It assists in coordinating state efforts for deploying ZEVs and works with stakeholders to address any barriers to market growth. On the federal level, The US Department of Energy supports research and development in clean energy technologies, including hydrogen and fuel cells. Besides, the US DOE provides funding and resources that enhance technological advancements and drive down the costs of fuel cell stacks in the FCEV market. The US Department of Transportation oversees national transportation policies. It can influence the adoption of FCEVs through its regulations and programs aimed at deploying zero-emission buses, including FCEVs, promoting the use of clean public transit options. These stakeholders impact the FCEV market, helping shape its growth, development, and direction. Their strategic decisions, regulatory measures, and funding programs contribute to adopting and expanding FCEVs in California.

Industrial organizations and associations

Industrial organizations and associations form an integral group of the FCEV market stakeholders in California, playing key roles in policy advocacy and forming a platform for infra-sector consultations. Among these organizations and associations, the California Hydrogen Business Council is an industry-based organization promoting the commercialization and market growth of hydrogen and fuel cell technology. By advocating for effective policies and regulations, it supports the development of the hydrogen infrastructure and the broader use of FCEVs in California. The Fuel Cell and Hydrogen Energy Association (FCHEA) represents companies involved in all fuel cell and hydrogen industry aspects. It provides advocacy for the industry in discussions with policymakers and plays a crucial role in driving market growth through advocacy, public outreach, and education. While the American Trucking Association (ATA) primarily focuses on the trucking industry, it significantly pushes for cleaner, more sustainable technologies, including FCEVs. The association advocates for supportive regulations and policies, and its members' adoption of these vehicles can significantly impact the FCEV market on the national level. The California Hydrogen Coalition advocates for policies and regulations that support the growth of the hydrogen and fuel cell sector. Their efforts help foster a conducive market environment and stimulate demand for FCEVs. The California Fuel Cell Partnership is a unique collaboration of auto manufacturers, energy providers, government agencies, and technology companies. This partnership promotes the commercialization of hydrogen fuel cell vehicles. It facilitates dialogue among stakeholders, supports the creation of a hydrogen infrastructure, and promotes public awareness and acceptance of FCEVs. Lastly, the Center for Transportation and the Environment (CTE) is a non-profit organization dedicated to improving the efficiency and sustainability of the US transportation system. Its efforts include promoting clean, alternative fuel technologies like FCEVs. Through their varied roles and efforts, these industrial organizations and associations contribute significantly to the FCEV market development in California. Their coordinated advocacy, education, and promotion efforts help shape policy, foster public acceptance, and drive the demand for FCEVs. The overview of the federal and state policies for establishing and developing the FCEV market in California was followed by a brief presentation of the FCEV market characteristics and refueling infrastructure landscape in California alongside the key stakeholders. The following chapter will evaluate the policies and strategies implemented for the FCEV market development from 1990 to 2022.

4. EVALUATION OF THE IMPACT OF SELECTED GREEN INDUSTRIAL POLICY INSTRUMENTS ON THE ESTABLISHMENT AND DEVELOPMENT OF THE FCEV MARKET IN THE STATE OF CALIFORNIA - RESULTS OF AN EMPIRICAL RESEARCH

In the previous chapter, the author demonstrated how California implemented its green industrial policy from 1990 until 2022 to establish and develop the FCEV market. While this policy aligns with federal regulations and policy acts, California's unique position to set its objectives and standards sets it apart. The state's distinctive independent approach, extended policy timeline, and an array of specific instruments set the scope of empirical research conducted as part of this dissertation. After a literature review, it is apparent that an evaluation of California's policy impact on the FCEV market is lacking. By assessing the effectiveness and impact of California’s state-level green industrial policy instruments within the federal legislative framework, this study intends to provide updated, evidence-based policy impact observations for FCEV market development beyond California.

The empirical research presented in this chapter addresses unresolved questions from previous studies, such as identifying the most effective policy instruments for the FCEV market's establishment and development in the state of California. Moreover, it explores potential improvements for future FCEV market development. The study adopts both retrospective and prospective perspectives, offering detailed policy impact observations considering the dynamics of both local and national FCEV markets. Conducted towards the end of 2022, this research is particularly relevant due to the need to update theoretical frameworks in light of recent FCEV market structure shifts and the post-COVID-19 economic landscape, highlighted by policies like the Federal Inflation Reduction Act.

The author conducted the empirical research activities in the state of California as a Visiting Graduate Student at the University of California San Diego (UCSD) in the School of Global Policy and Strategy between August 1, 2022, and February 1, 2023, which was possible thanks to the Fulbright-Schuman Award 2022/2023. While simultaneously supervised by both supervisors from the home university in Poland, the research was conducted by the author in cooperation with Prof. David G. Victor, who performed the function of the research project co-Principle Investigator at the host institution, and Dr. Ryan Hanna, who consulted the author with the advancement of the project at every development stage.

4.1. Description of the empirical research

4.1.1. The overview of criteria and techniques of policy evaluation

Policy evaluation is a complex process interlinked to the policy formulation and implementation. The UN brought up a holistic definition of evaluation, which states that evaluation is *an assessment, as systematic and impartial as possible, of an activity, project, program, strategy, policy, topic, theme, sector, operational area, and institutional performance. It focuses on expected and achieved accomplishments, examining the results chain, processes, contextual factors, and causality to understand achievements or the lack thereof. It aims to determine the relevance, impact, effectiveness, efficiency, and sustainability of the interventions and contributions of the organizations* (UN ECLAC, 2017). E. Vedung defines this process as a *retrospective assessment of the merit, worth, and value of administration, outputs, and outcomes of government interventions, which is intended to play a role in future, practical action situations* (1997, p. 3). Among many insights, he advocated that a policy evaluation is much more than impact analysis and should be a multicritorial, functional, and careful assessment of all policy-related ongoing, finished, and planned activities. It implies that policy evaluation is a process conducted continuously within the framework of adopted policies. According to a definition provided by the Development Assistance Committee within OECD (2007), a policy evaluation is *a systematic and objective assessment of an ongoing or completed project, program, or policy, its design, implementation, and results. The aim is to determine the relevance and fulfillment of objectives, developmental efficiency, effectiveness, impact, and sustainability. An evaluation should provide credible and valuable information, enabling the incorporation of lessons learned into the decision-making process of both recipients and donors*. Many state authorities introduce their definitions of policy evaluation. An example of such an approach can be found in the US definition. It defines evaluation as *an assessment using systematic data collection and analysis of one or more programs, policies, and organizations intended to assess their effectiveness and efficiency* (Foundations for Evidence-Based Policymaking Act of 2018, 2019).

Policy evaluation serves a multitude of purposes, such as recording the policy's developmental trajectory, capturing its evolution over time, and the various factors contributing to its formation. Secondly, policy evaluation allows for documenting the policy's execution, informing stakeholders about its operational nuances, and facilitating effective implementation and monitoring. Thirdly, it provides a structured framework for evaluating stakeholder adherence and compliance with existing policies, ascertaining engagement and compliance with the stipulated policy framework. Policy evaluation allows for illustrating the impacts and value derived from a policy, quantifying its effectiveness, and its direct and indirect contributions to the intended outcomes. This process also provides evidence, substantiating the policy's efficacy and impacts with empirical data, thereby fostering data-driven decision-making processes. Noteworthy, policy evaluation guides future policy development, providing insights into the success factors and potential pitfalls and informing the design of future policy interventions. Lastly, it can be stated that policy evaluation ensures accountability for resources deployed, tracks the utilization of investments, and assesses return on policy investments to uphold responsibility and efficiency.

The policy evaluation can be conducted within each phase of policy formulation (*content evaluation*), enactment (*implementation evaluation*), and once the policy is fully implemented or concluded (*impact evaluation*). *The content evaluation* focuses on evaluating the precision with which the policy specifies its requirements, performing a comparative analysis of policies to pinpoint commonalities and differences, and comprehending the sequence and method for policy selection and enactment. It can also be dedicated to advancing policy implementation and subsequent policy creation through incremental adjustments and facilitating the construction and decoding of evaluations concerned with policy deployment and its consequential effects. A policy *implementation evaluation* assesses the policy deployment mechanism, discerning critical disparities between intended and realized implementation, recording distinct degrees or variations of policy implementation, or providing input for future policy implementation. Lastly, *policy impact evaluation* serves several objectives, including illustrating the policy's impact through the measurement of changes in short-term, intermediate, and long-term outcomes, ascertaining whether changes in outcomes are directly attributable to the policy, evaluating the comparative impacts of policies composed of disparate components, and determining the cost-benefit or cost-effectiveness analysis of a policy to gauge its financial viability and efficiency (U.S. CDC, 2011). Policy impact evaluation can be conducted both with *ex-ante* (prospective) and *ex-post* (retrospective) approaches to serve different purposes (Gertler et al., 2016). Cost-effectiveness analysis concentrates on the expenditure associated with the inputs and the outcomes procured from the intervention associated with a studied policy. This is also recognized as a method for comparative analysis of the costs of two or more interventions designed to mitigate or yield a singular beneficial outcome (Crowley et al., 2018). Cost-benefit analysis entails assigning monetary values to both the costs and outcomes of an intervention, enabling a direct comparison of benefits derived from the intervention using identical units of measurement, such as dollars. This allows for assessing the intervention's economic efficiency by examining the ratio of costs to benefits (Steuerle & Jackson, 2016). Impact evaluations could also be characterized as an *ex-post* policy evaluation approach that addresses the question: *Does the policy deliver results?* The resultant effects of the policy could span a range, encompassing positive or negative impacts, primary or secondary outcomes, and intended or unintended consequences, both direct and indirect. The primary goal of these impact evaluations is to establish a causal linkage between the policy intervention and observed outcomes (OECD, 2010).

Many research methods and techniques can be used to conduct policy evaluation. Such evaluations have been traditionally conducted utilizing conventional econometric and statistical methodologies, including regression analyses. These quantitative techniques allow for a robust examination of policy effects by isolating the influence of the policy from other extraneous factors, thereby providing a more accurate estimate of the policy's impact (Mergoni & De Witte, 2022). This approach also applies to evaluating and forecasting economic policy (Lucas, 1976), as well as demonstrating causality between evaluated policy and outcomes (Athey & Imbens, 2017). Another quantitative approach is represented by a group of multi-criteria analysis models that can support both the decision-making process and the policy evaluation at each formulation and implementation phase. An example of this approach is *Social Multi-Criteria Evaluation*, a methodological framework that melds multi-criteria analysis with participatory approaches. This integrated model systematically appraises complex policy decisions, encompassing multiple, often conflicting, social, economic, and environmental criteria (Munda, 2004).

Qualitative methods represent a vast category of methods allowing policy evaluation through case studies, focus groups, interviews, and diagnostic surveys. In this context, it is worth underlying individual in-depth and structured interviews that allow the collection of detailed, nuanced information about individual experiences, perspectives, and attitudes toward the evaluated policy, which may not be captured through other data collection methods. Interviews can also allow the identification of unanticipated effects (both positive and negative) through open-ended discussions. Interviews can provide information about challenges, barriers, and facilitators to effective implementation, informing strategies for improvement. More importantly, by interviewing diverse stakeholders, including beneficiaries, policymakers, and implementers, individual interviews can capture various perspectives on the policy's effectiveness and impact in the specified domain. In contrast to the quantitative approach, interviews can also provide a contextual understanding of the policy environment, including the social, political, and economic factors that may influence policy outcomes.

Last but not least, the insights gathered through individual interviews can inform the development of future policies, ensuring they are more effectively formulated and implemented. However, the interviewing process can be affected by certain factors, such as cognitive biases of interviewees, time-intensiveness, insufficient competencies of interviewers, and limited generalization potential (if the selection technique was incorrectly implemented) (Boyce & Neale, 2006). As M.Q Patton suggests, to increase the credibility of qualitative inquiry, an investigator should focus on four distinct but related inquiry elements, including (1) *systematic, in-depth fieldwork that yields high-quality data*, (2) *systematic and conscientious analysis of data with attention to issues of credibility*, (3) *credibility of the inquirer, which depends on training, experience, track record, status, and presentation of self*, and lastly, (4) *the presentation of the results that will convince readers' and users'* to the value of qualitative inquiry, which is a *fundamental appreciation of naturalistic inquiry, qualitative methods, inductive analysis, purposeful sampling, and holistic thinking* (Patton, 2014, p. 653). These interviews, however, should be conducted as part of a mixed-method approach, in conjunction with other data collection methods such as surveys, document analysis, and case studies, to ensure a comprehensive understanding of the policy's impacts and effectiveness. Finally, policy evaluation must be conducted based on identified criteria, representing a wide range of factors that can be considered. The examples of these evaluation criteria include but are not limited to those in Table 8.

Policy evaluation criteria	***Selected definitions of the policy evaluation criteria***
Effectiveness	The extent to which the intervention achieved, or is expected to achieve, its objectives and results, including any differential results across groups (OECD, 2021) The extent to which the policy causes the observed changes/effects and how these observed changes/effects correspond to the objectives (European Commission, 2016).
Environmental effectiveness	The extent to which a policy meets its intended environmental objective or realizes positive environmental outcomes (IPCC, 2007). It can be measured directly through expected changes in environmental outcomes (e.g., levels of GHG emissions), or it can be measured indirectly through a shift in behavior that is expected to lead to environmental improvements (e.g., increased use of public transit, increased deployment of renewable energy) (Demerse & Bramley, 2008).
Efficiency	The extent to which they are keeping costs down, especially in monetary costs, as indicated by either total costs or a ratio that involves both benefits and costs (Nagel, 1986, p. 99). Efficiency is associated with the maximization of the result and the minimization of waste. Efficiency concerns whether the outcomes of a policy are achieved at the lowest cost or whether better outcomes could be obtained at the same cost (Shahab et al., 2017, p. 543).
Relevance	The extent to which the intervention objectives and design respond to beneficiaries, global, country, and partner/institution needs, policies, and priorities, and continue to do so if circumstances change (OECD, 2021).
Coherence	The extent to which intervention is coherent with other interventions that have similar objectives and the extent to which the intervention is internally coherent (European Commission, 2016).
Equity and distributional considerations	The distributional consequences of a policy that include dimensions such as fairness and equity, although there are others (IPCC, 2007). Fairness or justice in the distribution of a policy costs benefits and risks across population subgroups (Caputo, 2014, p. 62).
Institutional feasibility	The extent to which a policy instrument will likely be viewed as legitimate, gain acceptance, adopted, and implemented (IPCC, 2007).

Table 8. Review of selected policy evaluation criteria. Source: Own elaboration.

It is worth emphasizing the importance of defining and specifying the policy evaluation criteria, ensuring alignment with the policy's specific functions, objectives, and instruments. This precision ensures a relevant, insightful analysis of the policy's effectiveness, contributing to future policy improvements. During empirical research with structured interviews, the author aimed to discuss and evaluate the effectiveness of green industrial policy as perceived by the research participants. However, the policy impact evaluation was broadened with the mentioned retrospective and prospective considerations to understand potential adjustments in the past and future policy design, increasing its overall effectiveness.

4.1.1. Empirical research problem, objectives, and methods

Based on the presented overview of the state and federal green industrial policy framework for establishing and developing the FCEV market in California, followed by the market characteristics, the empirical research problem could be presented in the form of the synthesized question: *What was the impact and effectiveness of selected green industrial policy instruments on the establishment and development of the FCEVs market in the state of California between 1990 and 2022 as assessed by the identified participants and stakeholders of this market?* Therefore, the research aims to present:

- descriptive justification for setting particular policy objectives and policy instruments for establishing and developing the FCEV niche market in California,
- quantitative evaluation (ranking) of individual policy instruments based on their effectiveness in achieving different strategic objectives and the overall objective of niche market creation,
- retrospective and prospective revision of the policy objectives and policy instruments to propose the changes in the past and future green industrial policy approach established in California within the area of FCEV market development, and last but not least,
- strategic policy observations for follower jurisdictions given their own (likely different) objectives to create individual segments of or an entire FCEV niche market and for further development of California's FCEV market.

Research methods

The study was composed of a mixed mode of qualitative and quantitative research methods that involved individual structured interviews extended with a diagnostic survey with ranking questions as part of the interviews. The interviews were designed to last approximately thirty minutes. The interviews were conducted based on a CAWI mode using the host university's online communication platform (Zoom). Then, the interviews were transcribed, coded, and evaluated using the NVivo 13 software. Once the informed consent was verbally obtained, the author presented the interviewees with three open-ended knowledge-setting questions. The interview structure (with the questions and justification for posing them) is presented in Table 9.

No.	QUESTIONS	JUSTIFICATION
1.	***Why has California been supporting FCEV market creation, even though the other zero-emission vehicles, such as BEVs, were seen higher deployment numbers?***	The first knowledge-setting question was designed to: • understand the motivation of the state of California to establish and develop the FCEV market from the perspective of a diverse group of market participants and stakeholders represented by the interviewees; • probe the strategic and policy-driven rationale behind California's sustained support for the FCEV market establishment and development amidst the predominant trends in the ZEV landscape; • explore diverse perspectives of the interviewees to comprehend the long-term vision and diversification strategies that policymakers might be implementing. *Note:* Including the BEVs in this context was crucial since, as discussed before, the state policy objectives have been revolving around the ZEVs in general, supporting both vehicle constructions. In other words, since the contrast between BEV and FCEV market development is significant, it is crucial to understand why California has been targeting the FCEV market development, as BEVs could decrease tail-pipe emissions more dynamically. Understanding this rationale can also shed light on California's commitment to creating a diverse zero-emission transportation sector structure rather than relying on a single dominant technology.
2.	***How did the state of California want to establish and develop the FCEV niche market at its early stage?***	The second knowledge-setting question was designed to: • delve into the foundational policy objectives and initiatives employed to establish and develop the FCEV market; • glean insights into the state's vision, anticipated market development barriers, and the significance of each market segment; • diagnose how interviewees perceive the actions undertaken by the state of California to establish and develop the FCEV market in the studied period. *Note:* Understanding these issues was crucial for facilitating a holistic evaluation of the policy evolution and adaptability to changing market conditions, as perceived by the interviewees. The three support questions were asked to structure the responses: 1. *What were the strategic policy objectives?* 2. *Which FCEV market segment(s) were emphasized through policy?* 3. *What were the key policy instruments implemented in California?*
A SURVEY WITH RANKING QUESTIONS (as presented in Figure 32)		
3.	***Looking back on the design and implementation of these policy instruments, what could have been done differently to accelerate deployment and increase the FCEVs number deployed?***	In the author's opinion, the retrospective analysis is an invaluable tool in policy research. By seeking answers on potential modifications or alternatives to the implemented policies, this third question aims to: • derive lessons from past experiences as perceived by the interviewees to highlight gaps, inefficiencies, or overlooked opportunities in the original policy framework implemented by the state of California; • to extract observations to inform future policymaking, ensuring more effective strategies for developing FCEV markets within this state and beyond; • provide insights into the adaptability and resilience of the policy framework in responding to real-world outcomes; • understand and develop ideas that embrace the alternative pathways in the past that could have been more effective in increasing the total number of registered FCEVs in California.

4.	***Could you propose a policy instrument that would accelerate the FCEV market development in California in the last decade?***	Soliciting market participants' and stakeholders' suggestions for policy instruments was designed to bring a proactive approach to the research design. In the author's opinion, with firsthand experience with the existing policy environment, market participants and stakeholders can offer innovative solutions grounded in their practical realities. Therefore, as the extension of the third question, this question was designed to: • encourage interviewees to propose new instrument(s) that could have increased California's FCEV market development dynamics; • identify potential missed opportunities or novel policy instruments that might not have been considered during the earlier policy formulation phases; • to capture the evolving perspectives of stakeholders as the market matures, allowing the research to present actionable observations for future policy adjustments or developments.
5.	***Should the current policy approach be continued?***	The last question was designed to: • understand how interviewees perceive the current policy approach demonstrated in California and ask them for the critical revision of it and provide the justification for continuation or a need to revise and redesign the policy assumptions as of the end of 2022; • understanding the underlying reasons for either continuation or change to provide insights into the evolving challenges and opportunities within the FCEV market; • to discern perceived effectiveness and potential areas of improvement in the current policy framework. Such feedback can be a barometer for the policy's alignment with current market realities and future aspirations.

Table 9. The structure of the individual interview with the questions and justification of posing them.

Once the initial two questions were asked, the interviewees were invited to undertake a survey with ranking questions. As part of developing the diagnostic survey, the author was encouraged by the Co-Investigator from UCSD to conduct the survey using a highly time-efficient technique, where interviewees are asked to allocate 100 *chips* (points representing the weights of effectiveness) to the arrows that connect eleven selected green industrial policy instruments with four strategic policy objectives. After doing so, the interviewees were asked to allocate another 100 *chips* to assess the importance of achieving the individual policy objectives in establishing and developing the FCEV market, representing California's fundamental policy objective. The aggregated results from all interviewees were demonstrated as a Sankey (flow) diagram. The concept of the exercise is presented in Figure 32. Once the diagnostic survey was completed, the interviewees were asked the last three open-ended questions (presented in Table 9 and numbered 3, 4, and 5).

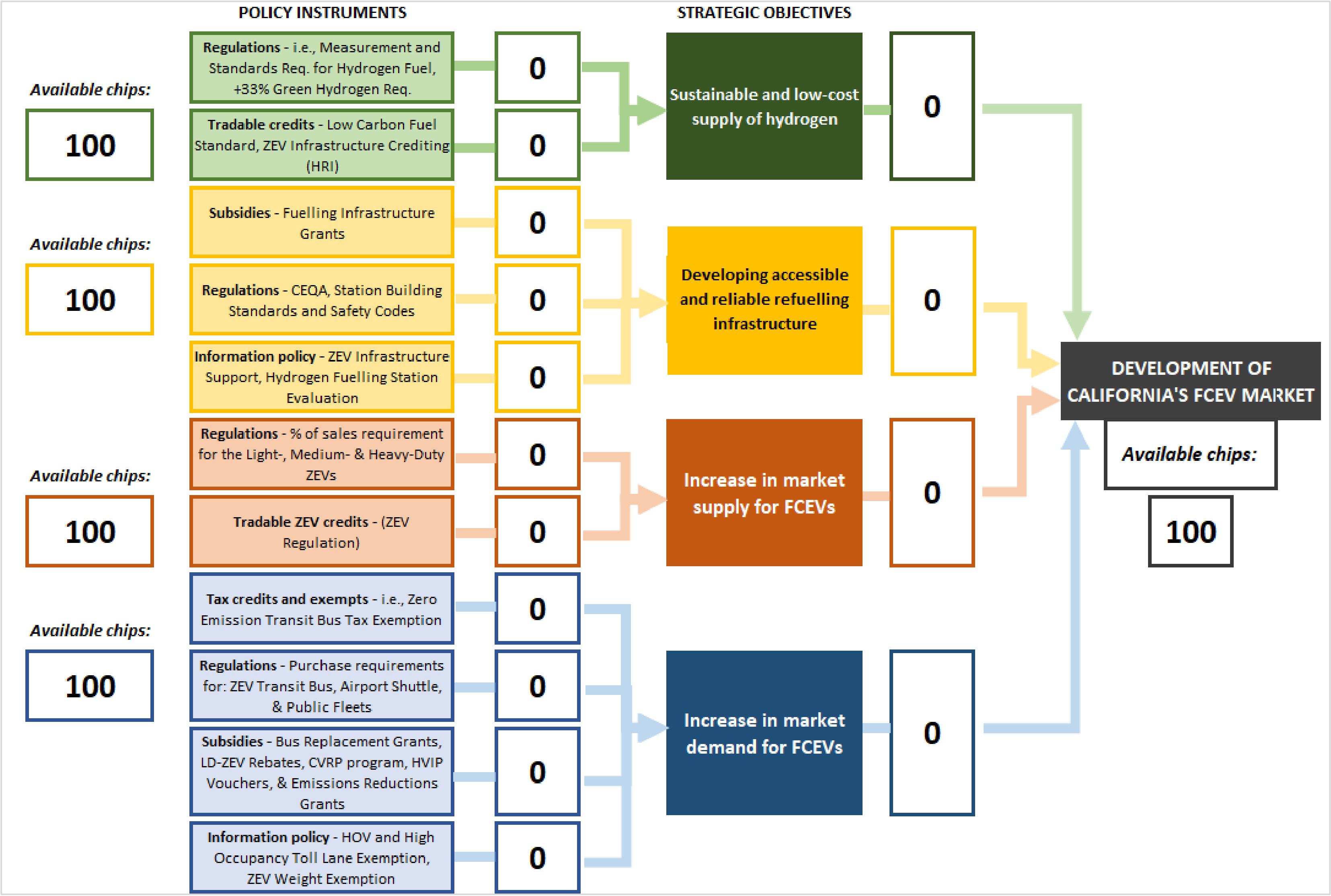


Figure 32. The design of the diagnostic survey used during the interviews. Source: Own elaboration.

4.1.3. *Selection of the research participants and the course of the research work*

Initially, the author assumed the research should include at least 30 participants (interviewees). This minimum expected number of interviewees was estimated based on the assumption that at least five entities should represent each of the six identified groups of market participants and stakeholders. Research participants were selected and invited to participate in a study based on purposive sampling to intentionally diversify the group of interviewees. Therefore, the selection procedure was as follows:

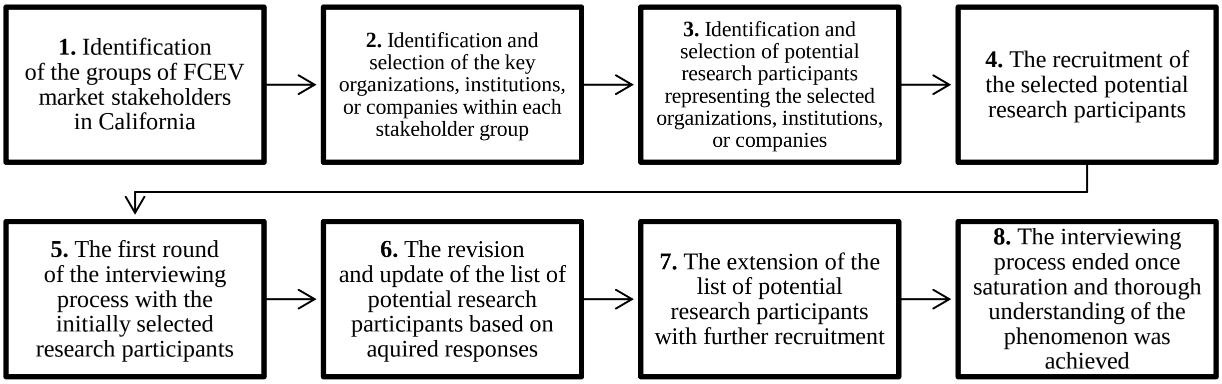


Figure 33. Selection procedure of the research participants. Source: Own elaboration.

The author developed a list of **inclusion criteria** that can characterize the selected research participants. Based on that, it can be stated that the research participants should have been:

- possessing strong (professional) relations or affiliations with organizations, institutions, or companies that represent California's FCEV market stakeholders,
- holding senior management positions in organizations, institutions, or companies that were either FCEV market participants or belonged to one of the identified groups of market participants and stakeholders in California,
- volunteers,
- of legal age,
- have been able to provide their informed consent to participate in the study.

It is worth noting that the author purposefully did not consider some other inclusion criteria that are commonly used in the studies with the participation of human subjects, including gender, ethnic background, membership within a minority group, possession of an immigrant status, health conditions, including whether the participants were pregnant, and lastly, belonging to the group of particularly vulnerable people, e.g., vulnerable to psychological trauma or suffering from mental health disorders, terminally ill, victims of traumatic experiences, or their family members. The omission of these typical inclusion criteria was dictated by the fact that the interviewees were not exposed to any risks during the interviews, including psychological or emotional threats, social or economic risks, physical risks, or harms, as well as legal risks resulting from participation in the proposed research.

Recruitment of the research participants

Based on the demonstrated inclusion criteria, the author invited the potential research participants to participate in the interview directly (with the assistance of Prof. David G. Victor). Potential research participants received the invitation by email (Attachment A) together with the information that this research was reviewed by the UCSD Institution Review Board (IRB), and the author obtained permission to conduct this study with the participation of human subjects. Once a potential research participant accepted the invitation, the time and date of the individual structured interview were set according to the research participant's availability. Between December 1, 2022, and February 10, 2023, the author conducted 46 structured interviews with the following interviewees listed in Table 10.

Group	Institution	ID
(1) The FCEV market actors **- supply-side - N=8**	Ballard Power Systems	1A
	Hyundai US	1B
	Hyundai US	1C
	American Honda Motor Company	1D
	New Flyer	1E
	Hyzon Motors	1F
	Toyota US	1G
	Nikola Motor Company	1H
(2) The FCEV market actors **- demand-side - N=7**	SunLine Transit Agency	2A
	Orange County Transportation Auth.	2B
	AC Transit	2C
	Port of Los Angeles	2D
	Port of San Diego	2E
	SamTrans	2F
	Foothill Transit	2H
(3) Research and Development entities - **N=8**	UC San Diego	3A
	UC Berkeley	3B
	Stanford University	3C
	National Renewable Energy Laboratory	3D
	UC Davis (ITS)	3E
	UC Irvine (NFCRC)	3F
	UC Davis (ITS)	3G
	UC Davis (ITS)	3H

Group	Institution	ID
(4) Industrial organizations and associations **- N=6**	California Hydrogen Business Council	4A
	Fuel Cell and Hydrogen Energy Association	4B
	American Trucking Associations	4C
	California Hydrogen Coalition	4D
	Hydrogen Fuel Cell Partnership	4E
	Center for Transportation and the Environment	4F
(5) Hydrogen suppliers and Infrastructure providers **- N=10**	SGH2 Energy	5A
	Nel Hydrogen	5B
	Air Liquide USA	5C
	Plug Power USA	5D
	Linde Gases US	5E
	San Diego Gas & Electric	5F
	Air Products and Chemicals, Inc.	5G
	SoCalGas	5H
	Iwatani corporation of America	5I
	True Zero (First Element Fuel Brand)	5J
(6) The state and federal governments **- N=7**	California Energy Commission	6A
	California Air Resources Board	6B
	California Air Resources Board	6C
	California Air Resources Board	6D
	Governor’s Office of Business & Economic Dev.	6E
	The U.S. Department of Energy	6F
	The U.S. Department of Transportation	6G

Table 10. List of research participants with the assigned ID number.

The overall invitation acceptance rate reached 86%. Candidates declined participation due to insufficient time or knowledge of a research topic. These candidates referred colleagues instead. The 46 interviews were conducted for 47 minutes on average. Figure 34 presents the duration of individual interviews.

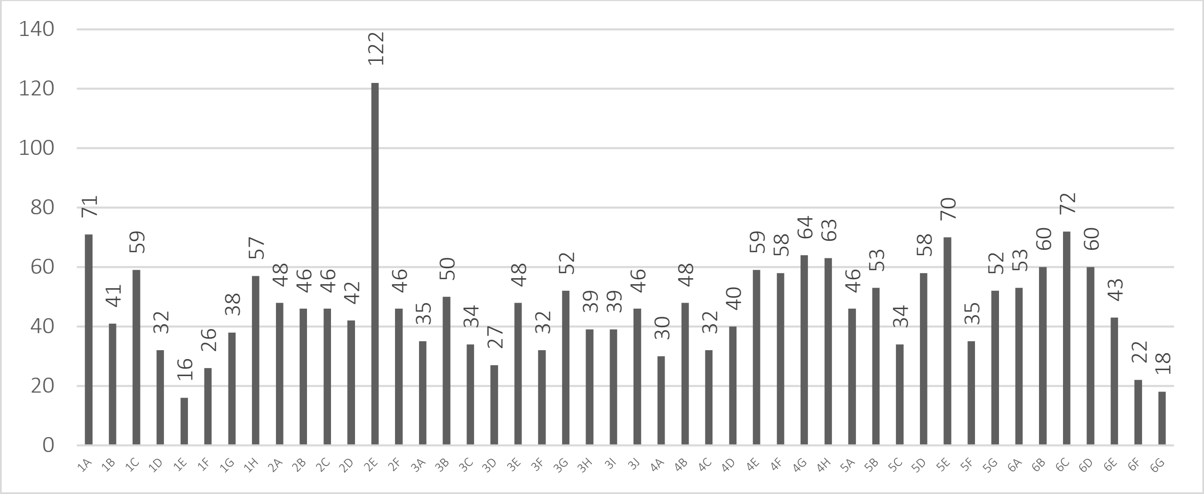


Figure 34. Duration of the individual structured interviews (in minutes).

Based on the acquired responses, the author decided to include all interviews in the final evaluation since there were no evident reasons to qualify individual interviews for exclusion. Besides, it is worth acknowledging that eight research participants (3C, 3D, 3E, 3F, 5A, 5D, 6F, and 6G) did not provide the answers using the core survey instrument (the exercise) either due to time constraints or the preference for assessing the eleven selected policy instruments without the chips allocations. The following review will demonstrate the key themes and subthemes identified by the author during the coding and evaluation process.

Obtaining informed consent

Since the discussed research procedure presented no more than minimal risk of harm to research participants and involved no procedures for which written consent is required outside of the research context and according to the US federal or state regulations, the author received a waiver of documented consent from the UCSD Institution Review Board. However, as instructed by the IRB, the following procedures were introduced to ensure the informed consent of the research participants. First, the research participants received the Informed Consent Form (Attachment B) before the interview. That document indicated that, i.e., the recordings might be stopped at any time and that portions and/or the entire audio recording might be erased at the participant's request. The document also briefly explained how the audio recordings generated expected outcomes. Secondly, at the beginning of the interview, the author asked each interviewee to confirm that they were familiar with the research assumptions, had read the Informed Consent Form, and had agreed to participate in this research study. That indicated that the informed consent was expressed verbally and recorded.

Processing private, identifiable information about research participants

The study processed personal data, including names, emails, occupations, and positions in the represented organizations, institutions, or companies. During the research using the individual structured interview technique, the author collected voice recordings of the interviewees, which represent a special biometric category of personal data. Before the interview, every participant was asked to verbally express their consent to be interviewed and allow the processing of personal data, including personal biometric data (voice). After transcribing and verifying the interviews, the author immediately and permanently removed the voice recordings. During the individual structured interviews, the author did not collect or process other personal data, including those related to health, genetic information, intimate life, political views, ethnicity, rituals, beliefs, and religious beliefs. The conducted research did not involve methods of continuous tracking or observation of participants, e.g., constant audio or video recording, monitoring, geolocation, or other forms of data processing that may result in a risk of violating the freedom and personal rights of research participants. Moreover, the personal data of research participants were fully anonymized after the completion of the study to minimize the risk associated with the study and related to the breach of research participants' confidentiality.

Training and research team responsibilities

Before conducting this study, the author (as the UCSD Visiting Graduate Student) had to undertake and complete the dedicated introductory CITI course[83]. The course was intended to familiarize the author with the US federal and California state regulations associated with research ethics and data management procedures whenever the study involves the participation of human subjects. The course was completed on November 14, 2022 (Completion Record ID: 52682989 – Attachment C). Since the project was primarily conducted by the author, who, according to the UCSD's regulations, was a non-PI-eligible USCD affiliate, Prof. David G. Victor served as the Co-Principle Investigator responsible for (1) assisting the author in evaluating the research project advancements after each phase, (2) organizing (at least once a month or, in necessary, more frequently) consultations for the author to review

---

[83] The Collaborative Institutional Training Initiative (CITI Program) is dedicated to provide training opportunities in the area associated to research procedures, ethical consideration, and safety issues to serve the needs of colleges and universities, healthcare institutions, technology and research organizations, and governmental agencies. More information can be found on the official CITI Program website: https://about.citiprogram.org/ (accessed on August, 1, 2023).

the progressions in project development, and lastly, (3) presenting constructive suggestions for improvement and continuation of the subsequent research tasks. Simultaneously, the author, as the official Co-Principle Investigator affiliated with UCSD at the time of this study, was responsible for the accomplishment of the research tasks following the agreed agenda, management, and integrity of the design, conduct, and reporting of the research project, as well as communication with research participants and the UCSD institutions. Besides, the author was solely responsible for conducting the individual structured interviews and evaluating the transcriptions using NVivo 13 software. Moreover, the author of this dissertation was responsible for presenting the project results and controlling the degree of compliance of the obtained results with the determined research objectives. Lastly, the author had to ensure that research activities were conducted per UCSD's procedures, especially in data management and ethical considerations, and provide a detailed summary of each study phase.

Data management and data processing procedure during the research

The author produced new data with individual structured interviews (voice recordings and their transcripts). Based on this, the author created a collective analytical file and then validated and analyzed the processed data to generate results in the form of a text report and spreadsheets. After transcription, voice recordings, which, according to the US and the EU regulations, represented a special personal biometric data category, were permanently removed. The survey (conducted as part of the interview) generated quantitative results, which were processed and presented as a Sankey diagram using a data visualization tool in MS Excel and saved as graphic files (JPEG). The interviews were voice recorded in PCM (WAV) format, transcribed, and then uploaded to the NVivo software for analysis. To facilitate the identification and evaluation of acquired results, the author developed a dataset that holds metadata consistent with the metadata standards, such as the Data Documentation Initiative. Metadata was described and stored in CSV. The bibliometric dataset (listing relevant literature) was prepared as a spreadsheet in a text format. All publications were described by title, year, source, and place of publication. If possible, the DOI link was provided. The naming and structure of the folders and files with the datasets were standardized to facilitate their specific recognition: *H2FCEV_type of data*, files: *YYMMDD_name_version*.*. All information about the content and organization of research data was included in the documentation saved in the *README* text files. The revised data were cataloged according to FAIR data standards (*Data Findability*, *Accessibility*, *Interoperability*, *and Reusability*). The data processed as part of the research project were stored on encrypted hard drives of the team members' work computers and in the author's Microsoft cloud (*OneDrive*). Data stored in the cloud were automatically synchronized and used to share and exchange data with the research team. The commercialization of the research results was not planned or expected.

4.2. Results of the empirical research and discussion

The subsequent subchapters (4.2.1. – 4.2.5.) and the inner sections demonstrate the synthetical results acquired during the empirical research and present the appropriate discussion where the author compares the results with the existing literature (if possible). Each bolded phase, i.e., "**California's longstanding tradition of supporting ZEV deployment,"** represents a separate theme identified and marked during the coding process (Appendixes D – H presents the complete lists of themes and their frequency). Furthermore, each bolded phase is followed by the brackets, i.e., "**(1C, 2A, 4BE, 5BCEH, 6BCE)**", where the IDs of research participants were marked in red following the order demonstrated in Table 10. Mentioning the ID of a participant means that the provided answers align with the identified theme. To increase the readability of marking, the IDs were reduced in each case so that the first digit represented a group of FCEV market participants or stakeholders, while the letter represented the particular interviewee.

4.2.1. Justification for implementing green industrial policy for the FCEV market establishment and development in California from the perspective of the interviewees

From the interviewees' perspective, it is worth presenting diverse arguments and justifications for implementing a green industrial policy for California's FCEV market establishment and development. Understanding: *Why has California been supporting FCEV market creation, even though the other zero-emission vehicles, such as BEVs, have seen higher deployment numbers?* is crucial in the impact evaluation process. First of all, it provides insights into the way the FCEV market creation is perceived not only through the lens of publicly demonstrated strategies and bills but also from the perspective of various FCEV market participants and stakeholders, who might have a diverse understanding of the policy objectives and their justification, especially in the context of rapidly growing BEV market, which overlaps FCEV significantly. The following themes that discuss the justification were grouped into three major categories, including ***political and legal arguments***, ***socio-economic arguments***, and, last but not least, ***technological arguments***, as expressed by the interviewees.

Political and legal arguments for FCEV market development in California – Appendix D

Undoubtedly, several interviewees acknowledged **California's longstanding tradition of supporting ZEV deployment (1C, 2A, 4BE, 5BCEH, 6BCE)**, including FCEVs, together with comprehensive infrastructure and market development, an example of which was *ZEV Regulation* and *Hydrogen Highway*. The interviewees recognized the holistic approach adopted in California, which involves simultaneous FCEV market, fuel supply, and infrastructure development, as all three are interdependent. This approach has been guided by a long-term vision and strategy, with policies and targets set for decades. Furthermore, interviewees highlighted the lessons learned from initial suboptimal assumptions about station sizes and locations, leading to necessary adjustments and realizing the need for larger stations, higher reliability, backup redundancy, and more consumer-friendly fueling locations. Thanks to California's historical leadership and influential position on a broader scale: *the world looks to California for good practices and lessons learned* **(4E)**. The consensus among various stakeholders underscores the vital role of FCEVs in **advancing state-level climate initiatives and air quality protection (1H, 2EF, 3BEG, 5AGHJ, 6BE)**. These interviewees highlighted the state's pursuit to reduce emissions from the transportation sector and promote ambitious climate neutrality goals while underlining the health costs associated with air pollution from tailpipe emissions. Some interviewees added nuance by discussing the state's efforts to promote only low-carbon and clean hydrogen to avoid counterproductive results, highlighting the tension between market development and environmental integrity. Even though the interviewees were underlying that FCEVs (together with BEVs) are the key ZEV technologies for achieving cleaner air and mitigating climate impacts of transportation, they acknowledged that California has been representing a **technology-neutral (agnostic) approach toward ZEV market development (1CDEH, 2E, 3BFGH, 4DE, 5BF, 6ABCE)**. The interviewees emphasized that the state avoids prioritizing FCEVs over BEVs or *vice versa*, which was perceived as critical to achieving zero-emission goals. Noteworthy, California's regulations explicitly refrain from favoring one technology over another, an example is the LCFS mechanism, which allows the market to decide on the most suitable low-carbon fuel types. California's technology-neutral approach was seen as a strategic asset, minimizing risks associated with relying on a single technological solution while fostering innovation and market development in various ZEV options. However, some interviewees highlighted the **biased and unequal state support for FCEVs in contrast to BEVs (1EFH, 2A, 3G, 4AE,**

5GH), which opposes the officially declared technology-neutral approach. It emerges in the form of disproportionate allocation of state funding for infrastructure development, unequal involvement of public utility providers, and a lack of equal representation in green industrial policymaking processes. As a result, the unequal market deployment, as summarized by the *David and Goliath* analogy **(1F)**, causes the bottlenecks for spurring FCEVs on a broad scale. Lastly, some interviewees shared that one of the potential explanations of this bias is insights regarding the policymakers' perceptions of BEV and FCEV investments - hydrogen refueling technology and FCEVs are less appealing to politicians who prefer quicker and less costly solutions, like battery-powered buses, to showcase their commitment to environmental sustainability. Nevertheless, both the air quality concerns and the technology-neutral approach guiding California's policy were perceived by interviewees as a **strive of the state of California to be a global leader in ZEV deployment** **(1CD, 2E, 3A, 4BC)**. First and foremost, progressive culture and forward-thinking public policy objectives emphasize a unanimous acknowledgment of California's historical role as an innovator in this sector. Some interviewees outline the practical benefits, stating that leading in ZEV technology could boost job creation and attract investments **(2E)**. Various stakeholders underlined California's cluster strategy for FCEV market development **(3BH, 4D, 5DJ, 6F)**. Interviewees initially pointed out the impracticality of California's early *Hydrogen Highway* strategy, advocating instead for a more localized, clustered approach **(3B, 5D)**, which ought to result in strategically locating 100 hydrogen stations in early adopter communities, such as Los Angeles and the Bay Area. Adding granularity to this, some interviewees emphasized the need to balance coverage and capacity and criticized the lack of customer-centricity among traditional industrial gas companies involved in the hydrogen sector **(5J)**.

These results also contribute to existing literature, emphasizing the political and legal argumentation for FCEV market development. It is worth underlining that California's long-standing commitment to ZEV deployment was also spotted by researchers, such as D. Sperling and A. Eggert (2014), who emphasized that the gradually advancing *portfolio policy approach* can be traced back to the 1960s, with the intensification, particularly around 2002. The researchers also noted that California could enforce its restrictive emission standards primarily because of its institutional setting coordinated by CARB, which possessed a unique authority to regulate vehicle emissions and fuels used within the state transportation sector. Noteworthy, the policy focused on economy-wide FCEV deployment can drive down the emissions from the transportation sector and increase air quality considerably, as demonstrated by S. Stephens-Romero et al. (2009) and strengthened by K. Forrest et al. (2020b). However, the policy implemented in California is gradually becoming less and less technologically neutral, as also evidenced by J. Bushnell et al. (2021) based on the example of the Low Carbon Fuel Standard as it leans toward BEVs (and FCEV to some extent). Noteworthy, the interviewees emphasized the biased and unequal institutional orientation of the policy framework conditions, which focuses more on BEVs than FCEVs, which is crucial for further discussion. Nevertheless, the provided perspectives are concurrent with the leading opinion that California's policy intensively supports FCEV market development, as expressed in the work by G. Trencher (2020).

Socio-economic arguments for FCEV market development in California – Appendix E

Many interviewees believed that complete electrification of the transportation sector is **impossible without FCEVs** **(3BFGH, 4ABEF, 5CEGH, 6ABCDE)**. In this context, participants were raising the diverse usage needs and driving modes among the typical categories of early-adopters (such as *super-commuters*), different infrastructural barriers and requirements for both BEVs and FCEVs, the skepticism around BEVs serving all vehicular needs, and emerging BEV battery charging risks. The overarching conclusion from the interviewees is that due to diverse population needs, technical constraints, and infrastructural challenges, a multifaceted approach incorporating both FCEVs and BEVs is crucial for a fully decarbonized transportation future in California. However, numerous interviewees mentioned that despite the advantages of FCEVs, the **BEVs are continuously dominating the ZEV deployment** **(1BCDGH, 2CE, 3AFG, 4ACDE, 5FG, 6ABE)**, mainly because the cost and infrastructure required for BEVs are substantially more manageable. For decades, BEVs have had higher technological readiness than FCEVs, leading to faster and more widespread commercialization and diffusion. Besides, consumer perception and adaptability also favor BEVs despite technological limitations around weight and range. Interestingly, the different sector structures also play a role – the BEV sector has more startups thanks to lower barriers to entry. In contrast, the FCEV sector mainly comprises legacy companies, which is a dynamic that impacts future planning and deployment **(2E)**. Even though BEVs are dominating the ZEV deployment process – ***BEVs are not one-size-fits-all solutions*** **(1BC, 2CEH, 3BDEFG, 4ADE, 5CE, 6ABCD)**. Some interviewees emphasized that while BEVs could be viable for 60-80% of the population, especially in suburban areas, a significant fraction remains for whom BEVs are impractical, notably those living in densely populated areas without dedicated parking spaces. Moreover, BEVs may not be suitable for heavier-duty or long-range applications, citing issues such as towing capabilities and high energy storage density. Therefore, FCEVs can better serve those who do not fit the typical BEV user profile, like people without home charging infrastructure or those with long, irregular commutes. The interviewees also stressed the importance of optionality and market adaptability for both BEVs and FCEVs, suggesting that while BEVs may be suitable for specific duty cycles and deployment situations, FCEVs fill a critical gap in the market, particularly for hard-to-electrify sectors. Noteworthy, the interviewees consistently indicated that the initial set-up costs for hydrogen refueling stations are higher than those for conventional BEV charging stations, which may impact the decisions of individual early adopters to choose BEVs over FCEVs due to the lower initial infrastructure costs. However, a recurring opinion is that the **marginal costs of hydrogen refueling stations decrease with scale** **(1ABEF, 2A, 4CE, 6D)**. Moreover, hydrogen fueling infrastructure could be more space-efficient in the long run because scaling it up does not require as much space as scaling up a BEV charging infrastructure (especially for fleet operators and transit bus companies). Specifically, vertical hydrogen tanks can be added to existing hydrogen stations to increase their capacity without requiring additional space. Interestingly, the interviewees mentioned electric power demand involved in the large-scale deployment of BEVs, implying that the energy requirements could necessitate the construction of an electrical substation on a property beyond a certain point. This case would involve significant additional costs and might reduce the attractiveness of large-scale BEV infrastructure. As indicated by **1E**, while a smaller number of hydrogen buses may appear more expensive due to the need for fueling station construction, the costs become more reasonable with larger-scale deployments. Initial findings reveal a shared consensus that while BEVs offer a cost-effective and more straightforward entry point, their scalability is fraught with escalating costs and complex infrastructural needs. However, FCEVs offer economic efficiency at scale, especially for fleets. The needs and requirements of fleets were repetitively appearing during the interviews. As interviewees were advocating, **deployment of FCEVs can increase fleet efficiency** through improved duty cycles and operational flexibility, as well as quick refueling times and extended range, aligning FCEVs more closely with the operational characteristics of traditional CNG and diesel vehicles **(1AE, 2EH, 4AF, 5CG, 6CDE)**. In an examination of opinions from multiple stakeholders, a consistent narrative emerges underscoring the compatibility of FCEVs with the utilization patterns and user habits traditionally associated with ICE vehicles, which convinces some early adopters to transition to FCEVs. Even though it seems that FCEVs represent higher applicability within fleets of buses and medium and heavy-duty vehicles, the interviewees noticed that California policy was **initially primarily oriented at a light-duty FCEV market segment (3GH, 4BDE, 5BEGH, 6BCE)**. As pointed out, it was related to the limited number of FCEV models available on the market, performance issues and outages at hydrogen refueling stations, and the rapid development and decreasing costs of battery technologies. There is a perception that light-duty-policy-oriented approaches have failed, leading to a shift in focus toward medium-heavy duty vehicles. However, this shift is seen as premature by some, who believe there should be a push to support all vehicle segments. It was strengthened by an observation that in recent years, California re-oriented at sizing the deployment and market potential of FCEBs and FCETs, perceived as a natural progression from light-duty vehicles to heavy-duty trucks. Interestingly, some interviewees were skeptical and suggested that BEV proponents might strategically push hydrogen into the heavy-duty space to eliminate competition in the light-duty market. Lastly, the interviewees revealed a complex interplay of factors driving **synergy across FCEV light-duty, FCEB, and FCET market segments (1B, 3D, 4AD, 5AG, 6ACDE)**. Economies of scale stand out as a cross-cutting theme, with light-duty FCEVs facilitating lower fuel-cell stack costs that, in turn, benefit FCEBs and FCETs. Concurrently, the FCEB and FCET segments catalyze reducing the overall cost of hydrogen fuel by pulling the demand in higher quantities. This synergy across market segments stands as the argument for supporting the deployment of all types of constructions despite the functionality of one over another in a broad sense.

These diverse findings from the interviews are largely concurrent with research results demonstrated by several researchers. For instance, supporting the deployment of the FCEBs and FCETs is much more economically feasible and reasonable than supporting BEVs, as demonstrated by K. Forrest et al. (2020a) based on the case of California's transportation sector. The wide-scale deployment potential of FCEVs within the fleets was also observed by G. Trencher and J. Wesseling (2022), who emphasized that hydrogen-powered vehicles can electrify hard-to-decarbonize fleets where BEVs are less likely to demonstrate comparative advantages. One of the strong arguments for such a wide-scale deployment is the total cost of ownership of the FCEVs. As G. Morrison et al. (2018), FCEVs are gradually decreasing the difference in TCO against BEVs, leading to a significant difference in favor of FCEVs as estimated by 2030. Currently, the TCO of FCEVs is considerably affected by hydrogen fuel and fuel cell costs, so the synergy across FCEV market segments, expressed by the interviewees, is essential for this market to develop with higher dynamics. It is evident in the context of FCETs, which may reach parity with ICEV trucks by 2025, thanks to a decrease in the cost of fuel cell stacks and expected hydrogen cost reduction in the following years (Burnham et al., 2021). Noteworthy, the emphasis that BEVs are not a *one-size-fits-all solution* to decarbonize the transportation sector strengthens the need to overcome the adoption gap of ZEVs among populations with lower socioeconomic status, who also deserve to benefit from the diffusion of these types of vehicles, leading to health and air quality co-benefits (Neves Almeida & García-Sánchez, 2016). In addition, it is essential to recognize the individual motivations of the early adopters. So do the interviewees, researchers like S. Hardman and G. Tal (2018), indicate that California's early adopters are primarily convinced to purchase FCEVs due to a lack of the opportunity to charge their potential BEV at home, even though the hydrogen refueling infrastructure is at an early development stage. In the author's opinion, the main contribution of the interviewees' perspectives is to underline that even though the FCEVs are yet to be deployed on a broad scale, they do demonstrate a significant alternative option to BEVs from the socio-economic perspective emphasized by the synergy across FCEV market segment, the decrease of marginal costs of hydrogen refueling stations development with scale, and a re-orientation of California policy that aims at seizing the opportunities related to the growth of FCEB and FCET segments.

Technological arguments for FCEV market development in California – Appendix F

The thematic synthesis of the research interviews indicates a shared emphasis on the advantage of FCEVs over BEVs in terms of the **weight of power modules**. Several key themes emerged, including **payload capacity limitations, regulatory constraints, and application versatility across vehicle classes (1C, 2E, 3B, 4F, 6E).** The interviewees' consensus is that FCEVs offer a distinct advantage over BEVs in terms of the weight of their power modules, affecting payload capacities, adaptability across a range of vehicle classes, and the feasibility of operating within existing regulatory frameworks, such as ZEV weight-exempt. Furthermore, interviewees from various groups almost unanimously emphasized that **FCEVs have a more excellent range than BEVs, shorter refueling times, offering *seamless* integration of FCEVs into existing operational fleets**, indicating that FCEVs can be refueled as quickly as diesel vehicles **(1CEH, 2ACEH, 3H, 4F, 5E)**. Moreover, the interviewees collectively indicated that FCEVs present a compelling alternative to BEVs in **mitigating power grid stress and addressing infrastructural challenges (1AH, 2BC, 4A, 6D).** They also highlighted hydrogen's role in supplementing the power grid for major BEV charging facilities. Lastly, experts gave a nuanced understanding of the **parallels between hydrogen and Compressed Natural Gas** regarding fleet operations and vehicle functionalities

(1E, 2ABH, 5J). A central theme is the critical role of infrastructure development, associated with the past challenges of CNG infrastructure, with limited route flexibility due to fuel availability, particularly during colder seasons. The long experience of transit companies and other fleets with CNG gives them an easier transition to hydrogen. This point emphasizes the importance of institutional knowledge and technical compatibility, especially in fueling utilities. Cost considerations, especially in the context of total ownership, were highlighted by transit companies, indicating that long-term maintenance costs of hydrogen-powered vehicles could reach parity with CNG ICEVs. The variations in transit agency attitudes towards alternative fuel adoption reflect the ongoing debates and considerations that influence the speed and extent of transitioning from traditional fuels to zero-emission alternative options, including FCEVs.

The observations and opinions shared by the research participants can strengthen the findings provided, for instance, by B.G. Pollet et al. (2019), who emphasized that FCEVs have finally improved significantly enough to meet the satisfying performance and durability of all major components compared to conventional ICEV. As they advocate, FCEVs must still achieve comparable durability and cost parity to become a competitive alternative to conventional vehicles. However, as the interviewees underlined, in contrast to BEVs, FCEVs have considerable advantages that emerged in various studies, including already mentioned lower power unit weight, extended range, and shorter refueling times (Ledna et al., 2022; Parikh et al., 2023). However, the author firmly believes that the main contribution derived from the interviewees' perspective is the comparison of FCEV usage and utility performance to CNG-powered buses, especially in the context of transit bus operators. Noteworthy, the interviewees emphasized one of the crucial advantages of the FCEV over BEVs, which is related to the fact that FCEVs do not cause direct power-grid stress. Such a feature is undoubtedly fundamental when considering the broad-scale deployment of both types of ZEVs in California and other jurisdictions.

The review of the interviewees' opinions regarding the justification for supporting California's FCEV market development provided an array of diverse arguments that determined the state's green industrial policy objectives. Moreover, these arguments contributed to implementing particular policy instruments, which could have impacted the FCEV market development differently. It is now worth concluding that California's policy is founded on complex reasoning based on long-term objectives derived from a historical commitment. The state authorities primarily focus on pursuing a technology-neutral approach to mitigating air pollution and decarbonizing the transportation sector while underlining the socio-economic gains and technological advancements of FCEVs over the BEVs, which represent complementary ZEV alternatives.

4.2.2. The impact and effectiveness of selected industrial policy instruments on the establishment and development of the FCEV market in the state of California as perceived by interviewees

The quantitative evaluation of the impact and effectiveness of selected green industrial policy instruments in achieving the four strategic policy objectives and thus developing the FCEV market development in California was conducted as part of the structured interview. **The Sankey diagram**[84], as a quantitative data visualization tool, was used to present the responses of research participants from a **diagnostic survey** (the *core survey instrument*) regarding the evaluation of the effectiveness of individual green industrial policy instruments implemented in California in establishing and developing the FCEV market in the studied time (Figure 35). In this version, the Sankey diagram starts from the left with the various green industrial policy instruments grouped based on their type, functionality, and connection to the four strategic policy objectives. Then, the rightmost column features the overarching strategic policy objectives for the FCEV market development, including *developing reliable and accessible refueling infrastructure*, *sustainable and low-cost hydrogen supply*, and *increasing market demand* as well as *supply for FCEVs*. The flows or arrows originate from each policy instrument and culminate in one of the strategic policy objectives, demonstrating the overall effectiveness of these instruments in developing the FCEV market, which is the primary and ultimate state policy objective. The width of the flow lines is directly proportional to the perceived effectiveness of each policy in achieving the stated objectives and weighted with the significance of each objective in developing the FCEV market in California, based on survey responses.

This Sankey diagram demonstrates a hierarchical flow of effectiveness, beginning with the policy instruments deemed most effective in developing the FCEV market in California. The most expansive stream connects the abovementioned objectives to two pivotal policy instruments: *Low Carbon Fuel Standard with Hydrogen Refueling Infrastructure Crediting System* and *Hydrogen Fuelling Infrastructure Grants*. This signifies a high concurrence among survey participants regarding the effectiveness of these policies in actualizing the strategic

---

[84] A Sankey diagram is a visual representation of flows between different nodes or stages within a system. The width of the arrows or lines in the diagram is proportional to the flow quantity they represent.

objectives. The Sankey diagram delineates secondary instruments that garnered considerable attention in the succeeding positions. These are the *Hydrogen Fuel Specifications, Measurements and Standards, Sales Requirements for ZEV manufacturers* (as % of sale – ACC II), *CVRP Rebates* and *HVIP Vouchers*, as well as *CEQA Review Exemption, Fuelling Station Building Standards and Safety Codes*. Moreover, a significant portion of the interviewees underscored the importance of hydrogen supply and stations as a precursor to generating demand, reinforcing that infrastructure development and fuel supply are crucial determinants in developing the studied market. In this configuration, the Sankey diagram provides a detailed, flow-oriented view of how policy instruments in California are perceived to contribute to the broader objectives of FCEV market development. The visual hierarchy and connections in the diagram allow for a nuanced interpretation of policy effectiveness as perceived by selected representatives of FCEV market participants and stakeholders.

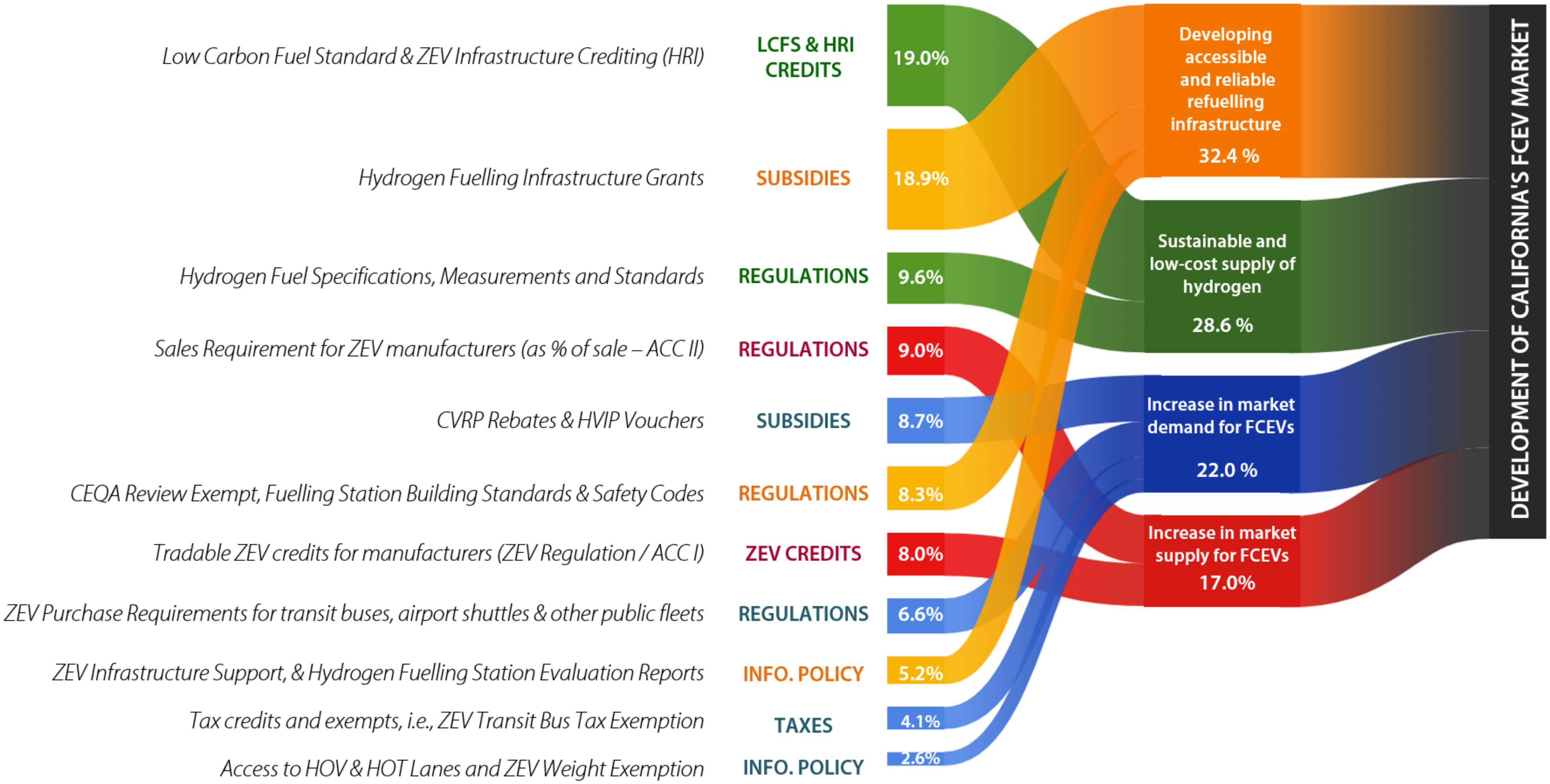


Figure 35. Complete ranking of the answers from the core survey instrument.

However, it is essential to consider the responses' distribution considering the research participants' groups. It is particularly enlightening to discern variations in the perception of the effectiveness of individual policy instruments. Even though *Fueling infrastructure grants* and the *LCFS with HRI Credits* were overly dominating, these policy instruments constituted points of high discussion and divergence in viewpoints, as presented in Figure 36.

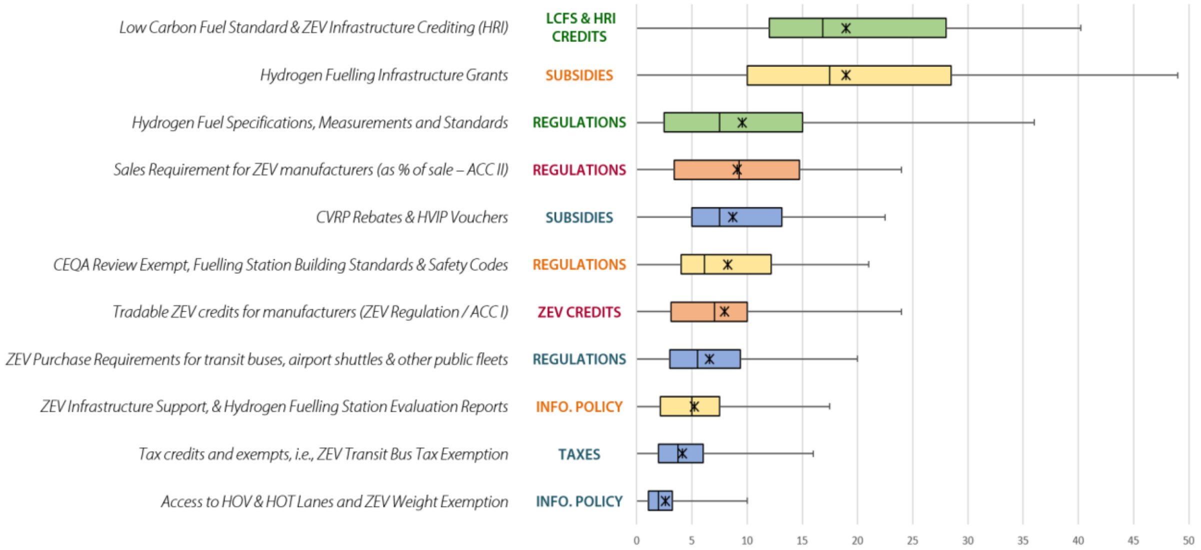


Figure 36. Distribution of the answers from the core survey instrument - all groups of research participants.

When parsed by the affiliations of the research participants, distinct preferences become evident. It can be stated that from the vantage point of Industrial Organizations and Associations, as well as Hydrogen Suppliers and Refueling Infrastructure Operators, Hydrogen *Fuelling Infrastructure Grants* were overwhelmingly perceived as the most effective tool for fostering FCEV market development. This aligns with their immediate operational needs and objectives, rooted in the practicalities of hydrogen supply and refueling infrastructure. On the other hand, stakeholders from academia, state and federal regulatory entities, OEMs, transit buses, and fleet operators rated the Low Carbon Fuel Standard with Hydrogen Refueling Infrastructure Credits as the most impactful. This likely reflects a broader, systemic viewpoint incorporating lifecycle emissions and long-term sustainability. Intriguingly, for the other policy instruments evaluated—such as *Hydrogen Fuel Specifications, Measurements, and Standards, Sales Requirements for ZEV manufacturers* (as % of sale – ACC II), *CVRP Rebates & HVIP Vouchers*—the distribution of perceptions across different market and stakeholder groups largely corresponded to the hierarchical order presented in the Sankey diagram. This differentiated lens provides additional depth to understanding policy instrument effectiveness, revealing that what might be considered beneficial or effective is deeply entwined with the specific objectives and operational realities of various stakeholder groups. This underscores the complexity of a balanced green industrial policy landscape that adequately addresses all participants and stakeholders' diverse needs and expectations in California's FCEV market.

Confrontation of qualitative and quantitative results regarding the effectiveness of the individual green industrial policy instruments – Appendix G

The quantitative results can be confronted with qualitative responses provided by research participants, which are discussed in detail in the following subsection of this chapter. Those qualitative insights can, therefore, be a way to understand how and why individual selected green industrial policy instruments contribute to the FCEV market development in California, as interviewees perceive. The order of the policy instruments considers their position demonstrated in the Sankey diagram (Figure 35).

The LCFS with ZEV Infrastructure Crediting (HRI) has emerged as one of the crucial policy frameworks, catalyzing the development of the FCEV market according to various institutions and stakeholders, who have emphasized that LCFS has been a major driving force for the demand for hydrogen, exceeding California's initial 33.3% clean hydrogen requirement **(1ABCDEFH, 2ACEH. 3ABEGH, 4ADEF, 5ABCEFGHJ, 6ABCDE)**. It was noted that LCFS incentivizes a broader range of low-carbon fuels to curb transportation emissions. The interviewees underscored the vital role of LCFS in sustaining the otherwise expensive low-carbon hydrogen market, with the latter terming LCFS as the most influential global decarbonization policy. The additional LCFS credits source coming from HRI capacity credits was perceived as one of the accelerators of the FCEV market growth. However, it should cover the MD-HD stations as well. As noted, the LCFS benefits not the hydrogen producers but those who perform retailing at the stations, discouraging investments in clean hydrogen generation facilities. Lastly, the interviewees mentioned the dynamic fluctuations of the market value of LCFS credits, which impact their operations and predictability of investment profitability.

The assessment of the LCFS is worth confronting with the results of relevant studies. According to a study by J. Axsen and M. Wolinetz (2023), the LCFS has demonstrated effectiveness in several domains – it has been successful in mitigating greenhouse gas emissions, and modeling suggests that a more restrictive LCFS could further enhance emission reduction in the long term when combined with other well-designed policies. However, its cost-effectiveness compared to carbon pricing, such as California's *Cap-and-*

Trade system, remains uncertain. While not as efficient as carbon pricing, the LCFS could effectively complement a policy mix that includes carbon pricing. Regarding political and social acceptability, the LCFS stands out for its substantial public opinion support, surpassing other carbon pricing mechanisms. Additionally, the LCFS has been a transformative signal for the energy sector, encouraging increased investment in low-carbon fuels, primarily concerning hydrogen and biofuels and the necessary refueling infrastructure. Lastly, the LCFS anticipates stimulating innovation in this sector over the long term. The previous studies also emphasized the high effectiveness of LCFS in diversifying California's portfolio of low-carbon fuels, including the significant increase in the share of clean hydrogen (Yeh et al., 2016), especially by subsidizing retailing fuel at the stations with the HRI capacity credits (Vijayakumar et al., 2021), and thus allowing driving down the cost of the clean hydrogen fuel supply and contributing to reaching the parity with diesel fuel (Reed et al., 2023).

The impact of **hydrogen fueling infrastructure grants on the FCEV market (1H, 2H, 3BDE, 4ABDF, 5BCEFGIJ, 6AD)** is multifaceted by playing a pivotal role in underwriting economic risks for station developers through offering cost-sharing support for developers in the form of subsidizing initial high CAPEX and helping with further maintenance and fixed costs (through interconnected LCFS and HRI capacity credits). However, some interviewees advocated for a shift towards self-sufficiency and a profitable business model that does not rely solely on grants. Complementary policies, such as clear regulations and standards and effective dissemination of information about station locations and functionalities, can amplify the effects of financial incentives. Lastly, despite these subsidies, there are concerns about the insufficiency and unreliability of the current infrastructure, underlining that while grants are essential for initial set-up and scaling, they are just one piece of a larger puzzle in creating a robust and self-sustaining FCEV market. These insights gleaned from the interviews can be confronted with existing studies that demonstrate the role of particular grant programs, such as CEC's *Alternative and Renewable Fuel and Vehicle Technology Program*, which was fundamental in the early years of developing the hydrogen refueling infrastructure (Muench, 2012). However, it can be noted that the fund allocation for the first stations at the beginning of the 2010s was insufficient compared to the desired policy outcomes, limiting the infrastructure development (Stephens-Romero et al., 2010). However, in the course of the next decade, the subsidies for the stations increased considerably, highly contributing to driving down the CAPEX of the stations, thus leading to considerable infrastructure development (Gao & Zhang, 2022).

The interviewees expressed differing but complementary perspectives on the importance of **hydrogen fuel specifications, measurements, standards, and specific low-carbon hydrogen requirements** in FCEV market development **(1BH, 2H, 3D, 4E, 5BEJ, 6AB)**. Hydrogen purity and adherence to specific standards were underscored as critical for the market's growth and maintaining tank reliability and durability, arguing that, unlike conventional gasoline stations, fueling FCEVs requires attention to multiple variables like cooling and speed of filling. Some interviewees indicated that meeting standard requirements regarding hydrogen impurities is a *must-have*, for the fuel cell manufacturers will not certify FCEVs if the hydrogen used does not meet the required purity standards. There was a consistent view that while regulations are necessary, they can also be potentially counterproductive, especially in terms of cost and speed of transition to low-carbon fuels, arguing that pushing for a quick transition to 100% clean electrolytic hydrogen would make FCEVs prohibitively expensive, impeding market growth. There was agreement that financial incentives like LCFS and HRI tradable credits and subsidies play a crucial complementary role beyond regulations.

The discussion surrounding **tradable ZEV credits and ZEV regulations** unveiled a solid need to guide OEMs and offer market-based incentives to introduce diverse ZEV options **(1BDEFH, 2AB, 3ABE, 4ABDEF, 5CEGJ, 6ABCE)**. The interviewees collectively stressed the need to employ ZEV regulations and ZEV tradable credits since they represent the *Carrot and Stick approach.* However, some interviewees observed that current mandates do little for specialized zero-emission OEMs but may enforce minimum compliance from their more diversified counterparts. Moreover, despite the efforts, OEMS delineates the limitations of current regulations, emphasizing the inability to boost FCEV supply due to existing infrastructure constraints in California. The role of ZEV regulations and tradable ZEV credits can be strengthened by the evidence from recent studies that emphasize the fundamental role of these policy instruments in introducing the ZEVs, including FCEVs, into the market in California (McConnell & Leard, 2021). As California's primary instrument to impact the ZEV supply, it was assessed as highly effective in achieving this objective, evidence of which can be found in the study by G. Trencher (2020). Interestingly, other studies demonstrate that the OEMs' response to ZEV regulations and tradable ZEV credit mechanism was positive, as they combined and intensified efforts to increase the innovativeness of the vehicles to meet the restrictive requirements, becoming more value-creating over time, which supported socio-technical change (Wesseling et al., 2015). Additionally, it is worth noting that the same approach to mandating ZEV sales was adopted toward the medium and heavy-duty fleet operators under the Advance Clean Trucks program (the first of its kind program globally). The regulation mandates manufacturers to sell an increasing number of zero-emission heavy-duty trucks (including FCETs). As emphasized by C. Buysse and B. Sharpe (2020), this regulation is expected to significantly lower the lifecycle emission of GHGs and eliminate tailpipe emissions of air pollutants, thereby promoting the market for zero-emission trucks. Given California's substantial share of the freight movement in the United States, this regulation's impact is anticipated to extend well beyond the state's borders. The truck OEMs dominating sales in California also have a presence in multiple global markets. These international companies are likely to spread their research and development costs by adopting similar technology platforms across various regions. Consequently, California's *Advanced Clean Trucks* regulation is projected to hasten the adoption of zero-emission and near zero-emission trucks, including FCETs, across North America and globally.

Based on the interviews conducted with various stakeholders, it is evident that subsidies and other market-based incentives for purchasing FCEVs, i.e., in the form of **CVRP Rebates and HVIP Vouchers**, play a critical role in shaping the FCEV market given the current expensive nature of this technology **(1ABDE, 2H, 3ABD, 4AB, 5BFG, 6BC)**. For instance, *HVIP Vouchers* have been crucial in mitigating the substantial cost differential between zero-emission buses and trucks and their diesel counterparts. The consensus overwhelmingly favors subsidies as an indispensable tool in fostering the FCEV market. The effectiveness of subsidies is noted in driving consumer demand and encouraging infrastructure development, influencing both the supply and demand sides of the market. Given the current cost structures and technological readiness, subsidies are considered the most pragmatic and practical routes to accelerate FCEV adoption and market development. Adding granularity to these findings, it is essential to acknowledge that recent studies demonstrate that usage of CVRP has been different across household income, ethnicity, and ambient air pollution. Initially, the *Clean Vehicle Rebate Project* was extensively used by affluent, educated, predominantly White communities with moderate NO_2 levels, issuing more rebates to them. Introducing an income cap and variable rebate amounts based on income improved equity, making it more progressive. However, disadvantaged, less-educated areas with higher Hispanic and Black populations still received fewer rebates, and overall rebate distribution decreased.

These findings, extracted from the studies conducted by Ju et al. (2020) and A.L. Ku and J.D. Graham (2022), suggest that CVRP program design features like income caps, tiered rebate amounts, broader vehicle eligibility, and enhanced benefits for disadvantaged communities can potentially better distribute rebates among diverse socioeconomic groups in more polluted areas. Interestingly, according to the study conducted by C. Sugihara et al. (2023), even though subsidy programs such as HVIP were highly effective in increasing demand for new or retrofit FCETs (and battery electric trucks simultaneously), this particular program was facing implementation challenges caused by high interest in these incentives – the program has previously run out of funding within 24-hours of approved spending. An insightful study was conducted J. Brito (2022), who identified HVIP as the key inclusive policy instrument for the wide ZEV trucks, including FCET deployment, emphasizing that both large and small fleets can access funding while small fleets registered to addresses in disadvantaged communities are eligible for a 15% voucher enhancement.

Multiple stakeholders **(1BEFH, 2CFH, 3ADG, 4ADE, 5BDF, 6ACD)** emphasized the necessity and benefit of uniform **building standards and safety codes for hydrogen refueling stations.** Standardized protocols and equipment were highlighted as critical for infrastructure success, such as a common nozzle design (*one nozzle to fuel them all* – **4E**). There was agreement that solid standards are crucial in case of accidents, ensuring the safe development of hydrogen fuel stations and gaining public confidence. Regulations help establish a foundation for safety and function. Standards are necessary before pursuing other initiatives like public education or tradable credits. Furthermore, despite being necessary, CEQA requirements and the full review waiver often lead to substantial project delays. Specifically, CEQA can push back a project by up to a year. Noteworthy, conventional permitting procedures require approval from local authorities - *Authorities Having Jurisdiction*, often on a city-by-city or county-by-county basis. This process slows down FCEV infrastructure development considerably. In addition, the interviewees underlined that the longer a project takes due to regulation compliance, the more expensive it becomes. *Time* is a crucial factor in the infrastructure development cost. Geographic and city-specific variables, like existing utility lines, add another layer of complexity to implementing building codes. Multiple sources cited variability in the permitting process depending on local jurisdiction as a significant challenge. In this process, the local fire marshals play a pivotal role by interpreting and implementing codes individually. As noted, the current level of understanding among fire marshals regarding hydrogen safety is considered a bottleneck. Some interviewees explicitly mentioned that the permitting process is time-consuming and financially draining. Developers require expensive lawyers to navigate through the bureaucratic procedural maze. It was also pointed out that local jurisdictions base their permitting processes on existing building standards and safety codes, implying that clear, updated regulations might mitigate some roadblocks. However, an interesting perspective came from the state regulator (CARB), which argued that building a hydrogen refueling station is less time-consuming than the timeline for other energy infrastructures like a 50 MW substation. In summary, hydrogen fueling stations' permitting and regulatory approval process is complex, time-consuming, and can vary significantly between jurisdictions. While some argue that the timeline and financial requirements are excessive, others assert that the development time is reasonable compared to other energy infrastructures. The insights offered by the research participants also reflect and contribute to the results of the previous studies, which underlined the significance of hydrogen stations' reliability for their long-term profitability (Kurtz et al., 2019).

Numerous experts noted the importance of **ZEV purchase requirements for transit buses, airport vehicles, and other public fleets** for FCEV market growth in California **(1AEFH, 2BCH, 4AB, 5FG, 6BCDE), because it** is a strong direct signal of demand. When forced to convert their fleet due to purchase requirements, the transit agencies choose the best available option considering the other incentives. This indicates that purchase requirements are essential in directing agencies toward adopting more efficient and cost-effective ZEV alternatives. Subsidies and incentive programs, such as the already discussed *HVIP program*, are critical for making ZEV affordable for fleets under the purchase requirements, especially for transit buses. *The Innovative Clean Transit Regulation* was particularly noted as a catalyst for transit agencies to start discussing the transition to ZEVs. There is also interest from the trucking and transit bus industry in battery electric and fuel cell technologies, which will be a much more significant driver when the product and infrastructure are in place. To strengthen and further discuss these insights, it is worth acknowledging that *The ICT Regulation* was designed in 2018 to convert California's transit fleet to 100% ZEV by 2040. Until now, as a recent study suggests, California transit agencies have been pioneers in adopting low- and zero-emission buses. However, the COVID-19 pandemic briefly hindered this progress, as transit agencies focused on adapting to new service levels and health requirements, delaying ZEB transition efforts. Nevertheless, the state's shift towards ZEBs positively impacts the economy, job creation, and local air quality. Despite this, official mandatory plans submitted by the transit agencies are to acquire around 8,000 ZEBs over the next two decades, combining BEBs and FCEBs. Interestingly, early adopters have favored BEBs, but concerns about range and infrastructure have caused a shift towards FCEBs, which still depend on individual needs determined by fuel availability, expected operational efficiency of the fleets, access to the advanced power grid, and the funding availability (Jeffers et al., 2022).

The following discussed policy instrument was the **ZEV Infrastructure Support and Hydrogen Fuelling Station Evaluation**, perceived as less impactful for the FCEV market growth and precisely infrastructure development **(1BEH, 2H, 3G, 4ADE, 6C)** but still contributing to this process that involves criteria like optimal locations, which are determined in collaboration with the CARB and OEMs. Station placements leverage demographic data and driving behaviors to maximize efficacy. On the topic of information policy, opinions diverge. While some interviewees insisted on the importance of information policy for public education and combating misinformation, others argued that it is less impactful, contending that information is already freely available in the industry thanks to close cross-sector partnerships. The role of information policy in enhancing public understanding of station usage was also noted, along with community resistance and safety concerns originating in a need to dispel public fears rooted in historical events like the Hindenburg disaster and the San Bruno incident, as well as misconceptions equating hydrogen with natural gas. The significance of the ZEV infrastructure support, in the form of the *Hydrogen Station Permitting Guidebook* or consultations offered by the *California Governor's Office of Business and Economic Development*, was also emphasized by J. Kurtz et al. (2019), who identified it as one of the examples of highly contributive action to disseminate information to builders and investors about hydrogen station construction, codes, and best practices in this domain. Among other examples, D. Greene et al. (2020) underline the role of *The California Hydrogen Infrastructure Tool* (the already mentioned geospatial-functional analytical model), which allows for making informed decisions about siting hydrogen stations.

In analyzing the effectiveness and impact of **tax exemptions** on the FCEV market development, several institutions, companies, and stakeholders offered their critical perspectives **(1FH, 2A, 4A, 6C)**. While tax credits exist, their efficacy is questioned – some interviewees pointed out that federal production tax credits do not even cover the federal excise tax. This sentiment is echoed by transit agencies, emphasizing that the current tax credits for buses have a diminished impact on smaller transit agencies. Furthermore, direct subsidies may be more effective than tax credits and cast doubt on the value of tradable credits under the Advanced Clean Trucks rule. Given the high replacement costs, the interviewees addressed the specific needs of transit buses and underscored the potential transformative role targeted tax incentives can play. CARB pushes for tax exemptions, especially for Class 8 commercial trucks, which are already considerably more expensive than their diesel counterparts. Finally, one of the interviewees adds complexity to the discourse by highlighting that tax credits and exemptions are not universally applicable or beneficial; some entities, like fleet operators, may find direct subsidies more practical. The recurring themes focus on the inadequacy of current tax structures and incentives and the need for targeted, possibly multipronged, financial solutions to catalyze the FCEV market in California.

The last synthesized analysis of interviews **(1EF, 2BH, 3H, 4BCE, 5BE, 6AC)** revolved around the competitive advantage of **ZEV Weight Exemptions** on FCEV and the varying perspectives on the impact of **access to HOV and HOT Lanes** on FCEV market development. Some stakeholders affirm the significant edge *ZEV Weight Exemptions* provide FCEVs, especially against BEVs and diesel vehicles in the medium-heavy duty segment. Others further stress the need for explicit regulations around these exemptions. However, transit agencies offer a caveat, cautioning that such exemptions could strain local infrastructure due to increased road maintenance costs. On the other hand, the impact of HOV lane access draws a more diversified range of opinions. While industrial organizations see it as a valuable proposition for California's urban users, other stakeholders argue that it is either insignificant or a diminishing incentive. Finally, it is noted that both *ZEV Weight Exemptions* and HOV lane access are supplementary and less impactful than financial incentives like subsidies and tax credits in promoting FCEV market growth. Overall, while there is a consensus on the benefit of weight exemptions that compensate for the weight of ZEV power units, opinions on HOV lane access are distinctly polarized, suggesting that a *one-size-fits-all* policy may not effectively address the diverse needs and concerns of the various stakeholders involved, especially in the context of the expected growth of the number of the vehicles with the access to those lanes.

4.2.3. Recommendations for changes in selected green industrial policy assumptions and instruments for the establishment and development of the FCEV market in the state of California in the opinion of interviewees

In this section, the author discusses the alternative pathways in the past, indicating what California could have done differently, following the retrospective approach in the analysis (Appendix H). In the latter part of the subchapter, the author studies the prospective policy reforms, thus providing an overview of the potential adjustments in California's existing green industrial policy setting to enhance its impact and effectiveness on the FCEV market development (Appendix I).

Retrospective approach to policy reforms – Appendix H

First, in pursuing advancing FCEVs in California, a range of stakeholders unanimously emphasize the pivotal role of **early and adequate infrastructure development - ahead of incentivizing FCEV purchases** **(1CH, 2BE, 4AD, 5C, 6E)**. The interviewees stress that limited refueling infrastructure has been a critical stumbling block, dampening consumer enthusiasm and slowing vehicle adoption rates. OEMs highlighted a paradoxical situation where the absence of initial infrastructure stymies the commercial availability of FCEVs. Aligning with this, the industrial organizations underscored the dissatisfaction among current FCEV users due to inadequate fueling stations in strategic locations, particularly along key corridors and populous areas like the Bay Area and Los Angeles. This sentiment is reiterated by station operators and fuel providers, who point out the mistake of simultaneous deployment of vehicles and infrastructure, resulting in many dissatisfied customers. The state agencies similarly advise better planning, emphasizing the need for supply chain redundancies to ensure a smoother FCEV market launch. Furthermore, the interviewees advocated for prioritizing infrastructure development ahead of vehicle incentivization, a viewpoint echoed by transit agencies and industrial organizations. In summary, a more coordinated and phased approach focused on first establishing a robust fueling infrastructure could have more effectively catalyzed the adoption and satisfaction rates of FCEVs in California.

Next, the interviewees discussed an **alternative approach to stimulating the demand side of the FCEV market** **(2BCE, 3H, 4F, 5CH, 6ACEF)**. First, there is a significant focus on timing and regulation alignment. Interviewees from transit agencies argued that earlier enforcement of CARB regulations could have catalyzed the market if technology had been mature enough. However, some interviewees cautioned that there were instances where policy outpaced technological readiness, thereby pushing immature technologies into the marketplace. The second central theme was the need to focus on heavy-duty vehicles. It was suggested that the simultaneous development of heavy-duty and light-duty FCEVs could have been a game-changer, leading to more efficient infrastructure and significant environmental impact. Regarding financial aspects, the interviewees emphasized the need for large-scale funding, with transit agencies explicitly arguing for a dedicated funding source for zero-emission public transit at a much earlier stage. Infrastructure development emerged as another crucial area. State agencies advocated for a proactive approach that prioritizes infrastructure ahead of vehicle deployment, leveraging public-private partnerships for station installations. Multiple stakeholders also noticed the lack of focus on infrastructure for heavy-duty FCEVs. Some interviewees cited public and industry engagement in educational programs, demonstrations, and large-scale pilot projects. Furthermore, the need for realistic assessments and data-driven policies was stressed. The stakeholders criticized the presence of unverified claims about FCEVs that have misled policymakers. Lastly, a holistic view should have needed to be adopted. In summary, California's approach to incentivizing FCEVs could have been more effective through earlier and more aligned regulations, a targeted focus on heavy-duty vehicles, secured large-scale funding for fleets, proactive infrastructure development, robust public and industry engagement, data-driven policies, and a comprehensive, inter-sectoral approach.

In light of California's efforts to shape the **FCEV market supply side**, a synthesis of different stakeholders' opinions reveals various strategies that could have been employed to optimize the policy assumptions and objectives **(3G, 4BF, 5AJ)**. Advocates from academia and industrial organizations have emphasized the necessity of specifying a portion of ZEVs to be FCEVs, suggesting a carve-out in *ZEV Regulation*, which would have not only sent a strong signal supporting FCEV development but also balanced the otherwise disproportionate focus on electric vehicles. Additionally, leveraging *ZEV tradable credits* and implementing a hydrogen production tax credit could have accommodated varying manufacturer capabilities and offset hydrogen production costs, thereby creating a more flexible and inclusive market. However, some noted that California's limited resources constrained its ability to offer more effective incentives, relying mainly on ZEV credits and Renewable Identification Numbers. Infrastructure development was a significant concern for fuel providers, who pointed out the substantial costs and logistical challenges associated with building fueling stations and storage facilities while also underlining the insufficiency of initial capital grants from the state to cover ongoing operational costs due to insufficient demand. Moreover, industrial organizations highlighted the difficulty in transitioning from prototype to mass production or crossing the valley of death at an initial R&D stage. It stressed that any incentivization strategy should aim to make FCEVs self-sustaining in the market without ongoing subsidies. Lastly, industrial organizations argued for incentives and policies based on precise market signals, cost-benefit, and performance metrics to encourage higher deployment of FCEVs in the long run. In conclusion, the interviews indicate a consensus on the importance of FCEV-specific carve-outs in ZEV mandates, flexible market tools, and tradable credits. However, they also acknowledge the constraints on available resources and tools, highlighting the necessity for effective infrastructure development and performance-based incentives.

The development of the FCEV market and **hydrogen fuel production and supply** in California has been subject to multiple policy gaps and delays, impacting the interest and investment in the sector **(1BE, 3FG, 4E, 5CDGJ, 6AB)**. First, the lack of an LCFS HRI capacity credit generation initially resulted in disinterest among station developers. The absence of HRI capacity credits at the onset was also identified as a significant oversight that could have otherwise accelerated infrastructure development and reassured investors. On the hydrogen fuel supply side, interviewees emphasized the importance of regulations and subsidies for hydrogen generation and delivery pipelines. Insufficient funding mechanisms were another critical issue. Fuel providers highlighted the inadequacy of existing grants for establishing production facilities. At the same time, state agencies pointed to the general lack of knowledge in the investment community, making it challenging for station developers to secure the necessary capital. Multiple stakeholders noted that programs like the Low Carbon Fuel Standards and HRI capacity credits could have been introduced earlier to catalyze development. Market fluctuations have also been a concern. Fuel providers indicated that the influx of cheaper biofuels had impacted the financial feasibility of hydrogen production due to a significant decrease in LCFS credit value. State agencies mentioned that clean hydrogen infrastructure should have been a focal point much earlier to mitigate supply disruptions. Finally, a need for a more holistic approach was suggested, which proposed an open-source hydrogen pipeline. CARB also indicated that diversified financial mechanisms, like loan guarantees, could be instrumental in incentivizing the hydrogen economy.

While retrospectively reviewing the California green industrial policy assumptions, objectives, and structure of policy instruments, we encouraged the interviewees to define

new (alternative) policy instruments that could have been implemented in the past to make the California policy more effective (1ACDH, 2CH, 4CDF, 5EGH, 6AB). Interviewees emphasized the importance of creating regionally-based incentives, suggesting that dedicated corridors along the I-5, I-10, and I-15 could help co-locate fueling stations and other hydrogen projects. Another interviewee suggested sitting refueling stations in pairs to sustain their operability even if one is down due to any malefactions or lack of fuel. OEMs discussed the challenges in the permitting process and stressed that easing this would financially benefit landowners willing to install hydrogen infrastructure. The state regulators mentioned that outreach and guidance for local agencies were needed to improve the permitting process for hydrogen station developments at an earlier stage. Transit agencies highlighted the cost challenges in purchasing hydrogen fuel cell buses compared to conventional options, calling for more robust funding mechanisms to bridge the financial gap. One of them specifically suggested that the state should conduct a bulk procurement for fuel cell vehicles, which could drive down costs and attract more FCEV suppliers. They further recommended collective procurement efforts to reduce administrative burdens on both suppliers and individual agencies. Fuel suppliers also called for a more sustainable policy over time instead of one-time grants. Interestingly, some interviewees proposed that the government could serve as an early adopter to drive the market, specifically mentioning the conversion of postal service fleets as a potential large-scale deployment. The industrial organizations pointed out that the heavy-duty FCEVs did not benefit from existing mobility solutions like access to HOV lanes and suggested that incentives like creating a *Clean Trucks Lane* at the Otay Mesa border crossing with Mexico could save fleets time and encourage broad adoption.

Prospective approach to policy reforms – Appendix I

Second of all, the author will discuss future policy reforms, indicating what California should change, following the prospective approach in the analysis. After discussing the alternative pathways in the past, the following deliberations will be focused on the prospective approach by focusing on **future policy reforms** expressed during the interviews. First, interviewees highlighted crucial insights regarding the **incentives for the potential increase in FCEV demand in California (1BCDFH, 2AC, 3G, 4A, 5H, 6CEF)**. One of the paramount identified obstacles is the public's misconception about hydrogen safety, which hinders market penetration and creates regulatory restrictions. To mitigate this, California should spearhead educational campaigns to correct these misunderstandings and revise outdated regulations.

Financial viability is another significant concern. According to OEMs, the current practice of providing free prepaid hydrogen fuel cards for light-duty vehicles poses a $15,000 *penalty* per vehicle, making it less cost-effective for manufacturers. Concurrently, others suggest that the Federal Excise Tax disproportionately burdens FCEV costs and advocates for tax reforms, including sales tax exemptions. These insights necessitate a comprehensive re-evaluation of existing fiscal policies affecting FCEVs. On the incentives and subsidies front, stakeholders advocate for maintaining or increasing existing financial incentives like HVIP and expanding them to include supply chain components (mainly fuel cell modules). Adjustments for inflation, as proposed by transit agencies, should also be incorporated into these incentives. Additionally, there is a call for a balanced weight exemption policy, particularly for heavy-duty FCEVs, or even increase the exemption to 3000 pounds (thus benefiting mainly FCEVs and making an insignificant difference for BEVs). The consumer focus and education sector is another domain requiring urgent attention. Lastly, challenges related to supply chain and scale were highlighted. Interviewees stressed the need for economies of scale in vehicle numbers and component manufacturing. OEMs also pointed out the geographic limitations due to insufficient inter-state travel infrastructure. In summary, California should consider a multipronged FCEV market development approach involving educational campaigns, financial re-evaluations, recalibrated incentives, and infrastructure development. Tax reforms, including adjustments for the Federal Excise Tax, sales tax, and specialized incentives for private trucking operators, are essential for ensuring a level playing field for FCEVs in the competitive ZEV markets.

The need for policy to **remain technology-neutral or agnostic** was a significant theme that permeated the interviews **(3AFG, 4CEF, 5C, 6BC)**. They stressed that policymakers should not solely favor BEVs over FCEVs or other technologies. OEMs argued that such a focus would be short-sighted, especially when the aim is for total ZEV market coverage - *policy should focus on objectives rather than prescribing solutions.* OEMs highlighted that policies should aim for technology parity and assess funding somewhat over time. Interviewees from academia stated that despite federal support and California's initiatives, current policies are insufficient for full decarbonization by 2045. They suggested doubling down on the current policy framework and factoring in health and quality-of-life impacts, which are not currently accounted for in programs. Other interviewees also emphasized the need for policy to create certainty for private investors. Interestingly, several interviewees mentioned that as the FCEV market matures, the policy may need to become more selective in the technologies it supports, thus breaking the rule of a technology-neutral approach. Interviewees stressed that the state is still in the stage where various low-carbon technologies need to grow, but a narrowing might be necessary.

Multiple interviewees mentioned **Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) as a hydrogen hub initiative**, standing at the forefront of California's FCEV market development, serving as a multi-stakeholder platform actively supported by the Governor's Office and the US Department of Energy **(3AFG, 4CEF, 5C, 6BC)**. The Universities of California, alongside two associated national labs, are taking a leadership role in ARCHES, emphasizing the importance of public-private collaboration. However, challenges such as slow technology adoption highlighted by the industrial organizations and the need for geographical inclusion, especially in Southern California, indicate that policy measures need refinement. For future policy reform, California should focus on a multipronged approach that addresses the needs of diverse stakeholders involved, including universities, regulatory bodies, and industry entities. First, the state should increase long-term infrastructure funding and incentivize private investment to make hydrogen technology economically competitive. Second, public-private partnerships should be encouraged to share knowledge and coordinate with pre-existing initiatives like the Hydrogen Council and Fuel Cell Partnership. Third, a focus on commercialization pathways, particularly for fuel-cell trucks, is essential to address the primary interests of fleets in freight movement. Lastly, there should be a focus on cost competitiveness with fossil fuels to achieve both economic viability and zero-emission goals. This comprehensive approach could help California create a more robust and equitable FCEV market, fulfilling the promise of ARCHES as a hydrogen hub initiative for hydrogen technology adoption.

In light of **emerging federal initiatives**, California should undertake several challenges that emerge from the opinions of the FCEV market participants and stakeholders **(1F, 3A, 4BF, 5ABCEG, 6CFG)**. First, with the launch of federal programs such as the *Hydrogen Shot initiative* and the **US Department of Energy's hydrogen hubs**, significant federal funding is being allocated for hydrogen production and infrastructure. California should harmonize its policies with these federal programs and leverage them, particularly the **Inflation Reduction Act** and the **Infrastructure Act of 2021**, to maximize funding and possibly alleviate the state's financial burden for developing hydrogen infrastructure. Second, the state should reassess its existing policies, especially infrastructure grants, in light of new federal incentives. The repercussions and game-changing nature of these programs are perceived even as a reason to implement *a clean sheet of paper* approach. This re-evaluation should be geared toward achieving a balanced funding model for fuel, infrastructure, and vehicle incentives. Third, recognizing that tax subsidies may not be the most effective means to incentivize nonprofits and municipalities, the state should consider implementing direct payments from the U.S. Treasury for these stakeholders. Additionally, as the cost of hydrogen fuel is expected to decrease, and federal initiatives are covering production and infrastructure, California should shift its focus toward stimulating demand for FCEVs, particularly heavy-duty trucks, in alignment with state-specific requirements. Fourth, hydrogen's potential can be further realized by lobbying for its inclusion in federal Renewable Identification Number Programs (RINs), thereby opening up additional revenue streams and incentives for hydrogen production. Alongside, California should explore state-specific Production Tax Credits (PTCs) to harness hydrogen’s high energy density and attract investments in clean hydrogen production. Finally, to bridge the gap to commercialization, state-funded large-scale pilot projects, specifically designed for fuel-cell trucks, are essential and could be developed in collaboration with state agencies like CARB.

In light of **the LCFS model's challenges and potential reforms**, there is a pressing need for a holistic re-evaluation and strategic realignment in California's FCEV market development policies **(1D, 3H, 4DE, 5E, 5HJ, 6BEF).** Firstly, OEMs and fuel providers highlight the unsustainability and misalignment of the current LCFS system, urging both the state and suppliers to make the system more congruent with its intended goals. Moreover, interviewees expressed concerns over the market volatility created by an influx of biofuels, destabilizing LCFS credit values and consequently inflating hydrogen prices. This issue warrants cautious intervention by the CARB, which has been reluctant to meddle in carbon trade markets. Regarding *clean* hydrogen, academia advocates for incentives akin to the renewable portfolio standard for electricity, as well as policy mechanisms to stabilize refueling costs. As for future policy reforms, interviewees suggest better adjusting LCFS targets to balance fuel supply and demand. A theme closely related to LCFS reforms is the need to **stabilize the hydrogen fuel prices** expressed in multiple interviews **(1BD, 2EFH, 4C, 5E, 6BCDF).** Major stakeholders further contextualize this by highlighting the industry's dependence on volatile natural gas markets and the fluctuating value of LCFS credits. State regulators stress that hydrogen's cost-per-mile needs to reach parity with conventional fuels for the FCEV market to be self-sustaining. Regarding infrastructure, interviewees also underline the critical necessity for reliable and cost-effective fueling stations.

Given the converging concerns, several policy reforms are needed. First, price regulation and subsidies should be on the table, although care must be taken not to distort market forces. Second, state and federal regulators suggest that investment priorities should shift from capital costs to operational aspects like hydrogen production and distribution. CARB specifically calls for long-term price stabilization mechanisms to offer certainty to producers and consumers alike, which could encourage market participation from fleet owners and households. Other interviewees' emphasis on reducing dependence on volatile natural gas markets signals a need for more research and development grants for sustainable and low-carbon hydrogen production. Government-backed infrastructure expansion and standardization initiatives could mitigate concerns. Finally, suppose market dynamics fail to spur FCEV adoption. In that case, the US DOE suggests regulatory mandates in specific sectors like long-haul trucking could be a last-resort measure. At the same time, CARB advocates for consumer incentives like free fueling cards to lessen initial cost burdens.

Based on the articulated concerns by selected stakeholders **(1BCD, 4AE, 5G)**, California faces significant **gaps in FCEV market development and refueling infrastructure**. One of the most pressing issues is the lagging pace of hydrogen fueling station deployment, with Hyundai and Honda noting that the state has failed to meet even its modest past goals. Such infrastructural shortfalls not only hinder market growth but also exacerbate issues of station reliability. There is a consensus on the necessity for coordinated growth, aligning station deployment with increases in vehicle numbers, to fulfill the more ambitious aim of establishing 1,000 stations that could potentially service millions of FCEVs. The criticality of financial incentives is another unanimous viewpoint, albeit with disagreement on the existing fund allocation. Interviewees criticize the state agencies for a funding disparity that favors BEV charging stations. OEMs suggest tying financial incentives directly to infrastructure development, potentially resolving the funding inequity. In addition to financial issues, there is a recognized need for educational campaigns to address misconceptions and increase consumer awareness about FCEVs and hydrogen fueling stations (to deal with not-in-my-backyardism). For example, interviewees emphasize the educational role of visible and reliable stations, making them live tools for public education. Lastly, interviewees draw attention to specialized fleet programs and the higher throughput benefits of hydrogen stations, respectively. Such focused programs and advantages could be leveraged to accelerate both infrastructure and vehicle adoption rates.

4.2.4. Synthesis of the empirical research results and normative postulates for less prosperous jurisdictions

Several pivotal insights emerge from evaluating the California green industrial policy for the FCEV market development. Firstly, a technology-neutral policy approach is imperative, acknowledging that both FCEVs and BEVs possess unique advantages. This ensures a diversity of choices and encourages market participants to select technologies that best fit their individual, likely diverse needs. A synergy relationship across market segments is evident: as FCEBs and MD-HD FCETs bolster hydrogen fuel demand, subsequently reducing its price, an uptick in light-duty FCEVs promises to decrease the costs of fuel cell stacks. Policymaking should consistently exhibit commitment, combining political signals with financial incentives and clear regulations, increasing confidence among FCEV market stakeholders. Central to the success of FCEV adoption is the early incentivization of hydrogen refueling station infrastructure, a move that would persuade fleet operators to consider and possibly transition to FCEVs. Ensuring financial viability for early adopters through mechanisms like subsidies is pivotal to bridging the chasm often referred to as the *valley of death*, ensuring long-term profitability. The scalability of FCEVs, especially within transit buses and long-haul freight, is a promising avenue for future research and deployment projects. A streamlined, standardized, and safety-conscious approach to refueling station permitting will expedite development, offering clarity to stakeholders. Tradable credits, such as ZEV credits and LCFS with HRI capacity crediting, present lucrative market incentives during the early stages of market development. Collaborative efforts, underpinned by institutional and industrial public-private cooperation, promise to enhance policymaking efficacy, ensuring that policies resonate with stakeholder needs. Ultimately, the evolution of the FCEV market is intertwined with establishing a robust hydrogen ecosystem characterized by stable supply chains, favorable political climates, innovation, and efficient market mechanisms. Building regional hydrogen hubs will further catalyze the growth of both hydrogen fuel and FCEVs in California. By embracing these lessons from California's experience, less prosperous jurisdictions in that domain can create a conducive environment for FCEV market development, fostering sustainable transportation and contributing to FCEV market establishment and development.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This dissertation has systematically explored the impact of selected green industrial policy instruments on establishing and developing the FCEV market in the US state of California from 1990 to 2022. The research, guided by normative postulates of the economics of sustainable development, presented a comprehensive understanding of the dynamics shaping the FCEV market, with implications for policymakers, market participants, stakeholders, and academic researchers. The study addressed the four detailed research objectives and answered corresponding detailed research questions, spanning theoretical explorations and empirical analyses, and reflected in the four subsequent chapters of this dissertation.

The dissertation began by establishing a theoretical foundation, linking the assumptions of green industrial policy with the normative postulates of the economics of sustainable development. The first chapter provided a critical overview of the evolution and problem domains within this economic theory, a consequent evolution of neoclassical economics and environmental economics, paving the way for an informed discussion on policy implementation. It can be stated that green industrial policy became a new environmentally-oriented paradigm in industrial policy-making. Therefore, in the context of structural changes, green industrial policy is a multi-dimensional approach to tackling market failures beyond traditional market-based industrial policy instruments. It navigates complex uncertainties and long-term horizons in socio-economic systems, embracing innovative instruments like feed-in tariffs, emission trading systems, or tradable permits. The green industrial policy is instrumental in breaking path dependencies and carbon lock-in effects and fostering advanced low-carbon technologies that contribute to and shape energy transitions. Simultaneously, it challenges entrenched, environmentally harmful industries, promoting a structural horizontal shift through a strategic mix of incentives and disincentives. This comprehensive strategy is crucial in addressing stranded assets and reducing carbon emissions, positioning itself as an indispensable tool for guiding economies toward sustainable development. At the same time, the economics of sustainable development can provide a detailed analytical framework for further developing theoretical foundations and operationalizing the concept of sustainable development in economic sciences.

However, the author identified discrepancies between the studied theory and the green industrial policy approach. In this context, it can be concluded that green industrial policy, while a significant component of sectoral strategies, is not a panacea for all challenges identified in the economics of sustainable development. It represents a focused approach, impacting specific sectors or industries horizontally or sectorally. Nevertheless, it serves as a crucial framework for transitioning towards more sustainable industrial practices, aligning with the principles of this evolving theory. This is exemplified in applying green industrial policy in promoting hydrogen-powered fuel cell electric vehicles. Such a policy fits within the theoretical constructs and catalyzes a shift towards a hydrogen economy and a market for zero-emission vehicles, details of which were elaborated in subsequent chapters of this dissertation.

The investigation then transitioned to demonstrating a hydrogen economy concept that opened the second chapter. Hydrogen, as a secondary energy source with specific characteristics that pose numerous opportunities and risks, may soon become one of the dominant energy carriers. However, it requires a comprehensive value chain encompassing hydrogen production, transportation, storage, and final usage. In this context, the author demonstrated the significance of the FCEV market establishment and development in developing its value chain, broadened by emphasizing the synergy between market growth and normative postulates of the economics of sustainable development. Comparative analyses between FCEVs and other ZEVs underscored the unique potential of FCEVs in this domain by highlighting the more extended range, shorter refueling times, and higher operational efficiency of fleets where these vehicles are deployed (in contrast to the BEVs). At the same time, the author identified the main barriers to spurring FCEV market development, which he framed in a conceptualized FCEV deployment trilemma. As a response to the need to overcome the market development barriers, the green industrial policy approach is proposed and further elaborated based on the example of the US state of California.

In the third chapter, the study provided a detailed account of the green industrial policy instruments implemented in California both at the federal and state levels, with the consideration of the federal waiver that granted this state a unique independence in shaping its standards of the GHG emissions from transportation. The overview of the evolution of the green industrial policy approach in the context of policies for the FCEV market establishment and development provided a detailed analytical framework by identifying the main instruments and assumptions set out in 1990 – 2022 (with the consideration of the policy acts adopted between 1967 and 1990). The author also identified the four strategic policy objectives in this domain, which included the sustainable and low-cost supply of hydrogen fuel, developing accessible and reliable refueling infrastructure, as well as increasing FCEV market supply and demand. This policy analysis was followed by the FCEV market's structural evolution across three market segments – passenger LD-FCEV, FCEB, and FCET. It highlighted the pivotal role of numerous OEMs, such as Toyota, Hyundai, Nikola Motor Company, Hyzon Motors, and New Flyer, as well as described the categories of individual, commercial, and institutional consumers. In addition, the author demonstrated the advancements of the hydrogen refueling infrastructure and identified the main FCEV market stakeholders, including academic and research entities, governmental and regulatory bodies, and industrial organizations and associations. This overview provided a piece of comprehensive information about the structure of this market, its evolutions, and its status at the end of 2022, which was marked as the end of the studied period.

Finally, the dissertation culminated in the fourth chapter, which demonstrated a detailed evaluation of the effectiveness and impact of selected state green industrial policy instruments on the FCEV market establishment and development. It offered critical insights into the successes, shortcomings, and potential improvements while extending observations and suggestions for other jurisdictions inspired by California's pioneering efforts. These insights were possible thanks to 46 structured interviews with selected FCEV market participants and stakeholders. First, the author identified the crucial role of the Low-Carbon Fuel Standard, which exemplifies a tradable CO_2 emission permit mechanism introduced to stimulate the reduction of GHG emissions from transportation fuels. Significantly, this mechanism, in the opinion of the interviewees, effectively increased the supply of clean hydrogen, thanks to offering additional LCFS credits in case of refueling stations that offer the high installed capacity of the hydrogen storage tanks (even though they do not sell enough fuel to sustain its operation on market basis). Secondly, the author identified the fundamental role of grants for constructing hydrogen refueling stations alongside an array of necessary regulations and safety standards and practically useful tools, such as permitting guidebooks, consultations offices, and geospatial analytical tools, which can serve as a source of recommendations for setting the locations for future stations based on the existing shortages. Based on the interviewees' opinions, the author developed detailed suggestions of how the policy could have been implemented in the past and what should be done in the future to improve its effectiveness. Based on this, the author developed general observations, which might be useful for other jurisdictions considering introducing their likely different policy approaches to establishing and developing the FCEV market development.

RQ	Research questions	Research findings (synthesis)
RQ 1.	What are the origins, problem domains, and normative postulates of the economics of sustainable development?	The research established that the economics of sustainable development consequently evolved from neoclassical and environmental economics. This economic theory provides normative postulates that can be perceived as a guiding theoretical framework for informed policy-making focused on addressing this theory's economic, socio-cultural, and environmental problem domains.
RQ 2.	How can industrial policy be implemented considering the normative postulates of the economics of sustainable development?	The research demonstrated that green industrial policy has become a new paradigm in industrial policy-making, providing a broad portfolio of instruments, such as feed-in tariffs or tradable CO_2 emission permits. However, while green industrial policy is not a complete solution for sustainable development, it offers a set of instruments for transitioning industries towards sustainability, aligning with the theory's principles and aiding in adopting innovations like hydrogen-powered FCEVs.
RQ 3.	How does the FCEV market's establishment and development contribute to developing a hydrogen economy?	The research demonstrated that establishing and developing the FCEV market contributes to a hydrogen economy by developing its comprehensive value chain, highlighting FCEVs' unique potential in terms of range, refueling times, and operational efficiency. In addition, the author conceptualized the FCEV deployment trilemma, which can be overcome by implementing the green industrial policy, therefore contributing to the hydrogen economy development.
RQ 4.	How does establishing and developing the FCEV market fit into the normative postulates of the economics of sustainable development?	The research aligned the establishment and development of the FCEV market with the normative postulates of the economics of sustainable development by emphasizing the synergy between market growth and the theory’s principles in addressing the main problem domains.
RQ 5.	What green industrial policy instruments were implemented at the state and federal levels to establish and develop California's FCEV market between 1990 and 2022?	The research outlined and cataloged the green industrial policy instruments implemented in California at both the state and federal levels from 1990 to 2022, focusing on policies that shaped FCEV market establishment and development. In addition, the author demonstrated the pre-1990 policy acts that laid the foundation for future green industrial policies.
RQ 6.	How did the structure of the FCEV market in the state of California evolve between 1990 and 2022?	The research traced the structural evolution of California's FCEV market from 1990 to 2022, detailing the growth across three market segments (passenger FCEV, FCEB, FCET) and highlighting the contributions of crucial market participants on the FCEV market supply and demand side.
RQ 7.	What stakeholders contributed to the establishment and development of the FCEV market in the state of California between 1990 and 2022?	The research identified and cataloged the main stakeholders in developing California's FCEV market between 1990 and 2022, including academic and research entities, governmental and regulatory bodies, and industrial organizations and associations.
RQ 8.	Why has the state of California been supporting FCEV market establishment and development, even though the other zero-emission vehicles (ZEV), such as BEVs, have seen higher deployment numbers?	The research showed that California supported the FCEV market establishment and development based on the political, socio-economic, and technological arguments, as identified by the 46 research participants (Appendix D, E, F). These arguments encompassed diverse perspectives, with environmental considerations, the technology-neutral policy approach, FCEVs’ unique technological features, and the observation that none of the available ZEV options is a one-size-fits-all solution to decarbonize the transportation sector individually.
RQ 9.	Which selected green industrial policy instruments were the most effective in establishing and developing the FCEVs market in the state	The most effective instruments were the tradable CO2 emission permit mechanism (LCFS), grants for constructing hydrogen refueling stations, and regulatory frameworks, which collectively boosted the supply of clean hydrogen, infrastructure development, and the supply and demand for FCEV in the studied state, therefore spurring the market development. However, the effectiveness and the impact of the

	of California between 1990 and 2022?	selected green industrial policy instruments vary across individual groups of FCEV market participants and stakeholders, adding granularity to the research results, as outlined in Appendix G.
RQ 10.	Looking back in the past on the design and implementation of the selected green industrial policy instruments, what could have been done differently to accelerate the establishment and development of the FCEV market in California?	Based on the expert perspectives of the interviewees, the author suggested that earlier implementation of HRI LCFS tradable CO_2 emission permits and detailed recommendations, including practical tools like permitting guidebooks and geospatial analyses for station locations, could have accelerated FCEV market development. Using the retrospective approach, the author proposed diverse policy reforms, which could have been implemented in the past, as outlined in Appendix H.
RQ 11.	Should there be any future corrections in the assumptions, objectives, and design of the selected green industrial policy instruments implemented in the state of California for the further development of the FCEV market?	The dissertation recommends future enhancements in the policy's assumptions, objectives, and design, focusing on increasing effectiveness based on past experiences and insights gathered from the FCEV market participants and stakeholders (Appendix I). The author developed several future policy reforms, including the balance between FCEV and BEV support, a higher number and density of hydrogen refueling stations, especially for the FCEBs and FCETs, and increased ZEV weight exemption up to 3000 lbs. These suggested reforms revolve around enhancing the synergetic effect across FCEV market segments and exploring new opportunities, such as establishing the ARCHES hydrogen hub and federal instruments introduced by the IRA for hydrogen production, such as the production tax credits.
RQ 12.	What less-prosperous jurisdictions can learn from the experience of the state of California in establishing and developing the FCEV market?	Less-prosperous jurisdictions can learn from California's pioneering approach, especially in terms of a balanced mix of regulatory measures, financial incentives, and practical implementation tools for fostering FCEV market establishment and development. Studying the case of California can serve as a crucial benchmark that offers observations for less-prosperous jurisdictions, which may adjust their policies to internal FCEV market development barriers and determinants.

Table 11. The summary of the synthetized research results and their relevance to the research questions (RQ). Source: Own elaboration.

Limitations of the study

While this study has made some of the mentioned contributions, it is worth acknowledging some unavoidable limitations. Firstly, its scope is narrowly centered on green industrial policy in the context of the FCEV market, limiting its applicability to other sectors and broader sustainable development challenges. Besides, the economics of sustainable development is a considerably newly established economic theory that lacks international recognition and requires further conceptualization and operationalization based on the proposed normative postulates. Additionally, the study reveals a discrepancy between theoretical constructs and practical implementation of green industrial policy, potentially affecting real-world applicability. Spatially, the research is primarily scoped on the US state of California, which may not accurately reflect the diversity of global contexts. Temporally, the research is confined to developments from 1990 until the end of 2022, omitting subsequent advancements caused, i.e., by the ARCHES hydrogen hub establishment or IRA hydrogen production tax credit implementation. The complexity of the FCEV market and hydrogen economy may not be fully captured, possibly leading to oversimplifications, especially given the unique characteristics of hydrogen as an energy carrier and the relatively low technology readiness level of the associated solutions. The reliance on the 46 interviews with selected market participants and stakeholders could introduce biases, limiting the range of perspectives, even though the research participants' structure was purposefully diversified to enrich the final outcomes. The emphasis on policy effectiveness evaluation may overlook other influential factors like market forces, global economic trends, or technological advancements. Finally, the research methods and data sources used, especially in policy impact and effectiveness analysis, have inherent limitations that could impact the study's conclusions. Nevertheless, the author believes the demonstrated study has significant implications worth further presentation.

The implications of the study

The findings of this dissertation have several theoretical, empirical, and methodological implications. The dissertation has ***theoretical implications*** as it enhances the theoretical understanding of green industrial policy as a new paradigm in industrial policymaking intertwined with the economics of sustainable development. The author’s deliberations focused on this economic theory as this theory bridges the gap between neoclassical economics, environmental economics, and sustainable development, providing a comprehensive theoretical framework. The demonstrated dissertation contributes to further operationalizing the sustainable development concept within economic theories, particularly in the context of industrial policies, by deliberating on the significance of adopting the green industrial policy approach to meeting the normative postulates of the economics of sustainable development. The study also underscores the multi-dimensional nature of green industrial policy, emphasizing its role in addressing market failures and navigating uncertainties in socio-economic systems. The research highlights the importance of green industrial policy in overcoming carbon lock-in effects and fostering innovation growth of low-carbon technologies, thus contributing to the theoretical understanding of the low-carbon energy transition process. Furthermore, the author conceptualized the *FCEV deployment trilemma*, which can be further debated and studied as a theoretical and analytical framework for the studies revolving around the FCEV market development barriers and measures aimed at overcoming them.

The dissertation can be a source of ***empirical implications***. The dissertation empirically explores the hydrogen economy concept, mainly focusing on FCEV market establishment and development, providing evidence-based insights. It presents an in-depth analysis of green industrial policy instruments in California, offering empirical evidence of their diverse effectiveness and impact. The research also documents the FCEV market's structural evolution and the development of related policies from 1990 to 2022. The diverse effectiveness and impact of green industrial policy instruments in California underscores the need for a nuanced and context-sensitive approach in policy design, especially considering the technology-neutral policy approach since it is too early to pick the winners of the highly competitive technological competition between different ZEV options. Future policy adjustments should consider emerging market trends and technological advancements, especially in the context of FCEB and FCET, as those segments are growing dynamically. Besides, the growth of the FCEV market in California illustrates the practical application of the green industrial policy approach within the automotive industry and could be applicable in related markets. The research results emphasize the importance of holistic strategies that balance economic growth, environmental protection, and social considerations, the example of which is the FCEV market in the studied US state. Eventually, California's experience provides a valuable blueprint for other states or countries aiming to develop their FCEV markets, as the observations from this state can inform the crafting of effective green industrial policies, considering unique local factors and policy objectives.

Lastly, the dissertation can be a source of the ***methodological implications***. The dissertation employs a multi-dimensional approach to analyze market failures and green industrial policy instruments, offering a methodological framework for similar studies. The author utilized structured interviews with FCEV market participants and stakeholders to enrich the methodological approach by adding qualitative insights. The methodology includes a detailed evaluation of state green industrial policy instruments, setting a precedent for similar policy impact assessments.

In summary, the author firmly believes these implications can offer a robust foundation for future research and policy development considering the normative postulates of the economics of sustainable development and keeping the green industrial policy approach, especially in shaping the FCEV market in California and beyond.

Recommendations for future research

The author proposes that future research could expand in spatial scope to compare and contrast the effectiveness and impact of green industrial policies in different states or countries. It would also be worth investigating the transferability of California’s green industrial policy model to other socio-economic contexts in countries like Poland. The author also recognizes the potential of future research to conduct long-term studies to assess the sustained impact of green industrial policies on FCEV market dynamics or repeat this research after a certain period, i.e., in 2035 (when California plans to restrict registrations of new ICEV and allow only ZEV in the passenger light-duty segment). Exploring the evolving consumer preferences and technological advancements in the FCEV market could be insightful in the context of green industrial policy impacts. Furthermore, the cross-sectoral analysis could be worth examining the interdependencies between the FCEV market and other sectors, such as renewable energy and infrastructure development. This approach could allow for assessing the broader implications of FCEV market growth on the structural changes in related industries.

Final reflections

In conclusion, this dissertation has provided a thorough and nuanced understanding of the impact of green industrial policy on the FCEV market in California between 1990 and 2022. By intertwining theoretical frameworks of the economics of sustainable development with empirical insights, it has not only contributed to academic discourse but also offered practical policy impact observations for policymakers, market participants, and stakeholders in California and beyond. As the quest for sustainable development continues, the observations drawn from California's experience with FCEVs can illuminate paths for other jurisdictions and sectors, steering towards a more sustainable and hydrogen-powered future of transportation.

REFERENCES

AC Transit. (2022). *Zero EmissionTransit Bus Technology Analysis. Volume 4. Reported period: January 2022 - June 2022*. https://www.actransit.org/sites/default/files/2023-01/0430-22%20Report-ZEBTA%20v4_FNL_012423.pdf

Acaravci, A., & Ozturk, I. (2010). On the relationship between energy consumption, CO2 emissions and economic growth in Europe. *Energy*, *35*(12), 5412–5420. https://doi.org/10.1016/J.ENERGY.2010.07.009

Acheampong, A. O., Erdiaw-Kwasie, M. O., & Abunyewah, M. (2021). Does energy accessibility improve human development? Evidence from energy-poor regions. *Energy Economics*, *96*, 105165. https://doi.org/10.1016/J.ENECO.2021.105165

Aiginger, K., & Rodrik, D. (2020). Rebirth of Industrial Policy and an Agenda for the Twenty-First Century. *Journal of Industry, Competition and Trade*, *20*(2), 189–207. https://doi.org/10.1007/S10842-019-00322-3/TABLES/2

Alcott, B. (2005). Jevons' paradox. *Ecological Economics*, *54*(1), 9–21. https://doi.org/10.1016/J.ECOLECON.2005.03.020

Allan, B., Lewis, J. I., & Oatley, T. (2021). Green Industrial Policy and the Global Transformation of Climate Politics. *Global Environmental Politics*, *21*(4), 1–19. https://doi.org/10.1162/GLEP_A_00640

Altenburg, T., & Assmann, C. (2017). *Green Industrial Policy. Concept, Policies, Country Experiences.* (T. Altenburg & C. Assmann, Eds.). UN Environment; German Development Institute / Deutsches Institut für Entwicklungspolitk.

Ambroziak, A. A. (2017). Review of the Literature on the Theory of Industrial Policy. In A. A. Ambroziak (Ed.), *The New Industrial Policy of the European Union* (pp. 3–38). Springer International Publishing. https://doi.org/10.1007/978-3-319-39070-3

Athey, S., & Imbens, G. W. (2017). The State of Applied Econometrics: Causality and Policy Evaluation. *Journal of Economic Perspectives*, *31*(2), 3–32. https://doi.org/10.1257/JEP.31.2.3

Axsen, J., & Wolinetz, M. (2023). What does a low-carbon fuel standard contribute to a policy mix? An interdisciplinary review of evidence and research gaps. *Transport Policy*, *133*, 54–63. https://doi.org/10.1016/J.TRANPOL.2023.01.008

Ayaburi, J., Bazilian, M., Kincer, J., & Moss, T. (2020). Measuring "Reasonably Reliable" access to electricity services. *The Electricity Journal*, *33*(7), 106828. https://doi.org/10.1016/J.TEJ.2020.106828

Bae, Y., Mitra, S. K., Rindt, C. R., & Ritchie, S. G. (2022). Factors influencing alternative fuel adoption decisions in heavy-duty vehicle fleets. *Transportation Research Part D: Transport and Environment*, *102*, 103150. https://doi.org/10.1016/J.TRD.2021.103150

Balcerowicz, L., & Rzońca, A. (2015). *Puzzles of Economic Growth*. International Bank for Reconstruction and Development / The World Bank.

Ball, M., & Weeda, M. (2016). The hydrogen economy—Vision or reality? *Compendium of Hydrogen Energy*, 237–266. https://doi.org/10.1016/B978-1-78242-364-5.00011-7

Barbier, E. B. (1987). The Concept of Sustainable Economic Development. *Environmental Conservation*, *14*(2), 101–110.

Barreto, L., Makihira, A., & Riahi, K. (2003). The hydrogen economy in the 21st century: a sustainable development scenario. *International Journal of Hydrogen Energy*, *28*(3), 267–284. https://doi.org/10.1016/S0360-3199(02)00074-5

Barro, R. J., & Sala-I-Martin, X. (1992). Convergence. *Journal of Political Economy*, *100*(2), 223–251. https://doi.org/10.1086/261816

Beck, F. J., Gourlay, D., Lyons, M., & Venkataraman, M. B. (2021). The Hydrogen Economy. *Transitioning to a Prosperous, Resilient and Carbon-Free Economy*, 173–200. https://doi.org/10.1017/9781316389553.011

Bednar, D. J., & Reames, T. G. (2020). Recognition of and response to energy poverty in the United States. *Nature Energy 2020 5:6*, *5*(6), 432–439. https://doi.org/10.1038/s41560-020-0582-0

Belke, A., Dobnik, F., & Dreger, C. (2011). Energy consumption and economic growth: New insights into the cointegration relationship. *Energy Economics*, *33*(5), 782–789. https://doi.org/10.1016/J.ENECO.2011.02.005

Bezdek, R. H. (2019). The hydrogen economy and jobs of the future. *Renewable Energy and Environmental Sustainability*, *4*, 1. https://doi.org/10.1051/REES/2018005

Blanchard, O., & Summers, L. (2017). *Rethinking Stabilization Policy. Back to the Future*. https://www.piie.com/sites/default/files/documents/blanchard-summers20171012paper.pdf

Bockris, J. O. (1977). The Hydrogen Economy. In J. O. Bockris (Ed.), *Environmetnal Chemistry* (pp. 549–582). Plenum Press.

Bockris, J. O., & Appleby, A. J. (1972). The hydrogen economy - an ultimate economy. *Environment. This Month*, *1*(1), 29–35. https://doi.org/10.1126/SCIENCE.176.4041.1323

Bockris, J. O. M. (2013). The hydrogen economy: Its history. *International Journal of Hydrogen Energy*, *38*(6), 2579–2588. https://doi.org/10.1016/J.IJHYDENE.2012.12.026

Borys, T. (2014). Wybrane problemy metodologii pomiaru nowego paradygmatu rozwoju - polskie doświadczenia. *Studia i Rozprawy*, *3*(69), 3–21.

Boyce, C., & Neale, P. (2006). *Conducting In-depth Internviews: A Guide for Designing and Conducting In-Depth Interviews for Evaluation Input*.

Bratt, H. (2022). The Diffusion of Hydrogen Technology in the Road Transport Sector in Sweden. In *Examensarbete vid Institutionen för geovetenskaper*. Uppsala University

Brito, J. (2022). *No fleet left behind: Barriers and opportunities for small fleet zero-emission trucking* (ICCT Working Paper 2022-31). https://theicct.org/publication/small-fleet-ze-trucking-oct22/

Brown, T., Stephens-Romero, S., & Scott Samuelsen, G. (2012). Quantitative analysis of a successful public hydrogen station. *International Journal of Hydrogen Energy*, *37*(17), 12731–12740. https://doi.org/10.1016/J.IJHYDENE.2012.06.008

Bryner, G. C. (1995). *Blue skies, green politics: the Clean Air Act of 1990 and its implementation* (2nd ed.). CQ Press.

Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., & Boloor, M. (2021). *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains*. https://doi.org/10.2172/1780970

Burzyńska, D. (2015). Klastry ekologiczne instrumentem polityki innowacyjnej i ochrony środowiska. In A. Cudowska-Sojko (Ed.), *Współczesne wyzwania rozwoju gospodarczego: polityka i kreacja potencjału. Struktura gospodarki, rynek pracy, środowisko i jakość życia* (2nd ed., pp. 292–311). Wydawnictwo Uniwersytetu w Białymstoku.

Bushnell, J., Muehlegger, E., Rapson, D., & Witcover, J. (2021). *The End of Neutrality? LCFS, Technology Neutrality, and Stimulating the Electric Vehicle Market* (WP 318R).

Buysse, C., & Sharpe, B. (2020). *California's Advanced Clean Trucks regulation: Sales requirements for zero-emission heavy-duty trucks*. https://theicct.org/publication/californias-advanced-clean-trucks-regulation-sales-requirements-for-zero-emission-heavy-duty-trucks/

Byko, J. (2015). *Polityka gospodarcza. Wybrane zagadnienia*. Wydawnictwo Naukowe Uniwersytetu Szczecińskiego.

Caldwell, L. K. (1998). *The National Environmental Policy Act: An Agenda for the Future*. Indiana University Press.

California HVIP. (2023). *Impact - Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project*. https://californiahvip.org/impact/

California HVIP/CARB. (2023). *Voucher Map and Data. Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project*. https://californiahvip.org/impact/#deployed-vehicle-mapping-tool

Campos, N., Bruhn, P., Lelis, C., Calegario, L., Da, M., & Borges, S. (2021). Industrial policy, economic growth and international engagement: a comparison of selected countries. *CEPAL Review*, *135*, 7–28.

Capurso, T., Stefanizzi, M., Torresi, M., & Camporeale, S. M. (2022). Perspective of the role of hydrogen in the 21st century energy transition. *Energy Conversion and Management*, *251*, 114898. https://doi.org/10.1016/J.ENCONMAN.2021.114898

Caputo, R. K. (2014). Evaluating Policy Proposals. In R. K. Caputo (Ed.), *Policy Analysis for Social Workers* (pp. 57–75). SAGE Publications, Inc. https://doi.org/10.4135/9781544303550

CARB. (2015). *Annual Hydrogen Evaluation 2014*. https://ww2.arb.ca.gov/sites/default/files/2020-10/ab8_report_final_june2014_ac.pdf

CARB. (2016). *California Hydrogen Infrastructure Tool (CHIT) of California Air Resources Board*. California Air Resources Board. https://ww2.arb.ca.gov/resources/documents/california-hydrogen-infrastructure-tool-chit

CARB. (2018). *Annual Hydrogen Evaluation 2017*. https://ww2.arb.ca.gov/sites/default/files/2020-03/ab8_report_2017_ac_1.pdf

CARB. (2019). *States that have Adopted California's Vehicle Standards under Section 177 of the Federal Clean Air Act*. https://ww2.arb.ca.gov/sites/default/files/2019-03/177-states.pdf

CARB. (2020). *The History of the California Air Resources Board*. https://ww2.arb.ca.gov/about/history

CARB. (2021a). *Annual Hydrogen Evaluation 2020*. https://ww2.arb.ca.gov/sites/default/files/2020-09/ab8_report_2020.pdf

CARB. (2021b). *LCFS ZEV Infrastructure Crediting*. https://ww2.arb.ca.gov/resources/documents/lcfs-zev-infrastructure-crediting

CARB. (2023a). *Annual Hydrogen Evaluation 2022*. https://ww2.arb.ca.gov/sites/default/files/2022-09/AB-8-Report-2022-Final.pdf

CARB. (2023b). *Reporting Tool & Data - Bus Inventory Report*. https://ww2.arb.ca.gov/sites/default/files/2023-08/2022_BusInventory.csv

CARB. (2023c). *AB 32 - Global Warming Solutions Act of 2006*. California Air Resources Board. https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006

Carlisle, N., Van Geet, O., & Shanti, P. (2009). *Definition of a "Zero Net Energy" Community*. https://www.nrel.gov/docs/fy10osti/46065.pdf

Cass, D. (1965). Optimum growth in an aggregative model of capital accumulation. *Review of Economic Studies*, *32*(3), 233–240. https://doi.org/10.2307/2295827/2/32-3-233.PDF.GIF

CEC. (2023). *Light-Duty Vehicle Population in California. California Energy Commission*. https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/light-duty-vehicle

Chang, R. D., Zuo, J., Zhao, Z. Y., Zillante, G., Gan, X. L., & Soebarto, V. (2017). Evolving theories of sustainability and firms: History, future directions and implications for renewable energy research. *Renewable and Sustainable Energy Reviews*, *72*, 48–56. https://doi.org/10.1016/J.RSER.2017.01.029

Chapman, A., Itaoka, K., Farabi-Asl, H., Fujii, Y., & Nakahara, M. (2020). Societal penetration of hydrogen into the future energy system: Impacts of policy, technology and carbon targets. *International Journal of Hydrogen Energy*, *45*(7), 3883–3898. https://doi.org/10.1016/J.IJHYDENE.2019.12.112

CHBC. (2023). *Class 8 Fuel Cell Electric Truck Info Page*. https://californiahydrogen.org/resources/fcet-info-page/

Chemerinsky, E. (2011). *Constitutional Law: Principles and Policies (Aspen Student Treatise Series)* (4th ed.). Wolters Kluwer.

Chmielewski, K. (2023). Federalism. In Editors of Encyclopaedia Britannica (Ed.), *Britannica*. https://www.britannica.com/topic/federalism

Chmielniak, T., Lepszy, S., & Mońka, P. (2017). Energetyka wodorowa – podstawowe problemy. *Polityka Energetyczna - Energy Policy Journal*, *20*(3), 343–354. https://doi.org/10.2/JQUERY.MIN.JS

Chu, S., & Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *Nature*, *488*(7411), 294–303. https://doi.org/10.1038/nature11475

Cieślukowski, M. (2014). Podatki i system podatkowy w ekonomii zrównoważonego rozwoju. *Studia Oeconomica Posnaniensia*, *2*(6), 193–207.

Clark, W. C., & Munn, R. E. (1986). *Sustainable Development of the Biosphere*. Cambridge University Press.

Constantine, C. (2017). Economic structures, institutions, and economic performance. *Journal of Economic Structures*, *6*(1), 1–18. https://doi.org/10.1186/S40008-017-0063-1/FIGURES/1

Conte, M. (2009). ENERGY | Hydrogen Economy. *Encyclopedia of Electrochemical Power Sources*, 232–254. https://doi.org/10.1016/B978-044452745-5.00084-8

Conte, M., Iacobazzi, A., Ronchetti, M., & Vellone, R. (2001). Hydrogen economy for a sustainable development: state-of-the-art and technological perspectives. *Journal of Power Sources*, *100*(1–2), 171–187. https://doi.org/10.1016/S0378-7753(01)00893-X

Cox, G. W., & McCubbins, M. D. (2007). Political Structure and Economic Policy: The Institutional Determinants of Policy Outcomes. *Presidents, Parliaments, and Policy, Cambridge University Press 2000*.

Criscuoloi, C., Gonnei, N., Kitazawai, K., & Lalanne, G. (2022). Are industrial policy instruments effective? A review of the evidence in OECD countries. *OECD Science, Technology and Industry Policy Papers*, *128*. https://doi.org/10.1787/57b3dae2-en

Crowley, D. M., Dodge, K. A., Barnett, W. S., Corso, P., Duffy, S., Graham, P., Greenberg, M., Haskins, R., Hill, L., Jones, D. E., Karoly, L. A., Kuklinski, M. R., & Plotnick, R. (2018). Standards of evidence for conducting and reporting economic evaluations in prevention science. *Prevention Science*, *19*(3), 366–390. https://doi.org/10.1007/S11121-017-0858-1/FIGURES/1

CTE. (2023). *NorCal ZERO: Zero-Emission Regional Truck Operations with Fuel Cell Electric Trucks*. https://cte.tv/project/norcal-zero-zero-emission-regional-truck-operations-with-fuel-cell-electric-trucks/

CVRP. (2023). *Clean Vehicle Rebate Project. Rebate Statistics*. https://cleanvehiclerebate.org/en/rebate-statistics

Czaja, S. (2012). Problemy badawcze oraz wyzwania rozwojowe ekonomii środowiska i zasobów naturalnych. *Ekonomia i Środowisko*, *3*(43), 28–50.

Daly, H., & Cobb, J. (1991). For the Common Good: Redirecting the Economy toward Community, the Environment, and a Substainable Future. *Bulletin of Science, Technology & Society*, *11*(1).

Daly, H. E. (1996). *Beyond Growth: The Economics of Sustainable Development*. Beacon Press.

Daly, H. E., & Farley, J. (2004). *Ecological Economics: Principles And Applications*. Island Press.

Demerse, C., & Bramley, M. (2008). Criteria for Policy Evaluation. Choosing Greenhouse Gas Emission Reduction Policies in Canada. In *Public Administration Review 39*(1). https://doi.org/10.2307/3110377

Demirbas, A. (2017). Future hydrogen economy and policy. *Energy Sources, Part B: Economics, Planning, and Policy*, *12*(2), 172–181. https://doi.org/10.1080/15567249.2014.950394

Deszczyński, P. (2009). Przestrzeń i czas jako determinanty polityki gospodarczej. *Ruch Prawniczy, Ekonomiczny i Socjologiczny*, *71*(1), 89–103.

Ditlev-Simonsen, C. D. (2022). Economic Theories and Sustainable Development. *A Guide to Sustainable*

Corporate Responsibility, 37–60. https://doi.org/10.1007/978-3-030-88203-7_3

Dou, Y., Sun, L., Ren, J., & Dong, L. (2017). Opportunities and Future Challenges in Hydrogen Economy for Sustainable Development. *Hydrogen Economy: Supply Chain, Life Cycle Analysis and Energy Transition for Sustainability*, 277–305. https://doi.org/10.1016/B978-0-12-811132-1.00010-9

Drelich-Skulska, B., Jankowiak, A. H., Mazurek, S., Bobowski, S., & Haberla, M. (2014). Klastry jako nośnik innowacyjności przedsiębiorstw i regionów. Czy doświadczenia azjatyckie można wykorzystać w warunkach gospodarki polskiej? In B. Drelich-Skulska (Ed.), *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu* 1, 369. Publishing House of the Wroclaw University of Economics. https://doi.org/10.15611/PN.2014.369.1.19

Elberry, A. M., Thakur, J., Santasalo-Aarnio, A., & Larmi, M. (2021). Large-scale compressed hydrogen storage as part of renewable electricity storage systems. *International Journal of Hydrogen Energy*, *46*(29), 15671–15690. https://doi.org/10.1016/J.IJHYDENE.2021.02.080

EPRS. (2023). *EU rules for renewable hydrogen. Delegated regulations on a methodology for renewable fuels of non-biological origin*. https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747085/EPRS_BRI(2023)747085_EN.pdf

Eudy, L., Battelle, K. C., & Gikakis, C. (2009). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2009*. https://www.nrel.gov/docs/fy10osti/46490.pdf

Eudy, L., Chandler, K., & Gikakis, C. (2007). *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*. https://www.nrel.gov/docs/fy07osti/41967.pdf

Eudy, L., Chandler, K., & Gikakis, C. (2008). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*. https://www.nrel.gov/docs/fy09osti/44133.pdf

Eudy, L., Chandler, K., & Gikakis, C. (2010). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2010*. https://www.nrel.gov/docs/fy11osti/49379.pdf

Eudy, L., Chandler, K., & Gikakis, C. (2011). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2011*. https://www.nrel.gov/docs/fy12osti/52927.pdf

Eudy, L., Chandler, K., & Gikakis, C. (2012). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012*. https://www.nrel.gov/docs/fy13osti/56406.pdf

Eudy, L., & Gikakis, C. (2012). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013*. https://www.nrel.gov/docs/fy14osti/60490.pdf

Eudy, L., & Post, M. (2017). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2017*. https://www.nrel.gov/docs/fy18osti/70075.pdf

Eudy, L., & Post, M. (2018). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018*. https://www.nrel.gov/docs/fy19osti/72208.pdf

Eudy, L., Post, M., & Gikakis, C. (2014). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2014*. https://www.nrel.gov/docs/fy15osti/62683.pdf

Eudy, L., Post, M., & Gikakis, C. (2015). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2015*. https://www.nrel.gov/docs/fy16osti/64974.pdf

Eudy, L., Post, M., & Jeffers, M. (2016). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2016*. https://www.nrel.gov/docs/fy17osti/67097.pdf

European Commission. (2014). *Communication from the Commission — Framework for State aid for research and development and innovation*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014XC0627(01)&from=EN

European Commission. (2016). *Scoping study on modelling of EU environment policy*. https://op.europa.eu/s/y55t

European Commission. (2019). The European Green Deal. Document no.: COM/2019/640.

European Commission. (2020). A hydrogen strategy for a climate-neutral Europe. Document no. COM/2020/301.

Fagerberg, J. (2000). Technological progress, structural change and productivity growth: a comparative study. *Structural Change and Economic Dynamics*, *11*(4), 393–411. https://doi.org/10.1016/S0954-349X(00)00025-4

Falchetta, G., & Tagliapietra, S. (2022). Economics of Access to Energy. *The Palgrave Handbook of International Energy Economics*, 567–594. https://doi.org/10.1007/978-3-030-86884-0_28

Falcone, P. M., Hiete, M., & Sapio, A. (2021). Hydrogen economy and sustainable development goals: Review and policy insights. *Current Opinion in Green and Sustainable Chemistry*, *31*, 100506. https://doi.org/10.1016/J.COGSC.2021.100506

Ferris, R. S., Ingram, N., Mough, J., Schnepp, K., & Fitch, P. (2020). *Measurement and Standards Requirements for Hydrogen and Biodiesel Used as a Transportation Fuel*. www.cdfa.ca.gov

Fiedor, B. (2006). Antropologiczne podstawy koncepcji zrównoważonego rozwoju z perspektywy ekonomicznej: od homo oeconomicus do homo sustinens. *Prace Naukowe Akademii Ekonomicznej We Wrocławiu*, *1131*, 104–119.

Fisher, A. G. B. (1939). Production, primary, secondary, tertiary. *Economic Record*, *15*(1), 24–38. https://doi.org/10.1111/J.1475-4932.1939.TB01015.X

Forrest, K., Mac Kinnon, M., Tarroja, B., & Samuelsen, S. (2020a). Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. *Applied Energy*, *276*, 115439. https://doi.org/10.1016/J.APENERGY.2020.115439

Forrest, K., Mac Kinnon, M., Tarroja, B., & Samuelsen, S. (2020b). Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. *Applied Energy*, *276*, 115439. https://doi.org/10.1016/J.APENERGY.2020.115439

Foundations for Evidence-Based Policymaking Act of 2018, (2019). https://www.congress.gov/bill/115th-congress/house-bill/4174

Fournier, V. (2008). Escaping from the economy: The politics of degrowth. *International Journal of Sociology and Social Policy*, *28*(11–12), 528–545. https://doi.org/10.1108/01443330810915233/FULL/PDF

Friedman, M. (1967). The Role of Monetary Policy. *The American Economic Review*, *58*(1), 1–17.

Frodyma, K., Papież, M., & Śmiech, S. (2022). Revisiting the Environmental Kuznets Curve in the European Union countries. *Energy*, *241*, 122899. https://doi.org/10.1016/J.ENERGY.2021.122899

Frowijn, L. S. F., & van Sark, W. G. J. H. M. (2021). Analysis of photon-driven solar-to-hydrogen production methods in the Netherlands. *Sustainable Energy Technologies and Assessments*, *48*, 101631. https://doi.org/10.1016/J.SETA.2021.101631

Frumkin, P. (2002). *On being nonprofit: a conceptual and policy primer*. Harvard University Press.

FTA. (2023). *2022 Annual Database Agency Information*. https://www.transit.dot.gov/ntd/data-product/2022-annual-database-agency-information

Gabardo, F. A., Pereima, J. B., & Einloft, P. (2017). The incorporation of structural change into growth theory: A historical appraisal. *EconomiA*, *18*(3), 392–410. https://doi.org/10.1016/J.ECON.2017.05.003

Gao, J., & Zhang, T. (2022). Effects of public funding on the commercial diffusion of on-site hydrogen production technology: A system dynamics perspective. *Technological Forecasting and Social Change*, *175*, 121380. https://doi.org/10.1016/J.TECHFORE.2021.121380

Gentswa, N. (2020). Środowiskowa krzywa Kuznetsa: przegląd teoretyczno-metodyczny. *Rozwój Regionalny i Polityka Regionalna*, *49*, 39–50. https://doi.org/10.14746/RRPR.2020.49.04

Gertler, P. J., Martinez, S., Premand, P., Rawlings, L. B., & Vermeersch, C. M. J. (2016). Impact Evaluation in Practice. In *Impact Evaluation in Practice, Second Edition* (2nd ed.). Inter-American Development Bank and World Bank. https://doi.org/10.1596/978-1-4648-0779-4

González-Eguino, M. (2015). Energy poverty: An overview. *Renewable and Sustainable Energy Reviews*, *47*, 377–385. https://doi.org/10.1016/J.RSER.2015.03.013

Goodland, R., & Ledec, G. (1987). Neoclassical economics and principles of sustainable development. *Ecological Modelling*, *38*(1–2), 19–46. https://doi.org/10.1016/0304-3800(87)90043-3

Gordon, R. J. (1990). Wages and employment under uncertain demand. *Journal of Economic Literature*, *28*(3), 1115–1171. https://doi.org/10.2307/2296397

Gorynia, M. (2016). Polish economic policy, internationalization, and globalization. In S. Katsikides & H. Hanappi (Eds.), *Society and Economics in Europe: Disparity versus Convergence?* (pp. 31–51). Springer International Publishing. https://doi.org/10.1007/978-3-319-21431-3_3/COVER

Gorynia, M., & Jankowska, B. (2010). *Klastry a międzynarodowa konkurencyjność i internacjonalizacja przedsiębiorstwa*. Centrum Doradztwa i Informacji Difin.

Graczyk, A. (2017). Wskaźniki zrównoważonego rozwoju energetyki. *Optimum. Studia Ekonomiczne* , *4*(88), 53–68. https://doi.org/10.15290/ose.2017.04.88.05

Greene, D. L., Ogden, J. M., & Lin, Z. (2020). Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. *ETransportation*, *6*, 100086. https://doi.org/10.1016/J.ETRAN.2020.100086

Greenwald, B., & Stiglitz, J. E. (1987). Keynesian, New Keynesian and New Classical Economics. *Oxford Economic Papers*, *39*(1), 119–133.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of the North American Free Trade Agreement. *John M. Ohlin Program Discussion Paper* , *158*. https://doi.org/10.4236/OJPS.2022.123019

Grossman, G. M., & Krueger, A. B. (1995). Economic Growth and the Environment. *The Quarterly Journal of Economics*, *110*(2), 353–377. https://doi.org/10.2307/2118443

Güney, T. (2019). Renewable energy, non-renewable energy and sustainable development. *International Journal of Sustainable Development and World Ecology*, *26*(5), 389–397. https://doi.org/10.1080/13504509.2019.1595214/SUPPL_FILE/TSDW_A_1595214_SM1378.RAR

Gupta, S., Tirpak, D. A., Burger, N., Gupta, J., Höhne, N., Boncheva, A. I., Kanoan, G. M., Kolstad, C., Kruger, J. A., Michaelowa, A., Murase, S., Pershing, J., Saijo, T., & Sari, A. (2007). Policies, Instruments and Co-operative Arrangements . In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 747–798). Cambridge University Press.

Hallegatte, S., Fay, M., & Vogt-Schilb, A. (2013). Green Industrial Policies : When and How. *Policy Research*

Working Papers, *6677*. https://doi.org/10.1596/1813-9450-6677

Hanley, N., McGregor, P. G., Swales, J. K., & Turner, K. (2009). Do increases in energy efficiency improve environmental quality and sustainability? *Ecological Economics*, *68*(3), 692–709. https://doi.org/10.1016/J.ECOLECON.2008.06.004

Hardman, S., & Tal, G. (2018). Who are the early adopters of fuel cell vehicles? *International Journal of Hydrogen Energy*, *43*(37), 17857–17866. https://doi.org/10.1016/J.IJHYDENE.2018.08.006

Harrod, R. F. (1939). An Essay in Dynamic Theory. *The Economic Journal*, *49*(193), 14–33.

Hashem, N., & Wang, C. (2016). Fuel cells. In M. H. Rashid (Ed.), *Electric Renewable Energy Systems* (pp. 92–113). Academic Press. https://doi.org/10.1016/B978-0-12-804448-3.00006-2

He, Y., Zhou, Y., Yuan, J., Liu, Z., Wang, Z., & Zhang, G. (2021). Transformation towards a carbon-neutral residential community with hydrogen economy and advanced energy management strategies. *Energy Conversion and Management*, *249*, 114834. https://doi.org/10.1016/J.ENCONMAN.2021.114834

Hill, R. J., & Magnani, E. (2002). An Exploration of the Conceptual and Empirical Basis of the Environmental Kuznets Curve. *Australian Economic Papers*, *41*(2), 239–254. https://doi.org/10.1111/1467-8454.00162

Hodgson, G. (2000). What Is the Essence of Institutional Economics? *Journal of Economic Issues*, *34*(2), 317–329. https://doi.org/10.1080/00213624.2000.11506269

Hopwood, B., Mellor, M., & O’brien, G. (2005). Sustainable Development: Mapping Different Approaches. *Sustainable Development*, *13*, 38–52. https://doi.org/10.1002/sd.244

Horodecka, A. (2011). Koncepcja homo sustinens i jej rola w polityce gospodarczej wobec wyzwań globalnego kryzysu. In K. Pająk & J. J. Tomidajewicz (Eds.), *Polityka gospodarcza wobec globalnego kryzysu ekonomicznego*. Wydawnictwo Adam Marszałek.

Hsu, A., Lloyd, A., & Emerson, J. W. (2013). What progress have we made since Rio? Results from the 2012 Environmental Performance Index (EPI) and Pilot Trend EPI. *Environmental Science and Policy*, *33*, 171–185. https://doi.org/10.1016/J.ENVSCI.2013.05.011

Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., & Zhang, C. (2021). *Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks*. https://doi.org/10.2172/1821615

Hydrogen Council. (2021). *Policy Review Policy Toolbox for Low Carbon and Renewable Hydrogen. Enabling low carbon and renewable hydrogen globally*. https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-Council_Policy-Toolbox.pdf

Hydrogen Fuel Cell Partnership. (2022). *Hydrogen Fuel Cell Partnership - Fuel Cell Electric Vehicles & Hydrogen Fuel*. https://h2fcp.org/

IEA. (2021a). *Hydrogen Projects Database*. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

IEA. (2021b). *Hydrogen Supply – Analysis*. https://www.iea.org/reports/hydrogen-supply

IEA. (2022a). *Global Hydrogen Review 2022*. https://www.iea.org/reports/global-hydrogen-review-2022

IEA. (2022b). *Renewables 2022. Analysis and forecast*. www.iea.org

IEA. (2023a). Global EV Outlook 2023. In *Transportation Research Part D: Transport and Environment 118*. Elsevier Ltd. https://doi.org/10.1016/J.TRD.2023.103693

IEA. (2023b). *Towards hydrogen definitions based on their emissions intensity*. www.iea.org

IPCC. (2007). *Climate change 2007: Synthesis report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar4/syr/

IRENA. (2020). Green hydrogen: A guide to policymaking. In *39th World Energy Engineering Conference, WEEC 2016* (Ed. 2). https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

Islam, E. S., Moawad, A., Kim, N., & Rousseau, A. (2020). *Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050*. https://doi.org/10.2172/1647165

Itaoka, K., Saito, A., & Sasaki, K. (2017). Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. *International Journal of Hydrogen Energy*, *42*(11), 7290–7296. https://doi.org/10.1016/J.IJHYDENE.2016.10.123

Jabareen, Y. (2008). A new conceptual framework for sustainable development. *Environment, Development and Sustainability*, *10*(2), 179–192. https://doi.org/10.1007/S10668-006-9058-Z/METRICS

Jahan, S., Mahmud, A. S., & Papageorgiou, C. (2014). What Is Keynesian Economics? In *Finance & Development* (pp. 53–54). International Monetary Fund. https://www.imf.org/external/pubs/ft/fandd/2014/09/pdf/basics.pdf

Jahan, S., & Papageorgiou, C. (2014). What Is Monetarism? - Back to Basics - Finance & Development, March 2014. *Finance and Development*, *51*(1), 38–39. https://www.imf.org/external/pubs/ft/fandd/2014/03/basics.htm

Jeffers, M., Kelly, K., Lipman, T., Fernandes Tomon Avelino, A., Johnson, C., Li, M., Post, M., & Zhang, Y. (2022). *Comprehensive Review of California's Innovative Clean Transit Regulation: Phase I Summary Report*. https://doi.org/10.2172/1892294

Jevons, W. S. (1865). *The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-Mines*. Macmillan. https://energyhistory.yale.edu/library-item/w-stanley-jevons-coal-question-1865

Johnson, C. (1984). *The Industrial Policy Debate*. ICS Press.

Ju, Y., Cushing, L. J., & Morello-Frosch, R. (2020). An equity analysis of clean vehicle rebate programs in California. *Climatic Change*, *162*(4), 2087–2105. https://doi.org/10.1007/S10584-020-02836-W/FIGURES/3

Kallis, G., Kerschner, C., & Martinez-Alier, J. (2012). The economics of degrowth. *Ecological Economics*, *84*, 172–180. https://doi.org/10.1016/J.ECOLECON.2012.08.017

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., & Schmelzer, M. (2018). Research On Degrowth. *Annual Review of Environment and Resources* , *43*, 291–316. https://doi.org/10.1146/annurev-environ-102017-025941

Kaplinsky, R., & Morris, M. (2012). *A handbook for value chain research*. Institute of Development Studies. Univeristy of Sussex.

Kar, S. K., Harichandan, S., & Roy, B. (2022). Bibliometric analysis of the research on hydrogen economy: An analysis of current findings and roadmap ahead. *International Journal of Hydrogen Energy*, *47*(20), 10803–10824. https://doi.org/10.1016/J.IJHYDENE.2022.01.137

Karmis, D., & Norman, W. (2016). Theories of federalism: A reader. *Theories of Federalism: A Reader*, 1–331. https://doi.org/10.1007/978-1-137-05549-1/COVER

Karp, L. S., & Stevenson, M. T. (2012). Green Industrial Policy: Trade and Theory. *World Bank Policy Research Working Paper*, *6238*. https://doi.org/10.1016/B978-0-444-52944-2.00001-X

Kerr, W. R., Lincoln, W. F., & Mishra, P. (2014). The Dynamics of Firm Lobbying. *American Economic Journal: Economic Policy*, *6*(4), 343–379. https://doi.org/10.1257/POL.6.4.343

Keynes, J. M. (1936). *The General Theory of Employment, Interest, and Money*. Palgrave Macmillan.

Khan, I., Hou, F., Zakari, A., & Tawiah, V. K. (2021). The dynamic links among energy transitions, energy consumption, and sustainable economic growth: A novel framework for IEA countries. *Energy*, *222*, 119935. https://doi.org/10.1016/J.ENERGY.2021.119935

Khan, I., Zakari, A., Dagar, V., & Singh, S. (2022). World energy trilemma and transformative energy developments as determinants of economic growth amid environmental sustainability. *Energy Economics*, *108*, 105884. https://doi.org/10.1016/J.ENECO.2022.105884

Kiełczewski, D. (2012). Conception of the economics of sustainable development. *Research Papers of Wrocław University of Economics*, *245*, 170–178. https://doi.org/10.2/JQUERY.MIN.JS

Kiełczewski, D. (2016). /Rationality of managing man in the concept of homo sustinens. *Research Papers of of Wrocław University of Economics*, *449*, 269–276.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/J.RESCONREC.2017.09.005

Klamut, M., & Szostak, E. (2016). *Polityka ekonomiczna we współczesnej gospodarce rynkowej* (M. Klamut & E. Szostak, Eds.). Wydawnictwo Uniwersytetu Ekonomicznego.

Kneese, A. V. (1988). The Economics of Natural Resources. *Population and Development Review*, *14*, 281. https://doi.org/10.2307/2808100

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, *143*, 37–46. https://doi.org/10.1016/J.ECOLECON.2017.06.041

Krugman, P. R., & Obstfeld, Maurice. (2009). *International economics : theory and policy* (8th ed.). Pearson Addison-Wesley.

Ku, A. L., & Graham, J. D. (2022). Is California's Electric Vehicle Rebate Regressive? A Distributional Analysis. *Journal of Benefit-Cost Analysis*, *13*(1), 1–19. https://doi.org/10.1017/BCA.2022.2

Ku, A. Y., De Souza, A., Mcrobie, J., Li, J. X., & Levin, J. (2021). Zero-emission public transit could be a catalyst for decarbonization of the transportation and power sectors. *Clean Energy*, *5*(3), 492–504. https://doi.org/10.1093/CE/ZKAB029

Kurtz, J., Sprik, S., & Bradley, T. H. (2019). Review of transportation hydrogen infrastructure performance and reliability. *International Journal of Hydrogen Energy*, *44*(23), 12010–12023. https://doi.org/10.1016/J.IJHYDENE.2019.03.027

Kuznets, S. (1973). Modern Economic Growth: Findings and Reflections. *The American Economic Review*, *63*(3), 247–258. https://doi.org/10.1086/450415

Ledna, C., Brooker, A., & Lee, D.-Y. (2022). *Projecting California Light-Duty Vehicle Attributes (2019-2035)*. https://doi.org/10.2172/1891203

Li, K., Acha, S., Sunny, N., & Shah, N. (2022). Strategic transport fleet analysis of heavy goods vehicle technology for net-zero targets. *Energy Policy*, *168*, 112988. https://doi.org/10.1016/J.ENPOL.2022.112988

Lin, J. Y. (2012). *New Structural Economics: A Framework for Rethinking Development and Policy*. The World Bank.

Lin, J. Y., & Nowak, A. Z. (2017). *New Structural Economics for less advanced countries*. University of Warsaw Faculty of Management Press. https://doi.org/10.7172/978-83-65402-92-9.2018.wwz.10

Lindbeck, & Assar. (1976). Stabilization Policy in Open Economies with Endogenous Politicians. *American Economic Review*, *66*(2), 1–19.

Loiseau, E., Saikku, L., Antikainen, R., Droste, N., Hansjürgens, B., Pitkänen, K., Leskinen, P., Kuikman, P., & Thomsen, M. (2016). Green economy and related concepts: An overview. *Journal of Cleaner Production*, *139*, 361–371. https://doi.org/10.1016/J.JCLEPRO.2016.08.024

Lopez Jaramillo, O., Stotts, R., Kelley, S., & Kuby, M. (2019). Content Analysis of Interviews with Hydrogen Fuel Cell Vehicle Drivers in Los Angeles. *Transportation Research Record, 2673*(9), 377-388. https://doi.org/10.1177/0361198119845355

Lorek, E. (2011). Ekonomia zrównoważonego rozwoju w badaniach polskich i niemieckich. In S. Swadźba (Ed.), *Transformacja gospodarki - poziom krajowy i międzynarodowy. Zeszyty Naukowe Wydziałowe Uniwersytetu Ekonomicznego w Katowicach. Studia Ekonomiczne 90* (1), 103–112. https://doi.org/10.2/JQUERY.MIN.JS

Lucas, R. E. (1976). Econometric policy evaluation: A critique. *Carnegie-Rochester Conference Series on Public Policy*, *1*(C), 19–46. https://doi.org/10.1016/S0167-2231(76)80003-6

Lucas, R. E. (1988b). On the mechanics of economic development. *Journal of Monetary Economics*, *22*(1), 3–42. https://doi.org/10.1016/0304-3932(88)90168-7

Luo, Y., Wu, Y., Li, B., Mo, T., Li, Y., Feng, S. P., Qu, J., & Chu, P. K. (2021). Development and application of fuel cells in the automobile industry. *Journal of Energy Storage*, *42*, 103124. https://doi.org/10.1016/J.EST.2021.103124

Lütkenhorst, W., Altenburg, T., Pegels, A., & Vidican, G. (2014). Green Industrial Policy: Managing Transformation Under Uncertainty. *Deutsches Institut Für Entwicklungspolitik Discussion Paper*, *28*, 1–62.

Lütkenhorst, W., & Pegels, A. (2014). *Stable Policies, Turbulent Markets-Germany's Green Industrial Policy: The costs and benefits of promoting solar PV and wind energy*. https://www.iisd.org/publications/report/stable-policies-turbulent-markets-germanys-green-industrial-policy-costs-and

Mac Kinnon, M., Shaffer, B., Carreras-Sospedra, M., Dabdub, D., Samuelsen, G. S., & Brouwer, J. (2016). Air quality impacts of fuel cell electric hydrogen vehicles with high levels of renewable power generation. *International Journal of Hydrogen Energy*, *41*(38), 16592–16603. https://doi.org/10.1016/J.IJHYDENE.2016.07.054

Maggio, G., Nicita, A., & Squadrito, G. (2019). How the hydrogen production from RES could change energy and fuel markets: A review of recent literature. *International Journal of Hydrogen Energy*, *44*(23), 11371–11384. https://doi.org/10.1016/J.IJHYDENE.2019.03.121

Malik, R., & Janowska, A. A. (2018). Megatrends and Their Use in Economic Analyses of Contemporary Challenges in The World Economy. *Prace Naukowe Uniwersytetu Ekonomicznego We Wrocławiu*, *523*, 209–220. https://doi.org/10.15611/PN.2018.523.18

Mankiw, N. G., Ball, L., & Romer, D. (1988). The New Keynesian Economics and the Output-Inflation Trade-off. *Brookings Papers on Economic Activity*, *1*, 1–65.

Marti, L., & Puertas, R. (2022). Sustainable energy development analysis: Energy Trilemma. *Sustainable Technology and Entrepreneurship*, *1*(1), 100007. https://doi.org/10.1016/J.STAE.2022.100007

McConnell, V., & Leard, B. (2021). Pushing New Technology into the Market: California's Zero Emissions Vehicle Mandate. *Review of Environmental Economics and Policy*, *15*(1), 169–179. https://doi.org/10.1086/713055

Meadows, D. H. M., Meadows, D. L., Randers, J., & Behrens, W. W. B. I. (1972). *The limits of growth. A report for The Club of Rome's Project on the predicament of mankind*.

Mealy, P., & Teytelboym, A. (2022). Economic complexity and the green economy. *Research Policy*, *51*(8), 103948. https://doi.org/10.1016/J.RESPOL.2020.103948

Mebratu, D. (1998). Sustainability and sustainable development: Historical and conceptual review. *Environmental Impact Assessment Review*, *18*(6), 493–520. https://doi.org/10.1016/S0195-9255(98)00019-5

Megia, P. J., Vizcaino, A. J., Calles, J. A., & Carrero, A. (2021). Hydrogen Production Technologies: From Fossil Fuels toward Renewable Sources. A Mini Review. *Energy and Fuels*, *35*(20), 16403–16415. https://doi.org/10.1021/ACS.ENERGYFUELS.1C02501

Mendoza, C. B., Cayonte, D. D. D., Leabres, M. S., & Manaligod, L. R. A. (2019). Understanding multidimensional energy poverty in the Philippines. *Energy Policy*, *133*, 110886. https://doi.org/10.1016/J.ENPOL.2019.110886

Mergoni, A., & De Witte, K. (2022). Policy evaluation and efficiency: a systematic literature review. *International Transactions in Operational Research*, *29*(3), 1337–1359. https://doi.org/10.1111/ITOR.13012

Michalik, A. (2016). Dydaktyka ekonomii zrównoważonego rozwoju jako jeden z aspektów strategii przedsiębiorstwa. *Acta Scientifica Academiae Ostroviensis. Sectio A*, *8*(2), 21–32.

Midor, K. (2012). Ekonomia zrównoważonego rozwoju alternatywą dla współczesnej gospodarki światowej. *Systems Supporting Production Engineering*, *2*(2), 56–68.

Minsky, H. P. (1986). *Stabilizing an Unstable Economy*. Yale University Press.

Missemer, A. (2018). Natural Capital as an Economic Concept, History and Contemporary Issues. *Ecological Economics*, *143*, 90–96. https://doi.org/10.1016/J.ECOLECON.2017.07.011

Mohideen, M. M., Subramanian, B., Sun, J., Ge, J., Guo, H., Radhamani, A. V., Ramakrishna, S., & Liu, Y. (2023). Techno-economic analysis of different shades of renewable and non-renewable energy-based hydrogen for fuel cell electric vehicles. *Renewable and Sustainable Energy Reviews*, *174*, 113153. https://doi.org/10.1016/J.RSER.2023.113153

Morrison, G., Stevens, J., & Joseck, F. (2018). Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. *Transportation Research Part C: Emerging Technologies*, *87*, 183–196. https://doi.org/10.1016/J.TRC.2018.01.005

Muench, T. R. (2012). California’s Hydrogen Infrastructure Funding Program. *ECS Transactions*, *42*(1), 91–94. https://doi.org/10.1149/1.4705483/XML

Munda, G. (2004). Social multi-criteria evaluation: Methodological foundations and operational consequences. *European Journal of Operational Research*, *158*(3), 662–677. https://doi.org/10.1016/S0377-2217(03)00369-2

Munksgaard, J., Christoffersen, L. B., Keiding, H., Pedersen, O. G., & Jensen, T. S. (2007). An environmental performance index for products reflecting damage costs. *Ecological Economics*, *64*(1), 119–130. https://doi.org/10.1016/J.ECOLECON.2007.02.006

Myrdal, G. (1974). What Is Development? *Journal of Economic Issues*, *8*(4), 729–736. https://doi.org/10.1080/00213624.1974.11503225

Naber, R., Raven, R., Kouw, M., & Dassen, T. (2017). Scaling up sustainable energy innovations. *Energy Policy*, *110*, 342–354. https://doi.org/10.1016/J.ENPOL.2017.07.056

Nagel, S. S. (1986). Efficiency, Effectiveness, and Equity in Public Policy Evaluation. *Review of Policy Research*, *6*(1), 99–120. https://doi.org/10.1111/J.1541-1338.1986.TB00651.X

National Research Council. (2002). *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards. National Research Council Transportation Research Board Division on Engineering and Physical Sciences Board on Energy and Environmental Systems Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*. National Academy Press.

Naudé, W. (2010). Industrial Policy Old and New Issues. *Working Paper United Nations University World Institute for Development Economics Research*, *106*.

Neo, H. (2009). Resource and Environmental Economics. *International Encyclopedia of Human Geography*, 376–380. https://doi.org/10.1016/B978-008044910-4.00225-X

Neves Almeida, T. A. das, & García-Sánchez, I. M. (2016). A comparative analysis between composite indexes of environmental performance: An analysis on the CIEP and EPI. *Environmental Science and Policy*, *64*, 59–74. https://doi.org/10.1016/J.ENVSCI.2016.06.011

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, *67*, 597–611. https://doi.org/10.1016/J.RSER.2016.09.044

NREL. (2002). *SunLine Test Drives Hydrogen Bus*. www.sunline.orgwww.eere.energy.gov/hydrogenandfuelcells

NREL. (2005). *VTA, SamTrans Look into Future with Bus Demo*. https://www.nrel.gov/docs/fy05osti/38265.pdf

NREL. (2006). *AC Transit Demos Three Prototype Fuel Cell Buses*. https://www.nrel.gov/docs/fy06osti/39441.pdf

Nussbaumer, P., Bazilian, M., & Modi, V. (2012). Measuring energy poverty: Focusing on what matters. *Renewable and Sustainable Energy Reviews*, *16*(1), 231–243. https://doi.org/10.1016/J.RSER.2011.07.150

Odenweller, A., Ueckerdt, F., Nemet, G. F., Jensterle, M., & Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. *Nature Energy 2022 7:9*, *7*(9), 854–865. https://doi.org/10.1038/s41560-022-01097-4

OECD. (2007). *Glossary of Key Terms in Evaluation and Results Based Management*. https://www.oecd.org/dac/evaluation/glossaryofkeytermsinevaluationandresultsbasedmanagement.htm

OECD. (2010). *DAC Guidelines and Reference Series Quality Standards for Development Evaluation*. OECD. https://www.oecd.org/development/evaluation/qualitystandards.pdf

OECD. (2011). Towards Green Growth. In *Innovation*. https://doi.org/10.1787/9789264111318-EN

OECD. (2021). Applying Evaluation Criteria Thoughtfully. In *Applying Evaluation Criteria Thoughtfully*. OECD. https://doi.org/10.1787/543E84ED-EN

Ogden, J. M. (1999a). Developing an infrastructure for hydrogen vehicles: a Southern California case study. *International Journal of Hydrogen Energy*, *24*(8), 709–730. https://doi.org/10.1016/S0360-3199(98)00131-1

Ogden, J. M. (1999b). Prospects for Building a Hydrogen Energy Infrastructure. *Annual Review of Energy and the Environment* , *24*, 227–279. https://doi.org/10.1146/ANNUREV.ENERGY.24.1.227

Ogden, J., & Nicholas, M. (2011). Analysis of a "cluster" strategy for introducing hydrogen vehicles in Southern California. *Energy Policy*, *39*(4), 1923–1938. https://doi.org/10.1016/J.ENPOL.2011.01.005

Oliveira, A. M., Beswick, R. R., & Yan, Y. (2021). A green hydrogen economy for a renewable energy society. *Current Opinion in Chemical Engineering*, *33*, 100701. https://doi.org/10.1016/J.COCHE.2021.100701

Osofsky, H. M. (2010). The Future of Environmental Law and Complexities of Scale: Federalism Experiments with Climate Change under the Clean Air Act. *Washington University Journal of Law and Policy*, *32*(79).

Ozturk, I. (2010). A literature survey on energy–growth nexus. *Energy Policy*, *38*(1), 340–349. https://doi.org/10.1016/J.ENPOL.2009.09.024

Pachauri, S. (2011). Reaching an international consensus on defining modern energy access. *Current Opinion in Environmental Sustainability*, *3*(4), 235–240. https://doi.org/10.1016/J.COSUST.2011.07.005

Pack, H., & Saggi, K. (2006). Is There a Case for Industrial Policy? A Critical Survey. *The World Bank Research Observer*, *21*(2), 267–297. https://doi.org/10.1093/WBRO/LKL001

Parikh, A., Shah, M., & Prajapati, M. (2023). Fuelling the sustainable future: a comparative analysis between battery electrical vehicles (BEV) and fuel cell electrical vehicles (FCEV). *Environmental Science and Pollution Research*, *30*(20), 57236–57252. https://doi.org/10.1007/S11356-023-26241-9/TABLES/2

Parris, T. M., & Kates, R. W. (2003). Characterizing and measuring sustainable development. *Annual Review of Environment and Resources*, *28*, 559–586. https://doi.org/10.1146/ANNUREV.ENERGY.28.050302.105551

Patton, M. Q. (2014). Qualitative Research & Evaluation Methods. In *Uniwersytet śląski* (4th ed., Issue 1). SAGE Publications, Inc . https://doi.org/10.2/JQUERY.MIN.JS

Pawłowska, B. (2015). Zrównoważony rozwój transportu jako przykład poprawy efektywności sektora. *Acta Universitatis Lodziensis Folia Oeconomica*, *2*(313), 63–78. https://doi.org/10.18778/0208-6018.313.05

Pearce, D. W., Atkinson, G. D., & Dubourg, W. R. (1994). The economics of sustainable development. *Annual Review Energy Environment*, *19*, 474.

Peneder, M. (2017). Competitiveness and industrial policy: from rationalities of failure towards the ability to evolve. *Cambridge Journal of Economics*, *41*(3), 829–858. https://doi.org/10.1093/CJE/BEW025

Penner, S. S. (2006). Steps toward the hydrogen economy. *Energy*, *31*(1), 33–43. https://doi.org/10.1016/J.ENERGY.2004.04.060

Persson, T., & Tabellini, G. (2004). Constitutions and Economic Policy. *Journal of Economic Perspectives*, *18*(1), 75–98. https://doi.org/10.1257/089533004773563449

Pezzey, J. (1992). *Economic Analysis of Sustainable Growth and Sustainable Development*. The World Bank.

Pezzoli, K. (1997). Sustainable development: A transdisciplinary overview of the literature. *Journal of Environmental Planning and Management*, *40*(5), 549–574. https://doi.org/10.1080/09640569711949

Polak, E., & Polak, W. (2017). Współczesne uwarunkowania polityki gospodarczej. *Prace Naukowe Uniwersytetu Ekonomicznego We Wrocławiu*, *498*, 263–272. https://doi.org/10.15611/pn.2017.498.24

Polish Ministry of Climate and Environment. (2021). *Polska Strategia Wodorowa do roku 2030 z perspektywą do 2040 r.* https://www.gov.pl/web/klimat/rozpoczely-sie-konsultacje-publiczne-projektu-polskiej-strategii-wodorowej

Pollet, B. G., Kocha, S. S., & Staffell, I. (2019). Current status of automotive fuel cells for sustainable transport. *Current Opinion in Electrochemistry*, *16*, 90–95. https://doi.org/10.1016/J.COELEC.2019.04.021

Popp, D. (2003). Pollution Control Innovations and the Clean Air Act of 1990. *Journal of Policy Analysis and Management*, *22*(4), 641–660. https://doi.org/10.1002/PAM.10159

Porter, M. (2000). The value chain and competitive advantage. In D. Barnes (Ed.), *Understanding Business Process* (p. 240). Routledge.

Portney, P. R. (1990). Policy Watch: Economics and the Clean Air Act. *Journal of Economic Perspectives*, *4*(4), 173–181. https://doi.org/10.1257/JEP.4.4.173

Poskrobko, B. (2012). Metodyczne aspekty ekonomii zrównoważonego rozwoju. *Ekonomia i Środowisko*, *3*, 10–27.

Poskrobko, B. (2013). Paradygmat zrównoważonego rozwoju jako wiodący kanon w badaniu nowych obszarów ekonomii. *Ekonomia i Środowisko*, *3*(46), 10–24.

Przychodzen, W., & Przychodzen, J. (2020). Determinants of renewable energy production in transition economies: A panel data approach. *Energy*, *191*, 116583. https://doi.org/10.1016/J.ENERGY.2019.116583

Reddy, B. S. (2015). Access to modern energy services: An economic and policy framework. *Renewable and Sustainable Energy Reviews*, *47*, 198–212. https://doi.org/10.1016/J.RSER.2015.03.058

Reed, J., Dailey, E., Shaffer, B., Lane, B., Flores, R., Fong, A., & Samuelsen, S. (2023). Potential evolution of the renewable hydrogen sector using California as a reference market. *Applied Energy*, *331*, 120386. https://doi.org/10.1016/J.APENERGY.2022.120386

Righter, R. W. (1996). Pioneering in wind energy: The California experience. *Renewable Energy*, *9*(1–4), 781–784. https://doi.org/10.1016/0960-1481(96)88399-6

Riker, W. H. (2018). Federalism. In R. E. Goodin, P. Pettit, & T. Pogge (Eds.), *A Companion to Contemporary Political Philosophy* (pp. 612–620). Blackwell Publishing Ltd. https://doi.org/10.1002/9781405177245.CH32

Robertson, I. M., Sofronis, P., Nagao, A., Martin, M. L., Wang, S., Gross, D. W., & Nygren, K. E. (2015). Hydrogen Embrittlement Understood. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, *46*(6), 2323–2341. https://doi.org/10.1007/S11661-015-2836-1/FIGURES/3

Robinson, J. (2004). Squaring the circle? Some thoughts on the idea of sustainable development. *Ecological Economics*, *48*(4), 369–384. https://doi.org/10.1016/J.ECOLECON.2003.10.017

Rodrik, D. (2007). Industrial Policy for the Twenty-First Century. In *One Economics, Many Recipes: Globalization, Institutions, and Economic Growth* (pp. 1–280). Princeton University Press.

Rodrik, D. (2014). Green industrial policy. *Oxford Review of Economic Policy*, *30*(3), 469–491. https://doi.org/10.1093/OXREP/GRU025

Rogall, H. (2010). *Ekonomia zrownowazonego rozwoju: Teoria i praktyka*. Warszawa: Zysk i S-ka.

Rout, C., Li, H., Dupont, V., & Wadud, Z. (2022). A comparative total cost of ownership analysis of heavy-duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel. *Heliyon*, *8*(12), e12417. https://doi.org/10.1016/J.HELIYON.2022.E12417

Ruggerio, C. A. (2021). Sustainability and sustainable development: A review of principles and definitions. *Science of The Total Environment*, *786*, 147481. https://doi.org/10.1016/J.SCITOTENV.2021.147481

Sadath, A. C., & Acharya, R. H. (2017). Assessing the extent and intensity of energy poverty using Multidimensional Energy Poverty Index: Empirical evidence from households in India. *Energy Policy*, *102*, 540–550. https://doi.org/10.1016/J.ENPOL.2016.12.056

Salvi, B. L., & Subramanian, K. A. (2015). Sustainable development of road transportation sector using hydrogen energy system. *Renewable and Sustainable Energy Reviews*, *51*, 1132–1155. https://doi.org/10.1016/J.RSER.2015.07.030

Sargent, T. J., & Wallace, N. (1976). Rational expectations and the theory of economic policy. *Journal of Monetary Economics*, *2*(2), 169–183. https://doi.org/10.1016/0304-3932(76)90032-5

Saritas, O., Meissner, D., & Sokolov, A. (2019). A Transition Management Roadmap for Fuel Cell Electric Vehicles (FCEVs). *Journal of the Knowledge Economy*, *10*(3), 1183–1203. https://doi.org/10.1007/S13132-018-0523-3/FIGURES/2

Schneider, F., Kallis, G., & Martinez-Alier, J. (2010). Crisis or opportunity? Economic degrowth for social equity and ecological sustainability. Introduction to this special issue. *Journal of Cleaner Production*, *18*(6), 511–518. https://doi.org/10.1016/J.JCLEPRO.2010.01.014

Schoenung, S. M., & Keller, J. O. (2017). Commercial potential for renewable hydrogen in California. *International Journal of Hydrogen Energy*, *42*(19), 13321–13328. https://doi.org/10.1016/J.IJHYDENE.2017.01.005

Schwarzer, J. (2013). Industrial Policy for a Green Economy. In *The International Institute for Sustainable Development*. https://www.iisd.org/system/files/publications/industrial_policy_green_economy.pdf

Sekulova, F., Kallis, G., Rodríguez-Labajos, B., & Schneider, F. (2013). Degrowth: from theory to practice. *Journal of Cleaner Production*, *38*, 1–6. https://doi.org/10.1016/J.JCLEPRO.2012.06.022

Shahab, S., Clinch, J. P., & O’Neill, E. (2017). Impact-based planning evaluation: Advancing normative criteria for policy analysis. *Environment and Planning B: Urban Analytics and City Science*, *46*(3), 534–550. https://doi.org/10.1177/2399808317720446

Sharifi, A., Feng, C., Yang, J., Cheng, W., & Lee, S. (2022). How Green Are the National Hydrogen Strategies? *Sustainability 14*(3), 1930. https://doi.org/10.3390/SU14031930

Sharpe, B., & Basma, H. (2022). *A meta-study of purchase costs for zero-emission trucks*. https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf

Shiva Kumar, S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies*, *2*(3), 442–454. https://doi.org/10.1016/J.MSET.2019.03.002

Smil, V. (2010). *Energy Transitions: History, Requirements, Prospects*. Praeger.

Sokołowski, J., Lewandowski, P., Kiełczewska, A., & Bouzarovski, S. (2020). A multidimensional index to measure energy poverty: the Polish case. *Energy Sources, Part B: Economics, Planning, and Policy*, *15*(2), 92–112.

Soliński, J., & Gawlik, L. (2012). Rys historyczny, rozwój i stan obecny światowego i polskiego sektora energii. *Polski Komitet Światowej Rady Energetycznej*, *March-April*, 142–149.

Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics*, *70*(1), 65–94.

Sorrell, S. (2009). Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy*, *37*(4), 1456–1469. https://doi.org/10.1016/J.ENPOL.2008.12.003

Sovacool, B. K. (2012). The political economy of energy poverty: A review of key challenges. *Energy for Sustainable Development*, *16*(3), 272–282. https://doi.org/10.1016/J.ESD.2012.05.006

Sperling, D., & Eggert, A. (2014). California's climate and energy policy for transportation. *Energy Strategy Reviews*, *5*, 88–94. https://doi.org/10.1016/J.ESR.2014.10.001

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, *12*(2), 463–491. https://doi.org/10.1039/C8EE01157E

Stephens-Romero, S., Carreras-Sospedra, M., Brouwer, J., Dabdub, D., & Samuelsen, S. (2009). Determining air quality and greenhouse gas impacts of hydrogen infrastructure and fuel cell vehicles. *Environmental Science and Technology*, *43*(23), 9022–9029. https://doi.org/10.1021/ES901515Y/SUPPL_FILE/ES901515Y_SI_001.PDF

Stephens-Romero, S. D., Brown, T. M., Kang, J. E., Recker, W. W., & Samuelsen, G. S. (2010). Systematic planning to optimize investments in hydrogen infrastructure deployment. *International Journal of Hydrogen Energy*, *35*(10), 4652–4667. https://doi.org/10.1016/J.IJHYDENE.2010.02.024

Stern, D. I. (2004). Economic Growth and Energy. In C. J. Cleveland (Ed.), *Encyclopedia of Energy* (2nd ed., pp. 35–51). Elsevier.

Stern, D. I. (2011). The role of energy in economic growth. *Annals of the New York Academy of Sciences*, *1219*(1), 26–51. https://doi.org/10.1111/J.1749-6632.2010.05921.X

Steuerle, E., & Jackson, L. M. (2016). Advancing the Power of Economic Evidence to Inform Investments in Children, Youth, and Families. In *Advancing the Power of Economic Evidence to Inform Investments in Children, Youth, and Families*. National Academies Press. https://doi.org/10.17226/23481

Stiglitz, J. E., Lin, J. Y., & Patel, E. (2013). *The Industrial Policy Revolution II: Africa in the Twenty-first Century (International Economic Association Series)* (2013th ed.). Palgrave Macmillan.

Sugihara, C., Hardman, S., & Kurani, K. (2023). Social, technological, and economic barriers to heavy-duty truck electrification. *Research in Transportation Business & Management*, *51*, 101064. https://doi.org/10.1016/J.RTBM.2023.101064

Święcki, T. (2017). Determinants of structural change. *Review of Economic Dynamics*, *24*, 95–131. https://doi.org/10.1016/J.RED.2017.01.007

Szablewski, A. T. (2021). *Transformacja energetyki i jej implikacje gospodarczo-społeczne*. Instytut Nauk Ekonomicznych Polskiej Akademii Nauk.

Szymczyk, K., Şahin, D., Bağcı, H., & Kaygın, C. Y. (2021). The effect of energy usage, economic growth, and financial development on co2 emission management: An analysis of oecd countries with a high environmental performance index. *Energies*, *14*(15). https://doi.org/10.3390/EN14154671

Tabandeh, A., Hossain, M. J., & Li, L. (2022). Integrated multi-stage and multi-zone distribution network expansion planning with renewable energy sources and hydrogen refuelling stations for fuel cell vehicles. *Applied Energy*, *319*, 119242. https://doi.org/10.1016/J.APENERGY.2022.119242

Tabrizian, S. (2019). Technological innovation to achieve sustainable development—Renewable energy technologies diffusion in developing countries. *Sustainable Development*, *27*(3), 537–544. https://doi.org/10.1002/SD.1918

Tagliapietra, S., & Veugelers, R. (2020). *A Green Industrial Policy for Europe* (S. Gardner, Ed.). Bruegel Blueprint Series.

Tarhan, C., & Çil, M. A. (2021). A study on hydrogen, the clean energy of the future: Hydrogen storage methods. *Journal of Energy Storage*, *40*, 102676. https://doi.org/10.1016/J.EST.2021.102676

Tarkowski, R. (2019). Underground hydrogen storage: Characteristics and prospects. *Renewable and Sustainable Energy Reviews*, *105*, 86–94. https://doi.org/10.1016/J.RSER.2019.01.051

Tinbergen, J. (1956). *Economic policy : Principles and design*. Elsevier Science Publishing Co Inc., U.S.

Tobin, J. (1964). Economic Growth as an Objective of Government Policy. *Proceedings of the Seventy-Sixth Annual Meeting of the American Economic Association*, *54*(3), 1–20.

Toktaş-Palut, P. (2023). The fuel cell electric vehicle market growth: Analyses of contracts and government incentives. *Computers & Industrial Engineering*, *176*, 108988. https://doi.org/10.1016/J.CIE.2023.108988

Tolba, M. K. (1987). *Sustainable Development: Constraints and Opportunities*. Butterworths.

Trencher, G. (2020). Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California. *Energy Reports*, *6*, 2503–2519. https://doi.org/10.1016/j.egyr.2020.09.008

Trencher, G., & Edianto, A. (2021). Drivers and Barriers to the Adoption of Fuel Cell Passenger Vehicles and Buses in Germany. *Energies 14*(4), 833. https://doi.org/10.3390/EN14040833

Trencher, G., & Wesseling, J. (2022). Roadblocks to fuel-cell electric vehicle diffusion: Evidence from Germany, Japan and California. *Transportation Research Part D: Transport and Environment*, *112*, 103458. https://doi.org/10.1016/J.TRD.2022.103458

Turoń, K. (2020). Hydrogen-powered vehicles in urban transport systems – current state and development. *Transportation Research Procedia*, *45*, 835–841. https://doi.org/10.1016/j.trpro.2020.02.086

UC Davis. (2002). *Toyota delivers first fuel-cell car to UC Davis*. https://www.ucdavis.edu/news/toyota-delivers-first-fuel-cell-car-uc-davis

UN ECLAC. (2017). *Evaluation Policy and Strategy*. United Nations Economic Commission for Latin America and the Caribbean. https://www.cepal.org/sites/default/files/static/files/evaluation_policy_and_strategy_eclac_2017.pdf

UN PAGE. (2017). *Green Industrial Policy and Trade*. https://archive.un-page.org/files/public/gita_manual_150ppi_full_3.pdf

United Nations. (1972). *Report of the United Nations Conference on the Human Environment*.

United Nations. (1992). Rio Declaration on Environment and Development. http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

United Nations. (2008). *International Standard Industrial Classification of All Economic Activities - Revision 4: Vol. Series M No. 4/Rev.4*.

United Nations. (2015). *Transforming Our World: The 2030 Agenda For Sustainable Development*.

United Nations. (2016). *2030 Agenda for Sustainable Development*. 2030 Agenda for Sustainable Development. https://www.un.org/sustainabledevelopment/development-agenda/

U.S. CDC. (2011). *Overview of Policy Evaluation*. http://www.cdc.gov/

U.S. DOE. (2006). *FreedomCAR and Fuel Partnership Plan*. https://www.hydrogen.energy.gov/pdfs/fc_fuel_partnership_plan.pdf

U.S. DOE. (2011). *American Recovery and Reinvestment Act of 2009: Summary of Annual Merit Review of American Recovery and Reinvestment Act Activities*. https://www.hydrogen.energy.gov/pdfs/review11/52716-12_arra.pdf

U.S. DOE. (2012). *H2USA. Hydrogen and Fuel Cell Technologies Office of the U.S. Department of Energy*. H2USA. https://www.energy.gov/eere/fuelcells/h2usa

U.S. DOE. (2022). *Alternative Fuels Data Center: Fuel Cell Electric Vehicles*. Fuel Cell Electric Vehicles. https://afdc.energy.gov/vehicles/fuel_cell.html

U.S. DOE. (2023). *U.S. National Clean Hydrogen Strategy and Roadmap*. https://www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html

U.S. DOE. (2023). *U.S. National Clean Hydrogen Strategy and Roadmap*. https://www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html

Vacin, G. B., & Eckerle, T. (2020). *Hydrogen Station Permitting Guidebook*. https://business.ca.gov/wp-content/uploads/2019/12/GO-Biz_Hydrogen-Station-Permitting-Guidebook_Sept-2020.pdf

Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews*, *122*, 109547. https://doi.org/10.1016/J.RSER.2019.109547

Vedung, E. (1997). *Public Policy and Program Evaluation*. Routledge Transaction Publishers.

Vijayakumar, V., Jenn, A., & Fulton, L. (2021). Low carbon scenario analysis of a hydrogen-based energy transition for on-road transportation in california. *Energies*, *14*(21). https://doi.org/10.3390/EN14217163

Wachter, L. M., & Wachter, S. M. (1981). *Toward a New U.S. Industrial Policy?* University of Pennsylvania Press Anniversary Collection.

Warwick, K. (2013). Beyond Industrial Policy: Emerging Issues and New Trends. *OECD Science, Technology and Industry Policy Papers*, 1–56.

WCED. (1986). *Our Common Future Towards Sustainable Development 2. Part II. Common Challenges Population and Human Resources 4*.

WEC. (2021). *Working Paper on National Hydrogen Strategies*. https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf

Wesseling, J. H., Farla, J. C. M., & Hekkert, M. P. (2015). Exploring car manufacturers' responses to technology-forcing regulation: The case of California's ZEV mandate. *Environmental Innovation and Societal Transitions*, *16*, 87–105. https://doi.org/10.1016/J.EIST.2015.03.001

Wiesmeth, H. (2022). The Price-Standard Approach to Environmental Policy. In H. Wiesmeth (Ed.), *Environmental Economics* (pp. 183–210). Springer. https://doi.org/10.1007/978-3-031-05929-2_10

Winiarski, B., Borowiec, J., Broszkiewicz, R., Cybulski, L., Gogolewska, J., Jenik, A., Klamut, M., Korenik, S., Pancer-Cybulska, E., Patrzałek, L., Przybyła, Z., Szostak, E., Wilk, K., & Winiarska, F. (2012). *Polityka gospodarcza* (B. Winiarski, Ed.). Wydawnictwo naukowe PWN.

Winzer, C. (2012). Conceptualizing energy security. *Energy Policy*, *46*, 36–48. https://doi.org/10.1016/J.ENPOL.2012.02.067

Woźniak, M. G. (2008). *Wzrost gospodarczy: podstawy teoretyczne* (2nd ed.). Wydawnictwo Uniwersytetu Ekonomicznego w Krakowie.

WTO/IAE/IRENA/UN/WHO. (2022). *Tracking SDG7: The energy progress report 2022*. www.worldbank.org

Wu, M., & Salzman, J. (2014). The next generation of trade and environment conflicts: the rise of green industrial policy. *Northwerstern University Law Review*, *108*(2), 401–474.

Yang, C., & Ogden, J. (2007). Determining the lowest-cost hydrogen delivery mode. *International Journal of Hydrogen Energy*, *32*(2), 268–286. https://doi.org/10.1016/J.IJHYDENE.2006.05.009

Yeh, S., Witcover, J., Lade, G. E., & Sperling, D. (2016). A review of low carbon fuel policies: Principles, program status and future directions. *Energy Policy*, *97*, 220–234. https://doi.org/10.1016/J.ENPOL.2016.07.029

Zakari, A., Khan, I., Tan, D., Alvarado, R., & Dagar, V. (2022). Energy efficiency and sustainable development goals (SDGs). *Energy*, *239*, 122365. https://doi.org/10.1016/J.ENERGY.2021.122365

Zhang, R., & Zhang, J. (2021). Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. *Transport Policy*, *110*, 28–36. https://doi.org/10.1016/J.TRANPOL.2021.05.018

Zilberman, D. (2014). The Economics of Sustainable Development. *American Journal of Agricultural Economics*, *96*(2), 385–396.

Zivar, D., Kumar, S., & Foroozesh, J. (2021). Underground hydrogen storage: A comprehensive review. *International Journal of Hydrogen Energy*, *46*(45), 23436–23462. https://doi.org/10.1016/J.IJHYDENE.2020.08.138

Zuo, X., Hua, H., Dong, Z., & Hao, C. (2017). Environmental Performance Index at the Provincial Level for China 2006–2011. *Ecological Indicators*, *75*, 48–56. https://doi.org/10.1016/J.ECOLIND.2016.12.016

Züttel, A. (2004). Hydrogen storage methods. *Naturwissenschaften*, *91*(4), 157–172. https://doi.org/10.1007/S00114-004-0516-X/FIGURES/6

LEGISLATIVE ACTS

The US federal level

The Federal Air Quality Act, 42 US Code, §7401 et seq. (1967).

The Clean Air Act, 42 US Code, §7401 et seq. (1970).

The National Environmental Policy Act, 42 US Code §4321 et seq. (1970).

The Energy Policy and Conservation Act, 42 US Code §§ 6272-6273, 6294 (1975).

The Public Utilities Regulatory Policies Act, 16 US Code ch. 46 §2601 et seq. (1978).

The Energy Policy Act, 16 US Code, ch. 46 §2601, et seq., 42 US Code, ch. 134 §13201 et seq. (1992).

The Energy Policy Act, 42 US Code, ch. 149 §15801 et seq. (2005).

The Alternative Fuel Infrastructure Tax Credit, 26 US Code, §30C, §30D, and §38 (2005).

The Energy Independence and Security Act, 42 US Code, ch. 152, §17001 et seq. (2007).

The American Recovery and Reinvestment Act, Public law 111-5 (2009).

The Public Transportation Innovation Act, 49 US Code §5312 and §5339 et seq. (2012).

The Fixing America's Surface Transportation Act, Public Law 114-94 (2015).

The Credit for alcohol fuel, biodiesel, and alternative fuel mixtures, Internal Revenue Service, 26 US Code, §6426 et seq. (2018).

The Regional Clean Hydrogen Hubs, 42 US Code, §16161a. et seq. (2021).

The Truck Emissions Reduction Study and Grant at Port Facilities, 23 US Code, §151 and Public Law 117-58 (2021).

The Infrastructure Investment and Jobs Act, Public Law 117-58 (2021).

The Charging and Fueling Infrastructure Discretionary Grant Program, 23 US Code, §151 (2021).

The Inflation Reduction Act, Public Law 117-169 (2022).

The Hydrogen Production Tax Credit, 26 US Code, §45V et seq. (2022).

California state level

Assembly Bill 1007, Pavley, *Air quality: alternative fuels* (2004).

Assembly Bill 118, Núñez, *Alternative fuels and vehicle technologies: funding programs* (2007).

Assembly Bill 2061, Ting, *Transportation electrification: electric vehicle charging infrastructure* (2014).

Assembly Bill 2289, Eng, *Smog check program: testing: penalties* (2010).

Assembly Bill 32, Pavley, Núñez, *The Global Warming Solutions Act* (2006).

Assembly Bill 544, Bloom, *Vehicles: high-occupancy vehicle lanes* (2017).

Assembly Bill 630, Cooper, *Vehicles: retirement and replacement* (2017)

Assembly Bill 71, Cunneen, *High-occupancy vehicle lanes: low-emission vehicles* (1999).

Assembly Bill 739, Chau, State vehicle fleet: purchases (2017).

Assembly Bill 8, Perea, *Alternative fuel and vehicle technologies: funding programs* (2013).

California Code of Regulations, §1960.1. *Exhaust Emission Standards and Test Procedures,* (1987).

California Code of Regulations, §4181.

California Health & Safety Code, §39000 et seq., *The Mulford-Carrell Air Resources Act* (1967).

California Health & Safety Code, §39719.2(c) and (d).

California Health and Safety Code, §43018.9.

California Health and Safety Code, §44274 and §44258.4. (2019).

California Public Resources Code, §21000–21189 et seq., *The California Environmental Quality Act* (1970).

California Public Resources Code, §25000 et seq., *The Warren-Alquist State Energy Resources Conservation and Development Act* (1974).

California Revenue and Taxation Code, §6377, *Zero Emission Transit Buses Tax Exemptions* (2019).

California Vehicle Code, §5205.5 and §21655.9, *High Occupancy Vehicle and High Occupancy Toll Lane Exemption.*

Executive Order N-79-20, Newsom, Gavin, California's Governor (2020).

Executive Order S-7-04, Schwarzenegger, Arnold, California's Governor (2006).

Senate Bill 110, Riches, California Transportation Commission: guidelines (2012).

Senate Bill 1204, Lara and Pavley, *Vehicle emissions reductions: California Clean Truck, Bus, and Off-Road Vehicle and Equipment Technology Program* (2014).

Senate Bill 1505, Lowenthal, *Fuel: hydrogen alternative fuel* (2006).

Senate Bill 350, De Leon, *The Clean Energy and Pollution Reduction Act* (2015).

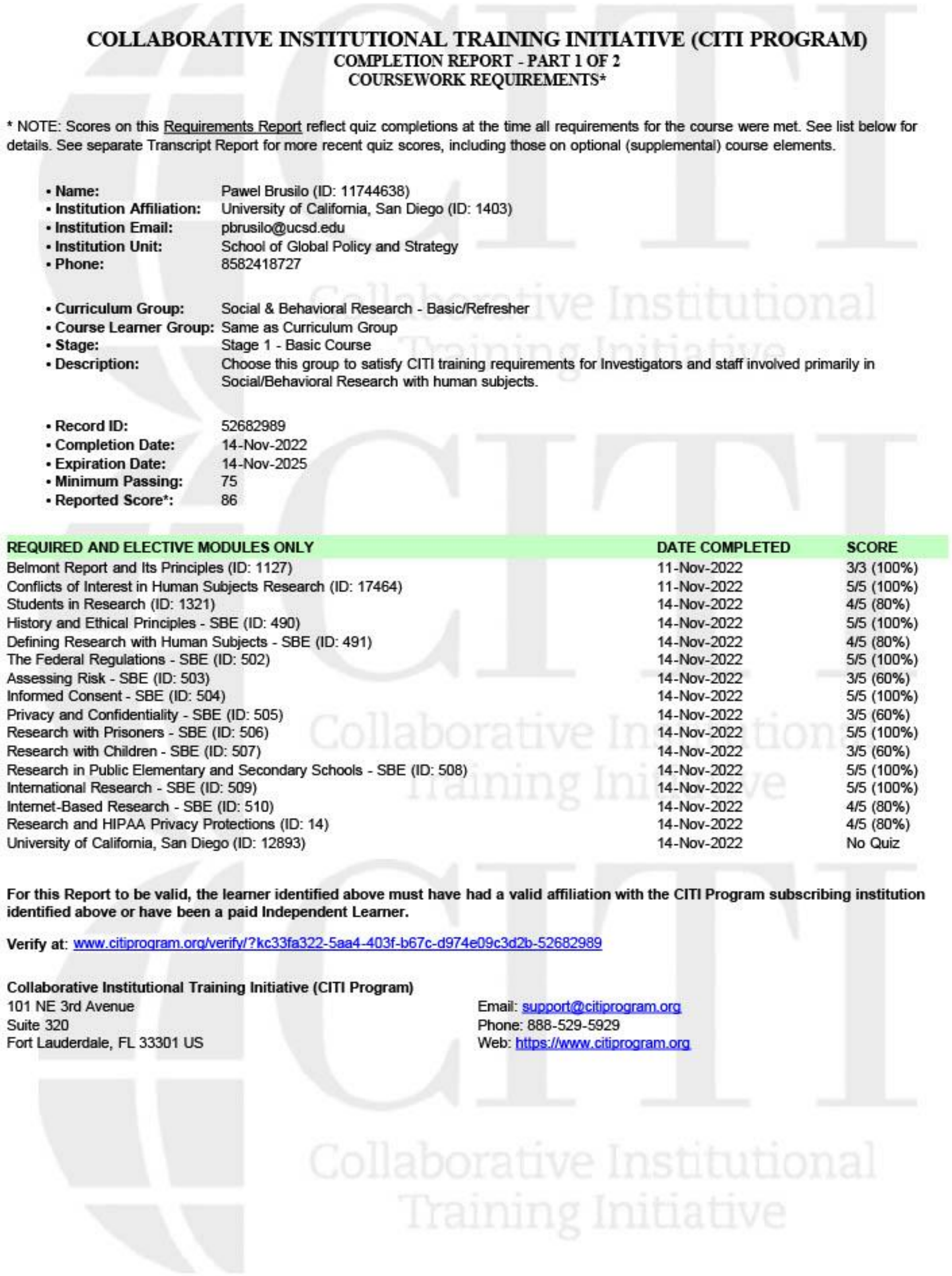
Senate Bill 375, Steinberg, *The California Sustainable Communities and Climate Protection Act* (2008).

Senate Bill 73, Wiener, *Energy: Proposition 39 implementation. California Clean Energy Jobs Act* (2013).

Senate Bill 76, Geller, *California Hydrogen Highway Network* (2005).

APPENDIXES

Appendix A. Certification of compliance and awareness of the research ethics and data processing in the case of conducting the research with human subjects.



COLLABORATIVE INSTITUTIONAL TRAINING INITIATIVE (CITI PROGRAM)
COMPLETION REPORT - PART 1 OF 2
COURSEWORK REQUIREMENTS*

* NOTE: Scores on this Requirements Report reflect quiz completions at the time all requirements for the course were met. See list below for details. See separate Transcript Report for more recent quiz scores, including those on optional (supplemental) course elements.

- **Name:** Pawel Brusilo (ID: 11744638)
- **Institution Affiliation:** University of California, San Diego (ID: 1403)
- **Institution Email:** pbrusilo@ucsd.edu
- **Institution Unit:** School of Global Policy and Strategy
- **Phone:** 8582418727

- **Curriculum Group:** Social & Behavioral Research - Basic/Refresher
- **Course Learner Group:** Same as Curriculum Group
- **Stage:** Stage 1 - Basic Course
- **Description:** Choose this group to satisfy CITI training requirements for Investigators and staff involved primarily in Social/Behavioral Research with human subjects.

- **Record ID:** 52682989
- **Completion Date:** 14-Nov-2022
- **Expiration Date:** 14-Nov-2025
- **Minimum Passing:** 75
- **Reported Score*:** 86

REQUIRED AND ELECTIVE MODULES ONLY	DATE COMPLETED	SCORE
Belmont Report and Its Principles (ID: 1127)	11-Nov-2022	3/3 (100%)
Conflicts of Interest in Human Subjects Research (ID: 17464)	11-Nov-2022	5/5 (100%)
Students in Research (ID: 1321)	14-Nov-2022	4/5 (80%)
History and Ethical Principles - SBE (ID: 490)	14-Nov-2022	5/5 (100%)
Defining Research with Human Subjects - SBE (ID: 491)	14-Nov-2022	4/5 (80%)
The Federal Regulations - SBE (ID: 502)	14-Nov-2022	5/5 (100%)
Assessing Risk - SBE (ID: 503)	14-Nov-2022	3/5 (60%)
Informed Consent - SBE (ID: 504)	14-Nov-2022	5/5 (100%)
Privacy and Confidentiality - SBE (ID: 505)	14-Nov-2022	3/5 (60%)
Research with Prisoners - SBE (ID: 506)	14-Nov-2022	5/5 (100%)
Research with Children - SBE (ID: 507)	14-Nov-2022	3/5 (60%)
Research in Public Elementary and Secondary Schools - SBE (ID: 508)	14-Nov-2022	5/5 (100%)
International Research - SBE (ID: 509)	14-Nov-2022	5/5 (100%)
Internet-Based Research - SBE (ID: 510)	14-Nov-2022	4/5 (80%)
Research and HIPAA Privacy Protections (ID: 14)	14-Nov-2022	4/5 (80%)
University of California, San Diego (ID: 12893)	14-Nov-2022	No Quiz

For this Report to be valid, the learner identified above must have had a valid affiliation with the CITI Program subscribing institution identified above or have been a paid Independent Learner.

Verify at: www.citiprogram.org/verify/?kc33fa322-5aa4-403f-b67c-d974e09c3d2b-52682989

Collaborative Institutional Training Initiative (CITI Program)
101 NE 3rd Avenue
Suite 320
Fort Lauderdale, FL 33301 US

Email: support@citiprogram.org
Phone: 888-529-5929
Web: https://www.citiprogram.org

COLLABORATIVE INSTITUTIONAL TRAINING INITIATIVE (CITI PROGRAM)
COMPLETION REPORT - PART 2 OF 2
COURSEWORK TRANSCRIPT**

** NOTE: Scores on this Transcript Report reflect the most current quiz completions, including quizzes on optional (supplemental) elements of the course. See list below for details. See separate Requirements Report for the reported scores at the time all requirements for the course were met.

- **Name:** Pawel Brusilo (ID: 11744638)
- **Institution Affiliation:** University of California, San Diego (ID: 1403)
- **Institution Email:** pbrusilo@ucsd.edu
- **Institution Unit:** School of Global Policy and Strategy
- **Phone:** 8582418727

- **Curriculum Group:** Social & Behavioral Research - Basic/Refresher
- **Course Learner Group:** Same as Curriculum Group
- **Stage:** Stage 1 - Basic Course
- **Description:** Choose this group to satisfy CITI training requirements for Investigators and staff involved primarily in Social/Behavioral Research with human subjects.

- **Record ID:** 52682989
- **Report Date:** 30-Oct-2023
- **Current Score**:** 86

REQUIRED, ELECTIVE, AND SUPPLEMENTAL MODULES	MOST RECENT	SCORE
History and Ethical Principles - SBE (ID: 490)	14-Nov-2022	5/5 (100%)
Defining Research with Human Subjects - SBE (ID: 491)	14-Nov-2022	4/5 (80%)
The Federal Regulations - SBE (ID: 502)	14-Nov-2022	5/5 (100%)
Belmont Report and Its Principles (ID: 1127)	11-Nov-2022	3/3 (100%)
Assessing Risk - SBE (ID: 503)	14-Nov-2022	3/5 (60%)
Informed Consent - SBE (ID: 504)	14-Nov-2022	5/5 (100%)
Privacy and Confidentiality - SBE (ID: 505)	14-Nov-2022	3/5 (60%)
Research with Prisoners - SBE (ID: 506)	14-Nov-2022	5/5 (100%)
Research with Children - SBE (ID: 507)	14-Nov-2022	3/5 (60%)
Research in Public Elementary and Secondary Schools - SBE (ID: 508)	14-Nov-2022	5/5 (100%)
University of California, San Diego (ID: 12893)	14-Nov-2022	No Quiz
International Research - SBE (ID: 509)	14-Nov-2022	5/5 (100%)
Internet-Based Research - SBE (ID: 510)	14-Nov-2022	4/5 (80%)
Students in Research (ID: 1321)	14-Nov-2022	4/5 (80%)
Research and HIPAA Privacy Protections (ID: 14)	14-Nov-2022	4/5 (80%)
Conflicts of Interest in Human Subjects Research (ID: 17464)	11-Nov-2022	5/5 (100%)

For this Report to be valid, the learner identified above must have had a valid affiliation with the CITI Program subscribing institution identified above or have been a paid Independent Learner.

Verify at: www.citiprogram.org/verify/?kc33fa322-5aa4-403f-b67c-d974e09c3d2b-52682989

Collaborative Institutional Training Initiative (CITI Program)
101 NE 3rd Avenue
Suite 320
Fort Lauderdale, FL 33301 US

Email: support@citiprogram.org
Phone: 888-529-5929
Web: https://www.citiprogram.org

Appendix B. Invitation email sent to candidates for research participants

Dear (name of candidate),

My name is Pawel Brusilo, and I am a visiting Ph.D. student at the University of California San Diego, sponsored under a Fulbright-Schuman fellowship and working with Prof. David Victor in the School of Global Policy and Strategy. Our research focuses on evaluating the impact of California's policies on the fuel cell electric vehicle market development. I want to determine whether state policies have succeeded in spurring market growth and what lessons can be learned and applied in other jurisdictions.

I would like to invite you to participate in an online 30-minute structured interview. The study seeks a range of expert perspectives, and given your professional background as *(…position or function in a company/organization/institution…)*, your insight would be extremely valuable.

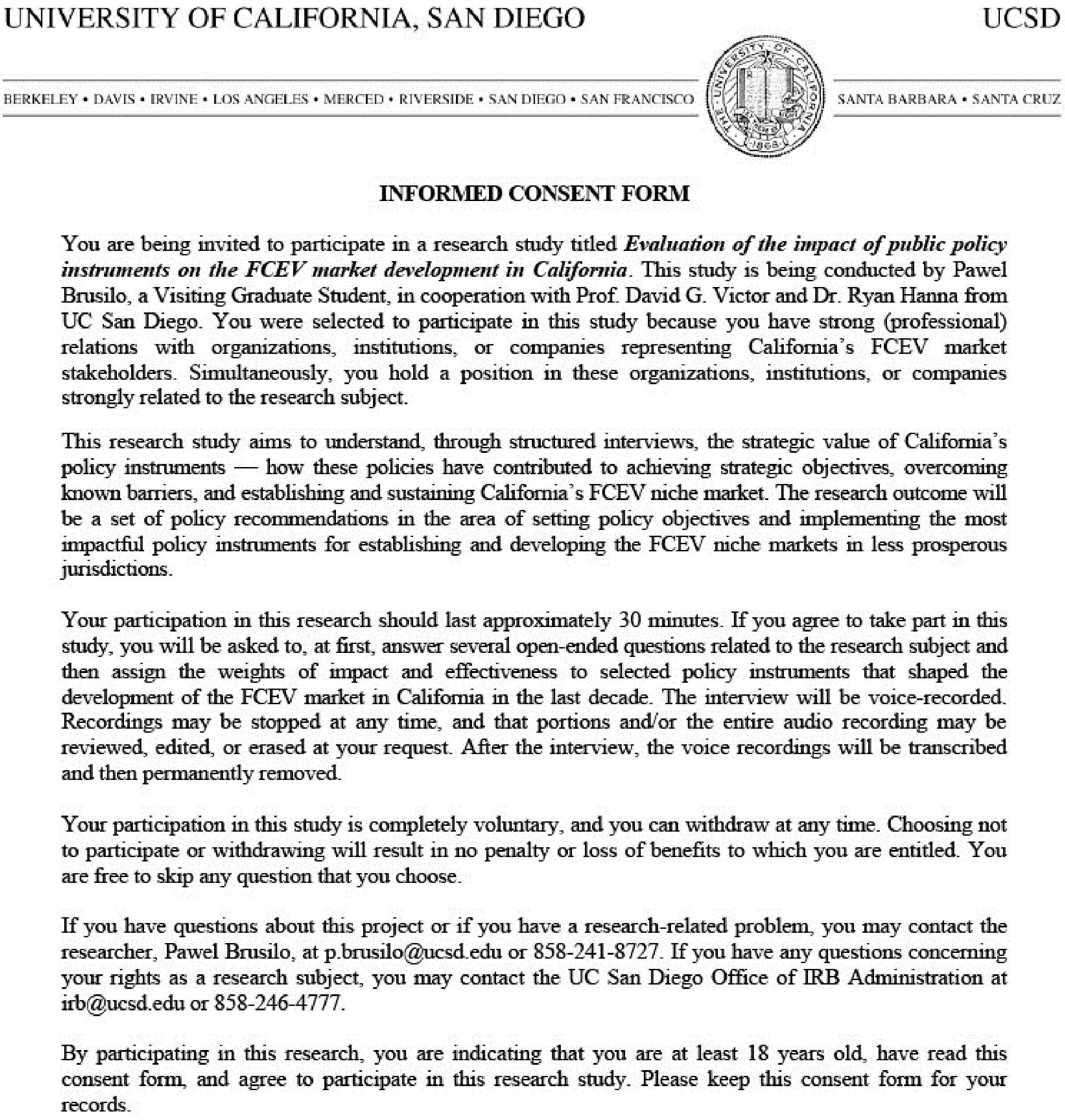
The interview will involve asking you a few open-ended questions about the effectiveness of individual policy instruments in overcoming known barriers to establishing and growing California's FCEV niche market. The outcome will be a set of policy recommendations for jurisdictions such as my home country, Poland, aiming to establish and develop domestic FCEV markets.

If you are willing to participate in the interview, **please suggest a day and time in** *(…month…)* that will be the most convenient for you. Attached you can find the Informed Consent Form. If you have any questions, please do not hesitate to ask.

Yours sincerely,

Pawel Brusilo
Visiting Graduate Student | Fulbright-Schuman Foreign Student
Deep Decarbonization Initiative
Center for Global Transformation
School of Global Policy and Strategy
University Of California, San Diego
US: +1 (858) 241 8727
E-mail: pbrusilo@ucsd.edu
Feel invited to visit my website: www.pawelbrusilo.com

Appendix C. Informed Consent Form submitted to the candidates to research participants



UNIVERSITY OF CALIFORNIA, SAN DIEGO UCSD

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

INFORMED CONSENT FORM

You are being invited to participate in a research study titled ***Evaluation of the impact of public policy instruments on the FCEV market development in California***. This study is being conducted by Pawel Brusilo, a Visiting Graduate Student, in cooperation with Prof. David G. Victor and Dr. Ryan Hanna from UC San Diego. You were selected to participate in this study because you have strong (professional) relations with organizations, institutions, or companies representing California's FCEV market stakeholders. Simultaneously, you hold a position in these organizations, institutions, or companies strongly related to the research subject.

This research study aims to understand, through structured interviews, the strategic value of California's policy instruments — how these policies have contributed to achieving strategic objectives, overcoming known barriers, and establishing and sustaining California's FCEV niche market. The research outcome will be a set of policy recommendations in the area of setting policy objectives and implementing the most impactful policy instruments for establishing and developing the FCEV niche markets in less prosperous jurisdictions.

Your participation in this research should last approximately 30 minutes. If you agree to take part in this study, you will be asked to, at first, answer several open-ended questions related to the research subject and then assign the weights of impact and effectiveness to selected policy instruments that shaped the development of the FCEV market in California in the last decade. The interview will be voice-recorded. Recordings may be stopped at any time, and that portions and/or the entire audio recording may be reviewed, edited, or erased at your request. After the interview, the voice recordings will be transcribed and then permanently removed.

Your participation in this study is completely voluntary, and you can withdraw at any time. Choosing not to participate or withdrawing will result in no penalty or loss of benefits to which you are entitled. You are free to skip any question that you choose.

If you have questions about this project or if you have a research-related problem, you may contact the researcher, Pawel Brusilo, at p.brusilo@ucsd.edu or 858-241-8727. If you have any questions concerning your rights as a research subject, you may contact the UC San Diego Office of IRB Administration at irb@ucsd.edu or 858-246-4777.

By participating in this research, you are indicating that you are at least 18 years old, have read this consent form, and agree to participate in this research study. Please keep this consent form for your records.

Appendix D. Political and legal arguments for FCEV market development in California

THEME (with frequency)	CODES SYNTHESIZED TO SUB-THEMES	CONTRIBUTORS
Improving air quality and addressing state-level environmental objectives (16)	• California aims to reduce GHG emissions from transportation sector • California sets ambitious climate-neutrality objectives • California recognizes health costs associated with air pollution • California aims at promoting only clean hydrogen • California aims at mitigating environmental costs associated with hydrogen production from methane (i.e., by applying CCUS) • FCEVs are recognized as a leading technology for achieving cleaner air and mitigating climate impacts of transportation sector	1H, 2E, 2F, 3B, 3E, 3G, 5A, 5G, 5H, 5J, 6B, 6E,
Technology-neutral (agnostic) approach toward ZEV market development (29)	• California represents a multi-technological approach for emission reduction from transportation • State policy is based on technological-neutrality • Regulatory framework and policy instruments equally support all ZEV options, particularly FCEV and BEV	1C, 1D, 1E, 1H, 2A, 2E, 3B, 3F, 3G, 3H, 4D, 4E, 5B, 5F, 6A, 6B, 6C, 6E
California has a longstanding tradition of FCEV support (15)	• California represented early initiatives and demonstration projects, • California has a long history of hydrogen refuling infrastructure and FCEV market development, • California represents a holistic approach, encompassing entire hydrogen economy value chain • California demonstrates high policy adaptably	1C, 2A, 4B, 4E, 5B, 5C, 5E, 5G, 5H, 6B, 6C, 6E
Biased and unequal state support for FCEVs vs. BEVs (18)	• Disproportionate allocation of funding between FCEV and BEV despite technology-neutral policy approach • Public utility providers are more involved on the BEV side • California state agencies are ideological biased – some toward BEVs and others toward FCEVs • Lack of equal representation of FCEV-lobbyist in policy-making process. • Policymakers' perceptions of BEV and FCEV investments is biased due to the expectations of fast gains resulting from the policy cycle	1E, 1F, 1H, 2A, 3G, 4A, 4E, 5G, 5H
California wants to be a global leader in ZEV deployment (12)	• California played a role of global ZEV innovator • Progressive culture and forward-thinking policy objectives • Job creation and attracting foreign investments	1C, 1D, 2E, 3A, 4B, 4C,
Cluster strategy of FCEV market development (9)	• Evolution from broad strategies to cluster approach • Clafiornia recognizes the significance of early adopters and strategic locations for the stations • California relies on public-private partnership and funding	3B, 3H, 4D, 5D, 5J, 6F

Appendix E. Socio-economic arguments for FCEV market development in California

THEME (with frequency)	CODES SYNTHESIZED TO SUB-THEMES	CONTRIBUTORS
100% electrification is impossible without FCEVs (21)	• Different users represent diverse usage needs and scenarios • Both technologies meet refueling/charging infrastructure development barriers • Both FCEVs and BEVs have technological limitations • The key differentiators are economies of scale and cost-effectiveness in terms of large scale deployments	3B, 3F, 3G, 3H, 4A, 4B, 4E, 4F, 5C, 5E, 5G, 5H, 6A, 6B, 6C, 6D, 6E
BEVs are dominating the ZEV market (24)	• The upfront CAPEX and infrastructure required for singular BEV is more attractive, • The BEVs and FCEVs represent different technology readiness, • BEVs face range limitations, but more developed charging infrastructure favors they deployment • Consumer perception and adaptability favor BEVs • Consumer awareness about FCEV is lacking • Policy support has further bolstered BEV at an initial stage • Industry structure determines the BEV success – the entry barriers are weaker resulting in higher number of startups, while FCEVs are developed by legacy automakers	1B, 1C, 1D, 1H, 2C, 2E, 3A, 3F, 3G, 4A, 4C, 4D, 4E, 5F, 5G, 6A, 6B, 6E
BEVs are not one-size-fits-all solutions (25)	• BEVs are not suitable for people living in densely populated areas without dedicated parking spaces, • BEVs may not be suitable for heavier-duty or long-range applications due to on-road vehicle weight limits • People without home charging infrastructure or those with long, irregular commutes might prefer FCEVs	1B, 1C, 2C, 2E, 2H, 3B, 3D, 3E, 3F, 3G, 4A, 4D, 4E, 5C, 5E, 6A, 6B, 6C, 6D
Developing refueling stations to offer equal opportunities in the context of BEVs (10)	• The policy instruments are indispensable, • The infrastructure is developed in cooperation with automakers, • Data-driven infrastructure planning and development targeted at early adopters	1A, 2E, 2F, 3H, 4B,5H, 6A, 6B,
FCEVs drive down the marginal cost of infrastructure development (4)	• There exists an initial cost barrier for hydrogen infrastructure, • Large-scale deployment causes increasing economies of scale • Hydrogen refueling infrastructure for large fleets offer a higher spece efficiency, • BEVs demonstrate higher electric energy demand, thereby requiring the enlargement of power grid substations • FCEVs offer a higher convenience factor for early adopters	1B, 1E, 2A
FCEVs have better-scaling potential than BEVs (8)	• BEVs offer a cost-effective and simpler entry point • FCEVs offer economic efficiency at scale	1A, 1B, 1F, 2A, 4C, 4E, 6D
FCEVs increase fleet efficiency - better duty cycles (7)	• FCEV fleet offer higher efficiency through improved duty cycles and operational flexibility • FCEVs demonstrate comparable operational characteristics of traditional CNG and diesel vehicles (ICEV) • FCEVs are operationally more efficient than BEVs • FCEVs fill a critical gap in the market, particularly for sectors hard to electrify (i.e., medium- and heavy-duty).	1A, 1E, 4A, 4F, 6C, 6D, 6E
FCEVs match ICEVs' utilization patterns and users' habits (7)	• FCEVs offer convenient and quick refueling process • Drivers can easily switch from ICEVs to FCEVs, • Hydrogen-powered vehicles functionally resemble ICEVs • FCEVs are a suitable replacements across a broad spectrum of diesel applications • Cost-effectiveness of FCEVs as compared to ICEVs	2E, 2H, 4A, 5C, 5G
The need to decrease hydrogen fuel prices (11)	• The costs associated with hydrogen fuel remain prohibitive for further development • Fluctuating hydrogen prices • Increasing economies of scale as a potential solution • High cost of hydrogen fuel is actively discouraging potential FCEV owners	2C, 2H, 3D, 3G, 4F, 6C, 6E

California policy was primarily oriented at a light-duty FCEV market segment (18)	• The initial policy emphasis was on light-duty vehicles • California demonstrates a shift in policy orientation toward FCET and FCEB segments • Light-duty-policy-oriented approach failed	3G, 3H, 4B, 4D, 4E, 5B, 5E, 5G, 5H, 6B, 6C, 6E
The policy is oriented at sizing the potential of hydrogen-powered fuel cell buses and MD/HD trucks (31)	• Gradual progression from light-duty FCEVs to FCETs and FCEBs • BEV lobbyists push hydrogen into the heavy-duty segment to eliminate competition in the light-duty segment • Technology is somewhat stagnant in light-duty applications • The OEMs' focus is shifting to FCET and FCEB applications	1B, 2E, 3G, 3H, 4B, 4C, 4D, 4E, 4F, 5B, 5E, 5F, 5G, 6A, 6B, 6C, 6D, 6E,
Predictions about the FCEV market development (18)	• Hydrogen should reach *cost-per-mile* parity with both BEVs and diesel, • Large fleet operators, capable of absorbing risks, as early FCEV adopters, • Competition between advancing BEV and FCEV technology.	1A, 1B, 1E, 3A, 3B, 3D, 3F, 3G, 5B, 5C,
The policy oriented at sizing synergy across FCEV market segments (14)	• Increasing economies of scale thanks to large deployment programs • Light-duty FCEVs drive down the price of fuel cell stacks, • MD/HD FCETs and FCEBs drive down the cost of hydrogen fuel	1B, 3D, 4A, 4D, 5A, 5G, 6A, 6C, 6D, 6E
Minorities and Less Favourable Communities in Transit and Environmental Sustainability (3)	• Transit, environmental sustainability, and socio-economic equity, • Social and energy equity-driven approach, • Disadvantaged communities are in the scope of the policy • Environmental sustainability and community well-being	2C, 2H, 5C

Appendix F. Technological arguments for FCEV market development in California

THEME (with frequency)	**CODES SYNTHESIZED TO SUB-THEMES**	**CONTRIBUTORS**
The policy oriented at sizing the lower weight of FCEV power modules (6)	• Diverse payload capacity of FCEVs and BEVs • Versatility across vehicle classes (mainly FCETs) • Range and operational context for FCETs • 2000-pound weight exempt as a primary regulatory constraint • Lower power module weights of FCEVs in contrast to BEVs	1C, 2E, 3B, 4F, 6E
FCEVs excel where longer ranges and shorter refueling times are required (14)	• Range advantages over BEVs • Shorter refueling times • Operational and logistical ease • Heavy-duty applications for FCEVs	1C, 1E, 1H, 2A, 2C, 2E, 2H, 3H, 4F, 5E
FCEVs' operation doesn't overload the power grid (10)	• Highlighting hydrogen's role in supplementing the power grid for major BEV charging facilities • Unreliability of the electric grid in California • Regulatory dimension - outlining the bureaucratic complexities and timelines in grid expansions	1A, 1H, 2B, 2C, 4A, 6D
Hydrogen resembles the CNG experiences in terms of fleet operations and vehicle functionalities (12)	• Challenges of CNG infrastructure • Long experience with CNG provides transit agencies with an easier transition to hydrogen • Cost considerations, especially in the context of total cost of ownership • CNG space-constrained yard operations can equally benefit from hydrogen.	1E, 2A, 2B, 2H, 5J

Appendix G. Confrontation of qualitative and quantitative results regarding the effectiveness of the individual green industrial policy instruments

THEME (with frequency)	**CODES SYNTHESIZED TO SUB-THEMES**	**CONTRIBUTORS**
The impact of Fuelling Infrastructure Grants (21)	• Underwriting economic risks for station developers • Cost-sharing support for developers • Helping with initial costs and maintenance • Subsidizing high capital (CapEx) costs • Technology for fueling stations must fit the geographical and climatic needs of their locations • Shift towards self-sufficiency and a profitable business model	1H,2H, 3B, 3D, 3E, 4A, 4B, 4D, 4F, 5B, 5C, 5E, 5F, 5G, 5J, 6A, 6D.
The impact of Low Carbon Fuel Standard with ZEV Infrastructure Crediting (52)	• LCFS as a major driving force for the clean hydrogen demand • LCFS incentivizes a range of low-carbon fuels • LCFS as the most influential global decarbonization policy • The market's sensitivity to costs and the viability of regulations • LCFS benefits are skewed towards end-sellers and consumers overlooking hydrogen producers • Use of tradable credits for fostering a sustainable and low-cost hydrogen production market • Potential for extending LCFS HRI credits to heavy-duty stations	1A, 1B, 1D, 1E, 1F, 1H, 2A, 2C, 2E, 2H, 3A, 3B, 3E, 3G, 3H, 4A, 4D, 4E, 4F, 5A, 5B, 5C, 5E, 5F, 5G, 5H, 5J, 6A, 6B, 6C, 6D, 6E,
The impact of sales requirement for ZEV manufacturers and Tradable ZEV credits for OEMs (ZEV Regulation) (35)	• Need to employ regulations and tradable credits to guide OEMs • Current mandates do little for specialized zero-emission OEMs • Subsidies must accompany mandates • *Carrot and stick* approach	1B, 1D, 1E, 1F, 1H, 2A, 2B, 3A, 3B, 3E, 4A, 4B, 4D, 4E, 4F, 5C, 5E, 5G, 5J, 6A, 6B, 6C, 6E.
The impact of hydrogen fuel measurement and standards with specific clean hydrogen requirements (10)	• Importance of hydrogen purity and standards • The trade-off between regulations and cost • Tradable credits and subsidies	1B, 1H, 2H, 3D, 4E, 5B, 5E, 5J, 6A, 6B
The impact of station building standards, safety codes, and CEQA (28)	• Uniformity of refueling stations • Safety imperative expressed in standards and codes • The bottlenecks caused by regulations and CEQA • The complexity of localized implementation • The inadequacy of codes as a standalone solution	1E, 1F, 1H, 2C, 2F, 2H, 3A, 3D, 3G, 4A, 4D, 4E, 5D, 5F, 6A, 6C, 6D,
The impact of permitting and local regulatory approval (7)	• Variability across jurisdictions • Time-consuming processes • Safety and technical standards • Relative speed compared to other energy solutions • Comparisons with other energy infrastructures	1B, 1E, 1H, 5B, 5D, 6D
The impact of Bus Replacement Grants, LD-ZEV Rebates, CVRP program, HVIP Vouchers, and Emissions Reductions Grants (35)	• Necessity of subsidies in market development • Subsidies and consumer incentives • Comprehensive approaches - push-and-pull strategy • Effect on different stakeholders and sectors • Specific programs and flexibility • Technological feasibility and regulatory implications • HVIP as a crucial instrument in mitigating the substantial cost differential	1A, 1B, 1D, 1E, 2H, 3A, 3B, 3D, 4A, 4B, 5B, 5F, 5G, 6B, 6C
The impact of ZEV purchase requirements for transit buses, airports, and other public fleets (36)	• Direct demand stimulation • Importance of subsidies and incentive programs • Effectiveness of regulation • Creation of demand through regulation • Equal importance of regulations and subsidies	1A, 1E, 1F, 1H, 2B, 2C, 2H, 4A, 4B, 5F, 5G, 6B, 6C, 6D, 6E
The Impact of ZEV Infrastructure Support and Hydrogen Fuelling Station Evaluation (13)	• Analysis of locating the refueling stations • Information policy's role • Community resistance and safety concerns	1B, 1E, 1H, 2H, 3G, 4A, 4D, 4E, 6C

The impact of tax credits, i.e., Transit Bus Tax Exemption or Federal hydrogen production tax credit (7)	• High taxes slow FCEV adoption rates • Limited impact of current tax credits • The role of subsidies and tradable credits • The role of tax incentives for transit buses • Tax exemptions for FCEV heavy-duty vehicles	1F, 1H, 2A, 4A, 6C
The impact of HOV access and ZEV weight exemption (20)	• Weight exemption as a comparative benefit over BEVs • Weight exempt as a source of increased road maintenance costs • Varying Opinions on the Impact of HOV Lane Access	1E, 1F, 2B, 2H, 3H, 4B, 4C, 4E, 5B, 5E, 6A, 6C

Appendix H. Recommendations for changes in selected green industrial policy assumptions and instruments for the establishment and development of the FCEV market in the state of California in the opinion of interviewees – retrospective (past) approach to policy reforms.

THEME (with frequency)	**CODES SYNTHESIZED TO SUB-THEMES**	**CONTRIBUTORS**
Constructing stations ahead of incentivizing FCEV purchases (11)	• Adequate infrastructure development • Key corridors and populous areas • Prioritizing infrastructure development ahead of vehicle incentivization	1C, 1H, 2B, 2E, 4A, 4D, 5C, 6E
The alternative policy approach toward the FCEV market demand side (23)	• Timing and regulation alignment • Need to focus on heavy-duty FCEVs • Large-scale funding • Leveraging public-private partnerships for infrastructure development • Insufficient early adopters studies • Considering the TCO for broad adoption	2B, 2C, 2E, 3H, 4F, 5C, 5H, 6A, 6C, 6E, 6F
The alternative policy approach toward the FCEV market supply side (6)	• Carving out FCEVs in ZEV Mandates • Flexible market tools and credits • Technology readiness and scalability • Focus on cost-effectiveness and performance metrics	3G, 4B, 4F, 5A, 5J
The alternative policy approach toward hydrogen fuel production and supply (16)	• Lack of an LCFS HRI credits generation • Regulations and subsidies for hydrogen generation and delivery pipelines • Clean hydrogen infrastructure should have been a focal point much earlier • Offering loan guarantees	1B, 1E, 3F, 3G, 4E, 5C, 5D, 5G, 5J, 6A, 6B
Proposal of new policy instruments that could be implemented in the past (20)	• Regionally-based incentives • Development of stations alongside the main transit corridors • Providing Clean Hydrogen Production Tax Credits	1A, 1C, 1D, 1H, 2C, 2H, 4C, 4D, 4F, 5E, 5G, 5H, 6A, 6B

Appendix I. Recommendations for changes in selected green industrial policy assumptions and instruments for the establishment and development of the FCEV market in the state of California in the opinion of interviewees – prospective (future) approach to policy reforms.

THEME (with frequency)	**CODES SYNTHESIZED TO SUB-THEMES**	**CONTRIBUTORS**
The policy reforms in the context of increasing the FCEV supply (5)	• R&D for cost reduction in tank manufacturing and precious metal use • Prioritizing the development of heavy-duty FCEVs • Implementing incentives or subsidies to lower FCEV initial costs • Continuing with existing programs like ACC II and ICT while evaluating new, targeted policies • Encouraging investments in the complete FCEV ecosystem	1B, 1D, 4C, 6B, 6C
The policy reforms in the context of increasing the FCEV demand (32)	• Spreading educational campaigns • Providing pre-paid fuel card as a penalty for OEMs • Federal Excise Tax • Expanding HVIP vouchers • Higher weight exempt • Developing inter-state travel infrastructure	1B, 1C, 1D, 1F, 1H, 2A, 2C, 3G, 4A, 5H, 6C, 6E, 6F
The policy reforms in the context of a technology-neutral (agnostic) approach (17)	• Sustaining a technology-neutral approach • Doubling down on the current policy framework • A policy might need to become more selective	1B, 1H, 2E, 3D, 3F, 3G, 3H, 4C, 5H, 5J, 6A
The policy reforms in the context of ARCHES initiatives (18)	• Public-private collaboration • Policies should be geographically inclusive • Focusing on commercialization pathways • Cost competitiveness with fossil fuels	3A, 3F, 3G, 4C, 4E, 4F, 5C, 6B, 6C
Leveraging Federal incentives at the state level (24)	• Harmonizing state policies with federal programs and leveraging them • Reassessing state policies • Shift its focus toward stimulating demand for FCEVs • Renewable identification number programs • Bridging the gap to commercialization	1F, 3A, 4B, 4F, 5A, 5B, 5C, 5E, 5G, 6C, 6F, 6G
The policy reforms in the context of revising LCFS (12)	• Holistic reevaluation and strategic realignment • The influx of biofuels destabilizing LCFS credit values • Incentives akin to the renewable portfolio standard for electricity • Self-sufficient hydrogen station network	1D, 3H, 4D, 4E, 5E, 5H, 5J, 6B, 6E, 6F
The policy reforms in the context of stabilizing hydrogen fuel prices (19)	• Fluctuating LCFS prices • Cost-per-mile parity with fossil fuels • Investment priorities shift from capital costs to operational costs • Federal regulations as a last-resort measure • Consumer incentives like pre-paid fueling cards	1B, 1D, 2E, 2F, 2H, 4C, 5E, 6B, 6C, 6D, 6F,
The policy reforms in the context of hand-in-hand development of infrastructure and FCEV market (10)	• Infrastructural shortfalls and unachieved goals • The more ambitious aim of establishing 1,000 stations • Policy disparity that favors BEV charging stations • Addressing misconceptions and increasing consumer awareness • Specialized fleet programs and the higher throughput benefits of hydrogen stations	1B, 1C, 1D, 4A, 4E, 5G,
The policy reforms in the context of MD/HD stations in ports & transit corridors (8)	• Balanced infrastructure development across FCEV market segments • The need for a gradual shift in state support from light-duty stations to subsidizing hydrogen production and heavy-duty infrastructure • Capital and FCEV deployment should be more efficient • Ensuring infrastructure is responsive to demand dynamics	1D, 1E, 3B, 3H, 4A, 5G, 5H,
The policy reforms in the context of the need for more stations (12)	• Strategic geographic expansion of hydrogen stations, including interstate locations • Private venture capital and fleet partnerships • Stringent uptime and maintenance standards for stations • Long-term goals targeting at 1,000 fueling stations • Cautionary against siting large stations in disadvantaged communities • Refueling stations as practical educational tools	1D, 1E, 3H, 4A, 4C, 4E, 5F, 5J,

LIST OF FIGURES

LIST OF TABLES