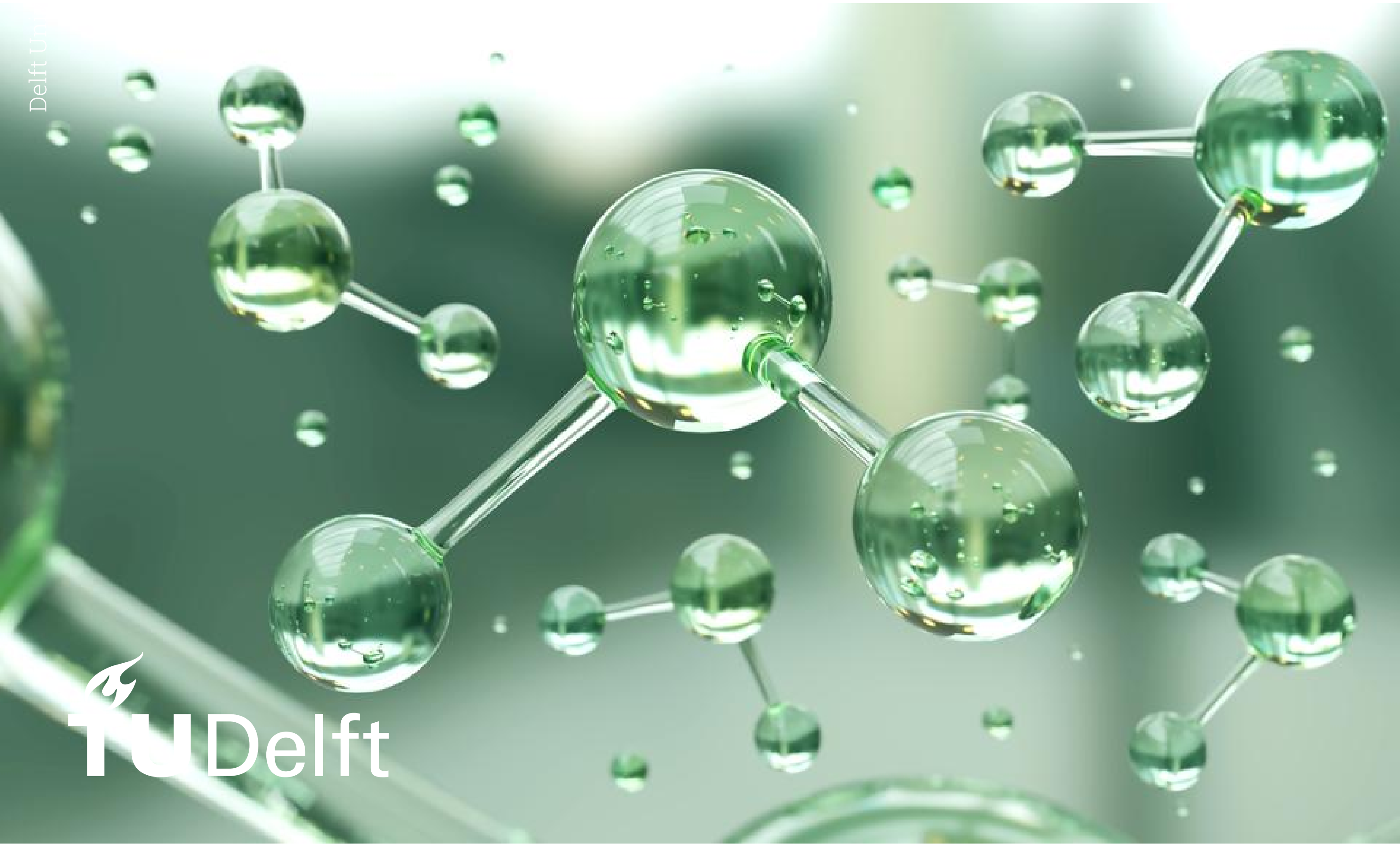
Green Hydrogen in India

"Fueling India's Green Future: The Tech Revolution Behind Policy Adoption for Green Hydrogen in India"

Master Thesis Report

By Suruthi Anushkumar



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To be defended in public on 25th August 2025

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I would like to acknowledge that, as English is not my first language, I have used ChatGPT to enhance the clarity and quality of writing in my thesis.

By Suruthi Anushkumar
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Abstract

Energy security and self-sufficiency have long been global concerns, but their significance has grown sharply following the Russia–Ukraine war. This geopolitical shift accelerated the search for sustainable energy sources, positioning green hydrogen as a promising candidate to replace fossil fuels and other carbon-intensive energy carriers. It is termed “green” because it is produced by splitting water into hydrogen and oxygen without generating carbon emissions most commonly through electrolysis, though non-electrolytic methods also exist.

Momentum in green hydrogen adoption began around 2020–2021 in countries such as the USA, Australia, and China. By 2023, several developing nations, including Saudi Arabia, parts of Africa, and India, also began entering the field. However, long-term energy transitions require significant structural and regulatory changes, particularly given the entrenched reliance on coal and other fossil fuels. Supporting such a transition demands a guiding framework namely, policies, which can be understood as structured sets of instruments and actions designed to achieve specific objectives and shape decision-making.

While green hydrogen technologies are rapidly advancing, governments are simultaneously introducing policies to encourage their uptake. This raises a central question: to what extent is policy adoption influenced by technological developments in green hydrogen? Although research on this subject exists, most prior studies have either focused on other sectors (such as photovoltaics or e-mobility) or examined developed nations like Germany and the UK. In the context of a developing economy like India—where green hydrogen remains an emerging sector this research aims to fill that gap. Accordingly, the guiding research question is: “How did technology dynamics influence policy adoption of production technologies for green hydrogen in India from 2020–2024?”

The study specifically focuses on production technologies, as these form the foundation of the green hydrogen value chain without them, downstream applications cannot be realized. The timeframe was selected because interest in green hydrogen accelerated post-COVID-19 and amid the Russia–Ukraine war. However, the literature review revealed that the technology dynamics of green hydrogen remain insufficiently defined. Technology dynamics generally refers to the patterns of change in technological development, including its innovation trajectory, maturity, performance improvements, cost evolution, industrial diffusion, and scaling potential. Furthermore, while previous research has analyzed hydrogen policies, more detailed examinations of their adoption processes remain scarce.

To address this, the study was divided into three subcomponents: (1) mapping the technology dynamics of green hydrogen production technologies, (2) examining policy adoption in India, and (3) exploring the link between the two. The first component analyzed international hydrogen industry reports using a qualitative hybrid abductive coding approach, combining inductive and deductive techniques. This process yielded five core themes: technological maturity, innovation maturity, performance, cost evolution, and industrial market scaling. Key findings showed that electrolysers continued to dominate, though alternative technologies began advancing notably from 2022 onwards. Major innovations included seawater and wastewater electrolysis and the integration of digital technologies in production processes. Geographically, manufacturing remained concentrated in China and Europe, with alkaline electrolysers emerging as the most cost-effective option.

The second study focused on identifying the policy instruments that were introduced or proposed for green hydrogen production technologies. To structure this analysis, the policy mix framework was employed as the basis for developing deductive codes, such as policy goals, year of introduction, type of instrument (technology-push or demand-pull), implementing bodies, and target groups. Additional deductive codes were also applied to capture the technology focus and the specific technological stage being addressed.

The findings, when analyzed chronologically, revealed a progression in India's policy approach: it initially emphasized enabling measures, then shifted toward actively promoting electrolyser technologies, and eventually moved toward more technology-agnostic pathways that support both electrolysis-based and biomass-based hydrogen production. Furthermore, innovations such as seawater and wastewater electrolysis, as well as the integration of digitalisation and automation in hydrogen production, were specifically supported through R&D-focused instruments and international collaborations.

The third study examined 2,048 newspaper articles, which revealed numerous activities related to stakeholder feedback. These findings were then compared with mechanisms discussed in the literature, such as advocacy coalitions, policy evolution, and compulsive policymaking. A recurring pattern emerged: whenever a policy was introduced, stakeholders tended to respond by raising concerns about aspects such as cost-effectiveness or suitability within the Indian context. This often led to suggestions to consider adopted policy measures on alternative, emerging technologies.

Although the analysis indicated some degree of linkage between stakeholder feedback and policy development, explicit conclusions could not be firmly established. One limitation of this study was its reliance solely on secondary data, which restricted the ability to draw definitive results. Future research could address this by incorporating primary methods such as interviews.

Overall, the thesis offers valuable insights for policymakers and stakeholders, including industry groups and government bodies. It highlights the crucial role of stakeholder feedback in sustainability transitions and suggests that their influence could be strengthened through more structured input and by fostering collaborative forums for collective participation.

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Nomenclature

Abbreviations

Abbreviation	Definition
NGHM	National Green Hydrogen Mission
PEM	Proton Exchange Membrane
ALK	Alkaline Water Electrolysis
AEM	Anion Exchange Membrane
GH	Green Hydrogen

1

Introduction

India is one of the world's most densely populated countries, with both its urban and rural populations expanding quickly. India's whole population is impacted by the country's severe air pollution problems. There are many health issues since the air quality in majority of the places are continuously above the acceptable thresholds advised by international health organizations [1]. Addressing the air pollution is not only a concern of public health but also a key component of India's climate strategy. In 2015, the Paris agreement was drafted which was later opened for signature on Earth Day (April 22) in 2016.The main goal of the agreement is to limit global warming to well below 2°C and efforts to stay below 1.5°C above the pre- industrial levels. As of 2025, 195 countries have ratified the Paris Agreement, making it one of the most supported international treaties in history [2]. The adoption of the Paris Agreement has encouraged countries to pursue ambitious climate strategies which is aimed at cutting greenhouse gas emissions. These ambitions include enacting carbon pricing systems, phasing out coal, boosting the proportion of renewable energy in national networks, establishing legally enforceable net-zero objectives, and encouraging energy efficiency across industries.

In alignment with these contributions, many governments have launched green industrial policies, provided clean technology subsidies, and made significant investments in decarbonising industries that are difficult to address, such as chemicals, heavy industry, and transportation. Furthermore, by highlighting the risks associated with heavy reliance on imported fossil fuels, the conflict between Russia and Ukraine has had a substantial impact on global energy transitions. In order to improve energy security and lower geopolitical risks, several countries felt pressured to quicken their transition to renewable and alternative energy sources in the wake of the conflict [3]. In light of these worldwide changes, India is likewise aggressively exploring green hydrogen as a potential energy source.

Green hydrogen is hydrogen produced using renewable energy sources, most typically by electrolysis, the process of splitting water into hydrogen and oxygen using electricity provided by solar, wind, or other clean sources. This technology guarantees that the hydrogen produced is entirely free of carbon emissions, making it a critical enabler of a low-carbon economy [4]. While electrolysis is the most commonly mentioned approach, green hydrogen may also be produced through various novel methods. These include photoelectrochemical water splitting, which utilizes sunlight to separate hydrogen from water; biomass gasification, which converts organic materials into hydrogen-rich gas; and biological processes involving algae or bacteria [4].

Green hydrogen does not emit greenhouse gases during production or use, which, in turn, makes it a key enabler of the climate goals set by the Paris agreement. Decarbonising hard-to-abate industries like steel, cement, chemicals, and long-haul transportation, where direct electrification isn't always practical, is one of its main environmental benefits [5]. Green hydrogen has the potential to take the role of fossil fuels like coal, natural gas, and diesel in power generation and industrial operations. For instance, it may be mixed into current gas networks to lower emissions, utilized as a reducing agent in green steel making, or utilized as a feedstock in the manufacturing of ammonia. Additionally, green hydrogen is a flexible fuel that can be transported, stored, and utilized in fuel cells to produce power with just water vapour as a byproduct. Because of this, it has promise as a zero-emission transportation option, especially in industries with battery technology restrictions like heavy-duty trucks, shipping, and aviation.

In order to better understand the role of green hydrogen,its better to consider the color coding system, which groups hydrogen according to how it is produced and how it affects the environment. As mentioned earlier, green hydrogen is the most environmentally friendly one, and the other types include grey hydrogen, made from natural gas with significant CO2 emissions. In contrast, blue hydrogen combines carbon capture and storage with comparable fossil fuel based techniques.Pink hydrogen is produced using nuclear energy to power electrolysis, while turquoise hydrogen is generated through methane pyrolysis, resulting in the formation of solid carbon as a byproduct. White hydrogen is a naturally occurring gas that is currently being investigated, whereas yellow hydrogen is produced utilising mixed-grid power. Strategic choices in clean energy planning are informed by this colour-coded system, which also aids in differentiating hydrogen's environmental effects [6].

However, there are barriers associated with the widespread implementation of green hydrogen which includes high production costs, the lack of a clean hydrogen value chain, and the lack of uniform international standards [7]. To triumph over these obstacles and completely include green hydrogen as a source of energy, policies serve as a crucial tool. Policy is a deliberate system of guidelines designed to guide decisions and achieve rational outcomes. It serves as a declaration of intent, and is carried out by means of processes or protocols, and it is typically adopted by governments. In addition to providing principles and frameworks, policy also encompasses the actual decisions made to address specific issues [8].

In order to fully understand how policies function and contribute to accelerating energy transitions, it is essential to examine the factors that drive their adoption, as well as the criteria by which they are formulated, modified, or adjusted over time [9]. The existing literature on policy processes highlights that policy adoption is shaped by a complex interplay of political, institutional, technological, and socioeconomic factors [9]. These include political will, stakeholder interests, institutional capacity, public acceptance, resource availability, and alignment with existing policy frameworks [10]. In particular, studies emphasize that the flexibility of policies to adapt to emerging technologies is critical for ensuring long-term transition success [10]. Given that energy transitions span extended periods, the strategies and tools used to implement policies must evolve to match the stages of technological developments [11]. Research on policy for sustainable transitions indicates that policies are usually a combination of various policy instruments such as regulations, economic incentives, research and development (R&D) support, public procurement, and market-based mechanisms. When well-designed, these instruments complement each other and collectively steer technological innovation and market adoption in a coherent direction [12].

Importantly, recent research highlights that it is not just the design of policy instruments but also how they are deployed, adjusted, and maintained over time that determines their effectiveness in enabling technological and systemic change [10]. The capacity of governments to strategically support innovation depends not only on political or institutional dynamics but also on the characteristics of the technologies themselves, such as their maturity, complexity, rate of innovation, and systemic relevance. While traditional policy science has focused heavily on political institutions as the primary source of change, there is growing recognition of the co-evolution between technology and policy [13]. These perspectives stress that technological change is not a passive outcome of policy but a dynamic factor that shapes and is shaped by policy choices. As technologies evolve, they bring new technical challenges, alter cost structures, create new stakeholder interests, and redefine investment priorities, all of which demand adaptive and responsive policy frameworks [13].

In this light, emerging technologies like green hydrogen play an active role in influencing policy agendas. Their development raises complex questions around infrastructure readiness, safety standards, certification schemes, and international coordination. As green hydrogen matures, it has the potential to reshape market dynamics and stakeholder coalitions, pressuring policymakers to revise or expand their instruments accordingly. However, despite increasing attention to the technological promise of green hydrogen, there is a notable gap in the literature regarding how technology influences policy adoption for green hydrogen. While such analyses exist for other sectors like renewable electricity or electric mobility, the policy dynamics specific to green hydrogen remain underexplored. Moreover, similar research has been conducted in developed countries; it remains largely absent in developing contexts such as India.

India is the country of analysis for this study because of its rapid advancement in green hydrogen policy and technology. The establishment of the National Green Hydrogen Mission (NGHM) in 2023, a major governmental effort aiming at advancing the green hydrogen industry, is an important milestone in this process. A wide range of activities are included in the NGHM, such as research and development initiatives, pilot projects, public awareness campaigns, and stakeholder engagement. Public-private partnership frameworks, regulatory support for infrastructure development, incentives for local manufacture, and viability gap funding for the electrolyser deployment are additional policy tools that assist green hydrogen in India.

This thesis aims to examine the evolution of green hydrogen production technologies and analyze how these technological developments have influenced the development and transformation of relevant policy tools in India. By examining the combination of policy instruments supporting green hydrogen in India, we can gain insights into how different measures interact to promote technology development, market creation, and long-term energy transitions. By doing this, it seeks to comprehend how the changing nature of technological progress has sparked policy change.

In line with this objective, this thesis seeks to address the following research and sub-questions:

Research Question: How did technology dynamics influence policy adoption of production technologies for green hydrogen in India from 2020 to 2024?

Sub-questions:

1. What were the technology dynamics surrounding green hydrogen production technologies in this timeframe?
2. What were the various policy instruments that collectively shaped the development of green hydrogen production technologies in India?
3. How could the link between technology dynamics and policy adoption be described?

The structure of this thesis is as follows:

Chapter 2 presents the literature review, summarizing existing research relevant to the study. Chapter 3 gives an overview of the value chain of green hydrogen. Chapter 4 outlines the study on technology dynamics, detailing the methods of data collection, analysis, and results. This chapter gives an overview of the technological landscape surrounding green hydrogen production technologies.

Chapter 5 introduces a Study on policy adoption, which focuses on the set of policy announcements related to green hydrogen production technologies in India. It explains the data collection and analysis process, presenting the results through a timeline to illustrate the evolution of policy over time. Chapter 6 explores the potential link between technological dynamics and policy adoption, culminating in the study's key findings. Chapter 7 offers a discussion of the results, their implications, identified limitations, and suggestions for future research. Finally, Chapter 8 concludes the study by summarizing the main findings.

2

Literature review

2.1. Introduction

This section presents a review of relevant literature that explores the relationship between technological development and policy adoption. The review also examines prior studies that have identified key factors influencing the adoption of green hydrogen policies, particularly within the context of India. Additionally, it highlights existing gaps in the literature, which this thesis aims to address. The section concludes by introducing the main research question and corresponding sub-questions that guide the direction of this study.

2.2. Technology and policy adoption

In order to comprehend the interaction between technological developments and policy adoption a thorough assessment of the literature on this topic was carried out.

In energy transitions, technological innovation plays a crucial role in driving policy adoption, affecting not just the policies that are adopted but also their implementation, timing, and method [14]. As new energy technologies like energy storage, green hydrogen infrastructure, and renewable power systems develop, they frequently serve as catalysts for changes in policy [14]. This dynamic reflects a growing understanding of how economic competitiveness and technical viability may influence institutional frameworks and political will. Energy transitions, according to scholars, are fundamentally socio-technical processes in which policy changes and technological advancements co-evolve in intricate and frequently reinforcing ways [14].

One foundational perspective is offered by [15] ,who describe the co-evolution as an iterative feedback: technological development lessen performance and market uncertainty, authorities are more inclined to create enabling conditions like standards, subsidies, or infrastructure investments which further spur innovation. In this way, technology influences policy at every level, from agenda-setting to policy formulation and execution, rather than just reacting to it. [16] presents the multi-level perspective (MLP) on transitions, which holds that specialized innovations like new renewable technologies challenge established regimes and lead to more extensive sociopolitical realignments. Policy changes that encourage the expansion of specialized technology frequently accompany these realignments. This point of view emphasizes the significance of ”windows of opportunity” brought about by technical advancements, when coordinated governmental action is not only feasible but also required.

The empirical work of [14] examines in more detail how shifting technology systems affect the selection of governance models and policy tools. For example, they demonstrate how, as technology develops, countries frequently shift from broad, experimental policy measures (such as R&D financing or pilot programs) to more focused and structural tools (such as market laws or infrastructure mandates). This trend demonstrates how policy mixes change as technology advances. Furthermore, [17] demonstrates how technical difficulties in integrating renewable into the grid and powerful political forces, such as industrial lobbying and ideological influences, influenced the development of Germany’s renewable energy policy. The study demonstrates the interplay between technology, politics, and policy in propelling energy transformations by demonstrating how continual legislative adjustments were required to handle these issues and assist the development of renewable energy technologies.

In a cross-national comparative study, [18] examines the ways in which technical advancements might act as a potential accelerator for the international adoption of renewable energy policies. According to their research, when a pioneering nation successfully deploys and scales a new energy technology, like offshore wind power or solar photovoltaic (PV) systems, it not only confirms the innovation’s technical and financial viability but also creates a model for policy imitation. This tendency is known as policy learning and policy emulation, whereby other nations frequently take note of these achievements and implement comparable institutional, financial, or regulatory frameworks. This relationship strengthens a positive feedback loop in which institutional adaptation is accelerated by technology advancements and vice versa.

Building on [18] work on international policy learning, the work of [19] highlights that technology advancements by themselves do not ensure policy acceptance, which adds an essential element of complication. Rather, their research demonstrates that each country’s or region’s institutional and political framework is intricately linked to the process of converting invention into workable policy. They believe that the ability of bureaucratic institutions, public opinion, advocacy networks, and political alliances all act as moderators in deciding if and how emerging technologies influence energy policy. Furthermore, [19] highlights that policy entrepreneurs and advocacy coalitions are often the missing link between technological promise and legislative action. Without active engagement from such actors, even the most promising technological innovations may stall due to regulatory inertia or opposition from entrenched interests.Their findings underscore the idea that technological momentum must be synchronized with political will and institutional preparedness. This helps explaining why some countries with similar levels of technological advancement have vastly different policy outcomes.

Similarly, results from [9] highlights that the feed-in tariff (FIT) system for photovoltaics (PV) in Germany has undergone many changes in legislation to solve technical system difficulties, according to evidence from earlier research. These shifts are strongly linked to the political environment, since party-specific goals frequently impact policy choices, such as restrictions for energy-intensive companies. Furthermore, the spread of technological information has been crucial in influencing changes in policy. The Chinese PV industry’s rapid growth is one such example. Before 2007, German companies were seen as world leaders in the PV sector, and the industry’s anticipated economic and job potential led to significant cross-party political support. But after 2004, unforeseen demand caused supply bottlenecks in wafers, cells, and modules, opening up a market for Chinese producers. By exporting to Germany and reinvesting their profits in R&D and cutting-edge production technology, frequently purchased from Western suppliers, these companies took advantage of the opportunity.

The relationship between policy adoption and technology advancements is frequently mediated by external forces like political pressure, disruptive events, or belief systems. Two theoretical frameworks have describes this connection. By emphasizing coalitions of actors that have similar normative views and collaborate over time to affect policy outcomes, the Advocacy Coalition Framework (ACF) explains policy change. According to [20], these coalitions function inside policy subsystems and adjust through external shocks and policy-oriented learning. The representation of the Advocacy Coalition Framework is illustrated in Figure 2.1. In contrast, compulsive policy making as described by [9] refers to impulsive policy choices made without careful consideration because of social pressure or political necessity. Adoption of policies may become fragmented or unstable as a result, especially in complicated areas like energy transitions or climate innovation.

In summary, advances in technology and the problems they raise not only influence energy policy but also operate as potent catalysts that alter the parameters of what policies are seen as desirable, practical, and acceptable by the general public. Furthermore, the political system is crucial in directing these policy changes, impacting both their course and execution.

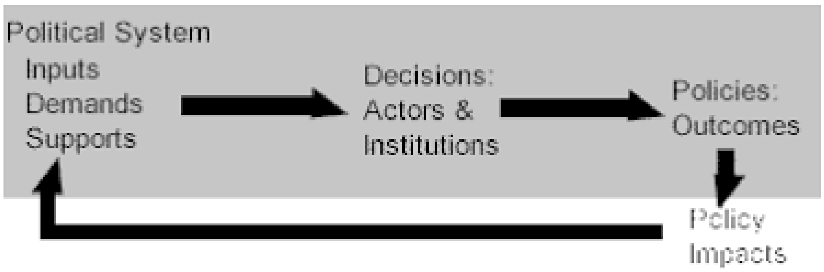

Figure 2.1: Advocacy coalition

2.2.1. Mechanisms linking technology dynamics to policy adoption

To make it clearer this section summarizes some ways in which technology dynamics influence policy adoption. For instance, according to [9], adoption of policies is dynamic by nature. This study demonstrates how systemic issues that arise in tandem with developments in technology frequently prompt policymakers to take action. New products, processes, and services are necessary for sustainable transitions, and they in turn necessitate behavioral adjustments from a wide range of stakeholders, including consumers and companies. In light of this, there is widespread agreement that public policy is essential to making such transitions possible. It is frequently argued that policies should help guide and expedite change by modifying institutional structures because of the severity of these issues. Building on the paper's findings, the author proposes a framework referred to as "compulsive policy learning." Compulsive policy learning refers to situations where policymakers are forced to learn and adapt in response to persistent or urgent problems, often driven by rapid technological change. These challenges emerge from complex socio-technical dynamics that influence policy design aimed at guiding technological transitions. Policymakers respond by introducing targeted incentives to address system-level issues. However, as technological developments can both solve and create new problems, policies must continuously evolve to address both emerging and existing challenges.

Similarly, [21] introduces a framework explaining the co-evolution of policy mixes and socio-technical systems in sustainability transition. It shows how policies influence system change through resource, interpretive, and institutional effects, while system changes generate feedback socio-political, fiscal, and administrative that shape future policies. Well-designed policies can trigger virtuous cycles of innovation and political support, whereas misaligned policies may lead to vicious cycles that hinder progress.

Another way was discovered in which technology influences policy adoption. According to Advocacy coalitions [22] people involved in policy (like governments,NGOs , industries, researchers) and who share same core beliefs (e.g., about the economy or specific technology) often form groups or ”coalitions”.These groups try to influence policies over a long period of time. According to the ACF, policy change usually happens gradually and is brought about by changes in coalition resources, external crises (such as international accords, environmental catastrophes, or economic crises), and policy-oriented learning. Emerging coalitions can use external shocks or policy windows to influence the policy agenda, frequently resulting in paradigm shifts in governance, whereas dominant coalitions tend to maintain the status quo.

One of the most important questions in the governance of innovation is why emergent technologies are regulated. This is addressed by [23], who use the adoption of the EU General Data Protection legislation (GDPR) as a case study and apply the Multiple Streams Framework (MSF) to explain how regulations evolves. According to their study, regulatory action occurs when four crucial factors political will, technical advancements, problem recognition, and viable policy solutions align within a window of opportunity. Policy entrepreneurs play a key role in this process by actively framing the technology as an urgent public concern, assembling coalitions, and coupling the streams to get regulation on the agenda. The policy entrepreneurs are key actors who drive policy change by linking problems, solutions, and political opportunities. They can be politicians, bureaucrats, experts, advocacy groups, industry leaders, or media figures. Their main role is to frame issues, build support, and act during critical moments called policy windows to push new policies forward. This makes them especially important in complex areas like sustainability and emerging technologies, where policy change is often difficult and uncertain.

There are the ways in which technology can influence the adoption of policies. However, it remains unclear which of these mechanisms are most relevant or aligned with the development of green hydrogen policy in India.

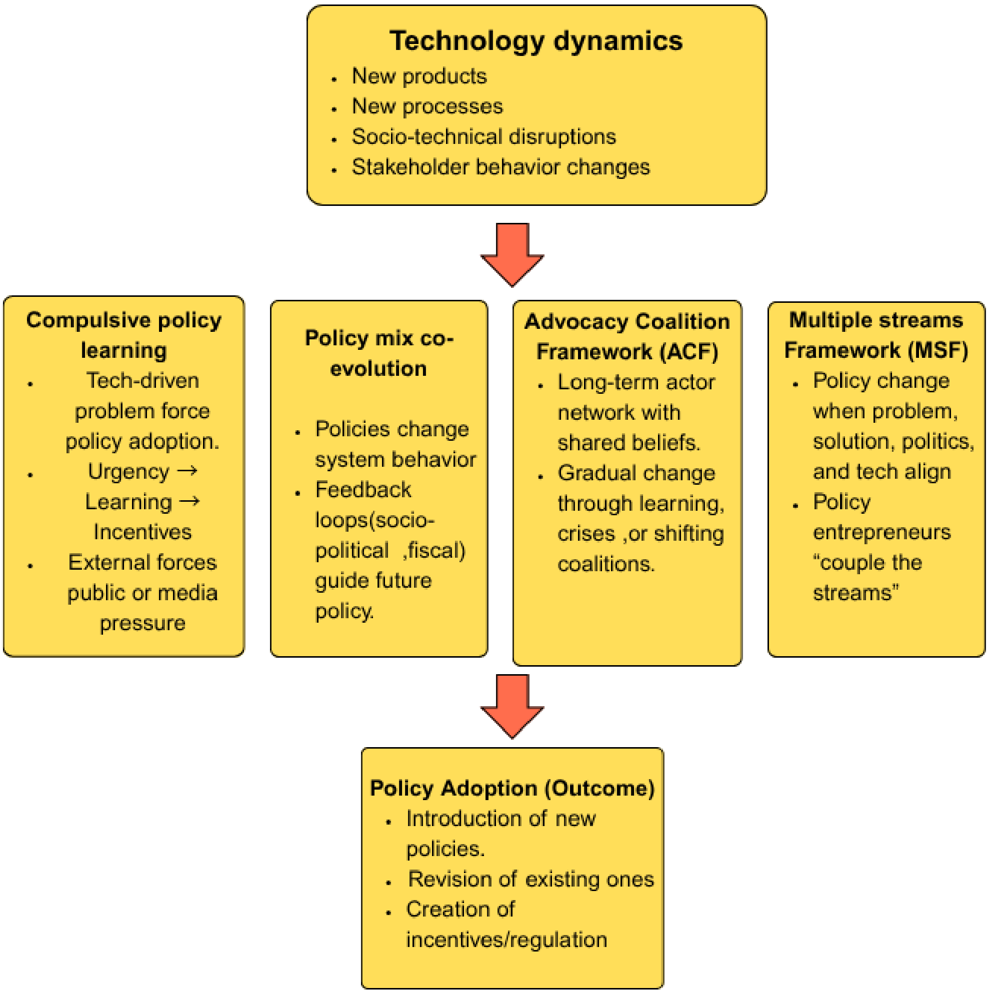

Figure 2.2: Conceptual framework showing mechanisms linking technology dynamics to policy adoption.

2.2.2. Factors influencing green hydrogen policy adoption

Relevant studies examining the factors influencing the adoption of green hydrogen policies were reviewed to identify whether existing literature in the field of Green hydrogen has explored the relationship between technological advancements and the adoption of corresponding policy measures. [24] highlights the regulatory barriers that can hinder diversification of hydrogen value chain, highlighting the necessity of technology-neutral policies in order to promote innovation. According to [24], the EU's current policies disproportionately favor electrolysis-produced renewable hydrogen, which might hinder the advancement of low-carbon, alternative hydrogen production methods. This emphasis runs the danger of producing a rigid regulatory framework, which would impede the uptake of cutting-edge technology supporting a more varied and sustainable hydrogen economy.

Adapting a similar approach [25] emphasizes how crucial it is to match technologies in production, transportation, and storage with supportive policies in order to facilitate affordable green hydrogen routes.

This paper further concludes that a holistic policy approach is vital for the green hydrogen economy to flourish. From a more geopolitical and industrial policy perspective, [26] examines China's national hydrogen policies, demonstrating how state policy both actively drives and responds to technical innovation. The paper's findings demonstrate how China's hydrogen policy have changed to take into account both technological leadership and energy security. Policies were initially sector-specific and dispersed, but they have since evolved into more integrated approaches that support national objectives for the industrial revolution and energy transition.

[27] echoes this sentiment globally, noting that green hydrogen is at the nexus of climate policy and industrial competitiveness. Their study highlights the growing importance of the global competition for technological leadership in the hydrogen industry on national agendas. They contend that green hydrogen offers a strategic advantage for countries hoping to take the lead in cutting-edge clean energy technology, not only a means of accomplishing decarbonisation objectives. Policies that simultaneously address industrial growth and environmental goals are necessary for this dual function. [28] stresses that effective production scaling in electrolyzer manufacturing depends on innovation sparked by specific policy. The key to enabling large cost reductions in green hydrogen production and increasing its economic viability is this scalability.

Furthermore, these policy-driven developments not only contribute to cost reductions but also enhance green hydrogen's competitiveness internationally, establishing it as a viable and alluring substitute in the changing clean energy market. The reciprocal relationship is explored in this study [29]. .[29] proposed a push-pull model which combines addressing both demand-side and supply-side issues through policies. According to this paper, successful scaling of green hydrogen depends on policy mixes that take advantage of both the supply-side and demand side of policies. Supply-side issues include technological challenges with electrolyzer technologies, lack of R&D support, and engineering knowledge among manufacturers. On the other hand, demand-side issues include lack of clear market, the need to retrofit natural gas infrastructure and need for private investment and public-private partnerships.

Comparative analysis from this paper indicates that green hydrogen leading countries like France,Germany and UK use use these policy combinations that foster market development and technological innovation at the same time. This demonstrates the crucial connection between policy acceptance and technology development, as strong policy frameworks encourage innovation and help create the market readiness required for the widespread use of green hydrogen[30].

However, no relevant study was found that looks at the opposite relationship, i.e how technological innovations and advancements themselves affect policy formulation and adoption. The majority of the reviewed literature concentrates on how policies can be framed to support technological innovation and how policy instruments influence the development and diffusion of green hydrogen technologies.

2.2.3. Green Hydrogen in India

In India, green hydrogen has started to emerge as a critical facilitator of deep decarbonisation, particularly in hard-to-abate industries such as refining, steel, and heavy transportation. The discussion of green hydrogen has mostly been driven by policy on a global scale, with governments initiating sources of financing, regulatory frameworks, and road maps to generate early market demand. However, India presents a nuanced case of how developments in technology is influencing and even speeding up decisions regarding policy, a phenomenon that has not received attention in the academic literature. The majority of current research is on how policy influences innovations in technology. For example, the

International Energy Agency [31] and the International Renewable Energy Agency [32] stress the need for international cooperation, mandates, and subsidies in promoting hydrogen research and implementation in India.

[33] [34] describe how national-level policy tools like the National Hydrogen Mission are intended to stimulate domestic hydrogen ecosystems in India. These studies seldom flip the lens to examine how technological development may influence or drive policy change, instead seeing technology as a passive recipient of policy stimuli.According to [35], in order for policy frameworks to be effective, they must carefully evaluate technical readiness, comprehend the role of hydrogen-related applications, and solve market failures, including high upfront capital costs and infrastructural shortages. Furthermore, [35] recommends against depending too heavily on blue hydrogen as a temporary fix, pointing out that lifetime emissions from the manufacturing of blue hydrogen might be much greater than expected and that related expenses can be higher than first projected. [36], on the other hand, contend that blue hydrogen can function as a workable short- to medium-term bridge towards green hydrogen when paired with carbon capture and storage (CCS).Studies like [37] emphasize the techno-economic feasibility and infrastructure gaps, while [38] stresses environmental alignment and the need for integrated stakeholder efforts. Together, they contend that responsible and flexible policymaking must coexist with technological innovation.

2.3. Research Gap

A thorough analysis of the body of existing literature identifies a number of significant gaps. Most significantly, nothing is known about how technological developments affect the adoption of policies, especially when it comes to green hydrogen in India. There is a dearth of research that methodically monitors how green hydrogen production and associated technologies have changed over time, despite the fact that several papers offer technical summaries of these fields. In a similar vein, while several articles outline India's green hydrogen policy environment, very few use a systematic methodology to examine how these policies have changed over time or how they interact with new technology.

This gap is crucial because a thorough understanding of the relationship between governmental policies and technological developments necessitates a thorough examination of both elements. Furthermore, current advancements in green hydrogen have not been subjected to the mechanisms that explain the relationship, such as those described in frameworks like the Compulsive Policy-Making Framework or the Advocacy Coalition Framework. Lastly, the academic literature still lacks a real-time, nation-specific study of the current policy changes and conversation around green hydrogen in India.

2.3.1. Research questions and sub-questions

By identifying the literature gap the following research and sub-questions were formed.

Research question: How did technology dynamics influence policy adoption of production technologies for green hydrogen in India from 2020 to 2024?

Green hydrogen production technologies form the primary focus of this study, as they represent the first and foundational stage of the hydrogen value chain without which storage, transportation, and utilization would not be possible [39]. Additionally, hydrogen hubs and hydrogen valleys are included within the scope of this research, as they represent integrated ecosystems that connect production with downstream applications across regional or localized networks. Technology dynamics are employed here as a crucial indicator for the study because the development of green hydrogen technological development is dynamic rather than being linear. The 2020–2024 study period was selected because literature indicates that significant worldwide events like the COVID-19 pandemic in 2020 and the Russia–Ukraine war in 2022 accelerated the adoption of green hydrogen [40]. The main goal is to comprehend how the dynamics of technology affect the adoption of policies throughout this period.

Subquestion-1:

What were the technology dynamics surrounding green hydrogen production technologies in this timeframe?
Explanation: Mapping the ways in which technological dynamics influences policy adoption, particularly with regard to green hydrogen production technologies is the ultimate goal of this research. Knowing how these technologies have changed throughout time is the main goal of this sub-question. It looks at (1) if and how one technology has supplanted another, (2) the rise of new technologies over time and (3) examples of numerous technologies co-evolving. By doing this, the research hopes to offer a thorough grasp of the technical forces influencing the field of green hydrogen production in recent years.

Subquestion-2:

What were the various policy instruments that collectively shaped the development of green hydrogen production technologies in India?

Explanation: The second part of the mapping focuses on the policies adopted during the selected time frame. This involves examining the policy mix, which includes various elements such as strategies, instruments, and their characteristics [12]. The aim is to assess whether and how these components have been designed specifically to support green hydrogen production technologies in India. The expected outcome is to identify the relevant policies, understand their structure.

Subquestion-3:

How could the link between technology dynamics and policy adoption be described?

Explanation: As highlighted in the literature review, there are various mechanisms through which technology can influence policy adoption. The section on ”Mechanisms Linking Technology Dynamics and Policy Adoption” outlines such approaches, including the Compulsive Policy-Making Framework and the Advocacy Coalition Framework, which help explain this connection. Therefore, this sub-question aims to explore how technology dynamics relate to policy adoption and assess which of these mechanisms are applicable to the case of green hydrogen in India.

3

Overview of green hydrogen value chain

3.1. Introduction

This section provides the necessary theoretical background to support and contextualize this thesis. It establishes a fundamental understanding of green hydrogen technologies, which serve as the core focus of the study.

3.2. Technologies of Green hydrogen

Below is an in-depth review of the literature on the technologies involved in the green hydrogen value chain. The four main components of the value chain are end-use, storage, transportation, and production. Each of these stages involves specific technologies that play a critical role in enabling the large-scale deployment of green hydrogen. In addition to these segments, ecosystem-level concepts like hydrogen valleys and hubs are also covered since they are integrated models that link different parts of the value chain to support local hydrogen economies.

3.2.1. Production Technologies

The main method to produce green hydrogen is electrolysis, which uses power from renewable sources like solar and wind to split water into hydrogen and oxygen. The two most extensively investigated and utilized electrolysis techniques are alkaline electrolysis and proton exchange membrane (PEM). PEM electrolysis is appropriate for fluctuating renewable energy input because it provides faster response and greater current densities. Alkaline electrolysis, on the other hand, is a more established and economical choice, despite its slower dynamics and poorer efficiency [40]. A third method, Solid Oxide Electrolysis Cells (SOECs), can be very effective when combined with industrial waste heat since it works at high temperatures. Anion Exchange Membrane (AEM) electrolysers combine features of alkaline and PEM technologies, offering a promising, low-cost, and efficient solution for green hydrogen production. The key to expanding green hydrogen is the advancement of electrolyser technology, which focuses on lowering costs, enhancing durability, and integrating with intermittent renewable energy sources [40]. These developments have a direct impact on investment choices and the viability of policies [40].

Other methods to produce green hydrogen include photo catalytic water splitting, photo electrochemical water splitting and biological methods such as microbial electrolysis or photo biological hydrogen production, etc. Photo catalytic water splitting splits water molecules directly using semiconductor materials and sunlight. It can produce hydrogen in a decentralized and inexpensive manner, although being at the experimental stage [39]. On the other hand, Biomass gasification for green hydrogen production is a thermochemical process in which organic biomass materials (like agricultural residues, wood chips, or municipal solid waste) are converted into syngas by reacting with a controlled amount of oxygen, air, or steam at high temperatures (typically 700–1000°C). The hydrogen is then separated from the syngas using techniques like water-gas shift reaction and gas purification (e.g., PSA, membranes) [39]. Photo electrochemical (PEC) water splitting is an additional strategy that combines electrolysis with light absorption in a single device, thereby increasing energy efficiency and streamlining system design [39]. Because of their low energy requirements and sustainability, biological processes like microbial electrolysis and photo biological hydrogen synthesis employing cyanobacteria and algae are also being researched. These techniques reflect novel approaches that could eventually supplement large-scale electrolysis, even if they are not currently economically feasible [39].

3.2.2. Storage Technologies

In the value chain of green hydrogen, storage technologies play a crucial role in enabling the challenge of balancing demand and intermittent production. Three main approaches are identified in the literature: solid-state storage, liquid hydrogen, and compressed gas. The most developed and popular method is compressed gas storage, which enables the storage of hydrogen at high pressures (350–700 bar). However, it needs strong containment systems and energy input for compression [39]. Cryogenic cooling to -253°C produces liquid hydrogen storage, which has a greater energy density but is energy-intensive and has boil-off issues [40]. Although they are still limited by slow kinetics and material costs, solid-state techniques such as metal hydrides and chemical carriers like ammonia or liquid organic hydrogen carriers (LOHCs) are becoming more popular due to their safety and volumetric efficiency [41]. These technologies are under ongoing development, with researchers highlighting the significance of material innovation and system integration to ensure long-term, scalable hydrogen adoption [41].

3.2.3. Transport Technologies

The third component of green hydrogen value chain is transport technology of green hydrogen .Pipeline transport, liquid hydrogen trucking, and transport using hydrogen carriers like ammonia or LOHCs (Liquid Organic Hydrogen Carriers) are the three primary approaches identified in the literature [40]. For large-scale, continuous delivery, pipeline transport is quite effective; nevertheless, it needs specialized infrastructure and works best over short-to-medium distances [40]. Cryogenic tankers are used to carry liquefied hydrogen over longer distances or for international trade; this requires a significant amount of energy for liquefaction and appropriate insulation to minimize boil-off losses. Chemical carriers like ammonia or methyl cyclohexane are emerging substitutes that enable hydrogen to be delivered in more stable liquid forms, allowing for the use of the fuel infrastructure already in place. Each approach involves trade-offs between infrastructure compatibility, safety, and energy efficiency, making the mode of transportation selection extremely context-dependent [40].

3.2.4. End-uses of green hydrogen

Green hydrogen, which is produced by using renewable energy through electrolysis, has diverse end uses across sectors. The most rapid and scalable use, according to the literature, is in industrial applications such as the manufacturing of ammonia and methanol, petroleum refining, and green steel manufacturing. This is particularly relevant in industries that are difficult to abate because of concentrated demand and existing hydrogen infrastructure [42]. In the transport sector, green hydrogen is gaining attention for heavy-duty vehicles, buses, trains, shipping, and potentially aviation, where battery electrification is less viable. Furthermore, hydrogen may be employed as a medium for long-term energy storage and in power production via fuel cells or gas turbines, though its competitiveness in comparison to batteries is limited by present efficiency losses. While blending hydrogen in natural gas for residential heating has been explored, studies suggest it is less efficient and more costly than direct electrification. Overall, recent literature emphasizes the industrial sector as the key driver of early adoption, with transport and power sectors following, contingent on infrastructure development, policy support, and cost reductions [42].

3.2.5. Hydrogen valley and hydrogen hubs

Hydrogen hubs and valleys operationalize the green hydrogen value chain by physically linking production, storage, distribution, and end-use in a single ecosystem, enabling systemic efficiency and large-scale deployment. Hydrogen hubs are localized networks that bring together hydrogen production, storage, distribution, and end-use applications within a specific geographic area to create a concentrated, self-sustaining hydrogen ecosystem. In contrast to hubs, which are more regional or sector-specific, hydrogen valleys usually encompass several industries, including transportation, manufacturing, and power. These models facilitate integration, economies of scale, and stakeholder coordination, as demonstrated by recent research [43]. The figure below shows the value chain of green hydrogen technologies.

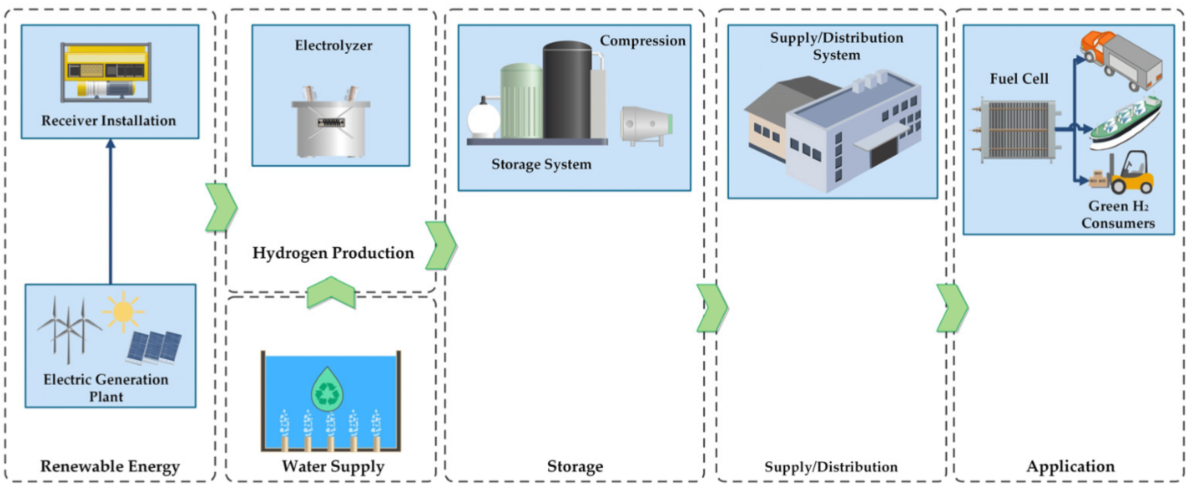

Figure 3.1: Green hydrogen value chain

4

Study on Technology dynamics

4.1. Introduction

The methodology used for this thesis is broken down into three sub-studies. Study one focuses on analyzing the technology dynamics of green hydrogen production technologies. Technology dynamics refers to the changes in performance, maturity, and commercialization of technologies across different time periods. This study provides a broad overview of the technology dynamics related to green hydrogen production technologies in India. Accordingly, this section addresses the sub-question:

What were the technology dynamics surrounding green hydrogen production technologies in this timeframe??

The first and second section of this study explains how the data was collected and analyzed, followed by the results of the analysis,and finally,key takeaways are highlighted.

4.2. Data collection

Secondary sources were utilized for this study because they offer a wider range of coverage, from historical changes to current trends. Analyzing changes over time, such as technical improvements, reductions in costs, and scaling initiatives, is essential to understand technology dynamics [44]. Furthermore, secondary sources provide a more thorough viewpoint by compiling data from a variety of stakeholders. To understand the basic factors influencing technological dynamics, studies on the life-cycle analysis of green hydrogen production technologies were conducted. Report databases like IEA and Hydrogen Council, which served as important sources of data for this study, were regularly cited in these research papers.
This section is divided into two parts: data sources and collection strategy. The reports and databases used in this study are listed in data sources, along with the time period they covered and the rationale for their selection. The collection strategy, on the other hand, outlines the process used to extract and filter through the vast amount of data that was accessible, guaranteeing that the attention stayed on

the most important and reliable findings.

4.2.1. Data sources

Data on the dynamics of green hydrogen production technology is constantly changing, especially from 2020 to 2024. Thus, gathering data annually was the main strategy used . Annual reports about the production of hydrogen and related technologies were examined. Reports from the International Energy Agency (IEA) were used as an important source of analysis. In scholarly articles addressing the lifecycle analysis and the advancement of production technologies, these databases were regularly mentioned and cited [45].

IEA reports:

Most publications discussing green hydrogen production technologies rely heavily on data provided by the International energy agency [45].Therefore for this study data was collected directly from the International Energy Agency(IEA),for its authoritative and comprehensive insights. These reports provided a clear picture of regional advancements, cost trends, and their associated innovations. In particular, the Hydrogen Overview Reports published by the IEA between 2021 and 2024 were gathered and examined.

Hydrogen council reports:

During the literature review, the Hydrogen Council papers were the second most often cited source [27]. As a result, the search started with a look at the official Hydrogen Council website.In order to identify the most relevant documents, a search using keywords was conducted. The keyword such as ”Green hydrogen technologies” was used. This search led to the identification of the Hydrogen Insights series, published annually from 2021 to 2024.These reports were reviewed in detail.Even while they mostly restated most of the information from the IEA reports, allowing for data triangulation between the two sources, they also included more in-depth information about project pipelines and market outlook, which were not fully discussed in the IEA publications.

Royal society of Chemistry

Most of the above-mentioned reports emphasize electrolysers and their evaluations.To get a clear idea about other production technologies other than electrolyser, the report named ”Hydrogen production, storage and transportation: recent advances” were studied. This report gave a clear picture of technological developments other than electrolysers for green hydrogen production from 2020-2024.

A summary of the evaluated reports and their main points of emphasis is given below.

Publisher	Reports reviewed and year
IEA	- Global Hydrogen review (2020-2024) - Break through Agenda Report 2023
Hydrogen Council	- Hydrogen Insights (2021-2024) - Hydrogen: Closing the cost Gap
Royal Society of Chemistry	- ”Hydrogen production, storage and transportation: recent advances”

Table 4.1: Reports selected for the study

4.2.2. Collection process

The process of compiling pertinent data on green hydrogen production technologies began after the data sources were chosen. A methodical and structured technique was used to extract just the most relevant material for the research because these documents are sometimes rather lengthy (usually between 100 and 300 pages).

4.2.3. Step by step Collection process

1. **Document Review and Scoping**
   For the yearly report the basis for collection was done by skimming through one sample document in each source for example, in the IEA yearly Hydrogen review the (IEA Hydrogen Report 2021). Following this first assessment, I made a thorough document outline in order to find and bookmark the chapters that were most pertinent to the research. Chapters that particularly discuss and give detailed explanations of production technology were the main focus of the selection criteria. Excluded were sections that mostly addressed other technologies or that concentrated more on the results or uses than the actual production technology.

   Sections addressing prices, advancements in electrolyser technology, and their performance indicators received particular focus within the chosen chapters. According to the literature currently in publication, these factors were given priority as these factors form the basis of assessing the technology of production technologies as seen in the literatures [46].

2. **Targeted extraction**
   For analysis, the relevant information from tables, text passages, and figures were gathered . For traceability, the extracted data was organized by section header, page number, and report source.

3. **Coding process**
   Once relevant data was collected, in order to enable a more effective and organized analysis, a set of predefined codes was developed, based on literature.

4. **Iterative refinement**
   Even though the analysis mostly used pre-defined codes, the process still remained open to find new insights or recurring themes.

4.3. Data Analysis

4.3.1. Hybrid coding

The methodology used for the data analysis was Hybrid abductive coding. It is an approach that combines inductive and deductive coding. Deductive coding involves developing codes before collecting the data, frequently based on pre-existing research, theoretical frameworks, or specific hypotheses. This approach ensures that the analysis stays organized and in line with established knowledge or research objectives. On the other hand, the inductive coding approach creates codes while the data is being analyzed, letting themes and patterns naturally emerge. Flexibility is provided by this inductive , which is especially helpful for collecting unexpected insights that predefined codes might not cover. Both the inductive and deductive coding approach were combined using hybrid coding. Initially, the data collection and analysis were structured using a set of pre-defined variables that were determined by reviewing relevant literature. As the data collection progressed, particularly when the reports were examined, additional codes emerged that were not part of initial coding scheme.These new insights were incorporated into the coding framework, reflecting the inductive approach [4].

4.3.2. Predefined codes

The predefined codes were derived from the existing literature on green hydrogen technologies. These papers identify the key variables (codes) that are essential for assessing such technologies. Based on what is described in these papers, these codes were developed so that they will show the growth of each technology in this particular timeframe. The literature on technology dynamics suggests that technology dynamics are typically assessed by focusing on key factors such as cost,performance,maturity, and innovation [47] [48]. These fundamental elements served as the basis for the formulation of these codes.

CAPEX

The initial investment required to purchase and install electrolyser systems, including manufacturing, shipping, and commissioning expenses, is known as CAPEX. CAPEX is a powerful indicator for examining technology dynamics since research shows that it is driven by innovations in technology. The CAPEX data in this study was methodically analyzed by year and kind of electrolyser, making it possible to compare cost patterns over time [49].

Electrolyzer efficiency

The cost of renewable electricity can account for almost 20% of the entire cost of operating an electrolyser, making it a significant factor. Therefore, the economic viability of producing green hydrogen is directly impacted by changes in energy costs. Given this, the electrolyser's efficiency becomes an important metric to track because a higher efficiency means less power is used per unit of hydrogen generated. It is a useful code for examining the technological dynamics of green hydrogen production technologies as it enables us to monitor advancements in the technology's performance over time [46]. The data collected on the efficiency was analyzed according to the type of electrolyser and their efficiencies in each years.

Electrolyser capacity

Electrolyser capacity is defined as the maximum hydrogen output an electrolyser can achieve, typically measured in terms of kilograms per hour or megawatts. It is a pivotal metric for assessing the technology dynamics of the electrolyser as an increase in capacity denotes significant improvements in design, materials, and system integration, enabling larger and more efficient units. Furthermore, because of shared infrastructure and more effective resource management, larger-capacity systems can lower the cost per unit of hydrogen generated, promoting wider adoption and economic feasibility. Tracking capacity trends can show how effectively a technology is developing to satisfy varied needs in many applications, ranging from industrial to small-scale hydrogen production [46]. Data from various years were arranged and analyzed according to electrolyzer capacity.

TRL Levels

From early-stage research (TRL 1) to commercial deployment (TRL 9), the Technology Readiness Levels (TRLs) are a standardized framework for evaluating a technology's maturity. TRLs are a useful metric for monitoring the development of various technologies, from laboratory testing to industrial use within our timeline in the context of green hydrogen production technologies. Using TRL as a code aids in capturing each technology's stage of development and offers information about its scalability, economic feasibility, and potential investment requirements [10]. Below is a list of TRL levels and what each level indicates.

TRL 1 – Basic principles observed.

TRL 2 – Technology concept formulated.

TRL 3 – Experimental proof of concept.
TRL 4 – Technology validated in laboratory.
TRL 5 – Technology validated in relevant environment.
TRL 6 – Technology demonstrated in a relevant environment.
TRL 7 – System prototype demonstrated in operational environment.
TRL 8 – System complete and qualified.
TRL 9 – Actual system proven in operational environment.

4.3.3. Derived codes

A number of codes were developed by inductively analyzing the collected data from secondary data sources mentioned previously. To systematically investigate the dynamics in these technologies. These codes were deliberately chosen to highlight important technological, geographic, and market-related aspects of green hydrogen technologies. They were found based on recurrent trends in the data. The codes, along with their rationale for selection and definitions, are given below.

Patent activity
International patent applications are a useful measure of innovation in any field of technology. Monitoring the quantity and kind of patents in relation to green hydrogen technologies offers a clear window into the rate and course of technological developments. According to the [31], patent data is useful for evaluating the competitiveness and maturity of developing technologies in addition to reflecting continuing research and development efforts. As a result, examining global patent patterns is essential to comprehending the dynamics of innovation in electrolyser technologies and the larger field of hydrogen generation [31]. In the IEA report in particular, information was provided on the introduction of new patented technologies and the increase in patent numbers for specific technologies; therefore, this code was developed during the analysis.

Learning rate
One important element affecting the electrolyser cost dynamics is the learning rate. Electrolyser costs can be considerably reduced through economies of scale and learning effects in production processes [31]. This code permits the assessment of how rapidly the green hydrogen sector, specifically electrolyser technology is progressing toward economic viability. It is essential for assessing the future competitiveness and scalability of green hydrogen in comparison to alternatives based on fossil fuels. A higher learning rate suggests more possibilities for effectively scaling up electrolyser deployment.

Share per region
This code was specifically included to track global trends in electrolyser adoption over time, allowing for comparison of yearly changes, identification of countries that have newly adopted electrolyser technologies, and recognition of which nations lead in specific electrolyser types.

Electrolyser share
Electrolyser share means how much of the total market each type of electrolyser represents.The market share or % utilization of various electrolyser technologies is captured by this code. It provides insightful information on annual trends by examining the adoption distribution of different electrolysers from 2020 to 2024. It assists in determining which technologies were the market leaders in a particular year and which were progressively phased out or replaced over time, indicating changes in industry preferences, advancements in performance, and cost competitiveness of each electrolyser technology.

Commercialization

The maturity levels of several hydrogen production systems, i.e., electrolysers as well as alternative hydrogen production methods, are tracked by this code. However, literature does indicate that many of these alternate approaches are still in the development stage [50]. Thus, the goal of using this code is to evaluate the advancements made in the technologies over time and determine which technologies are getting close to being ready for the market in a particular year. It makes it possible to comprehend the technology pipeline and possible future contributions to the hydrogen economy more clearly.

Incremental innovations

The literature on technology dynamics defines incremental innovation as gradual improvements to current technologies, processes, or products rather than revolutionary discoveries [51]. Since it accurately depicts the consistent, incremental advancements in the hydrogen production methods, this code was used while analyzing data gathered from secondary sources. A crucial component of technological evolution, incremental innovation is essential to comprehend how these technologies have progressed over time.

Cost predictions

This code was developed using future electrolyser cost estimations available the secondary sources considered in this study. It shows projected patterns in capital and operating expenses of the electrolyser, indicating predicted declines or rises over time. Examining how policy planning corresponds with cost and technological projections using this code helps determine how responsive policy adoption is to these economic and technological expectations.

Emerging technologies

This code includes hydrogen production technologies that have not yet been widely implemented and are presently in the pre-commercial, pilot, or early research stages. It covers technologies that are still being developed or demonstrated, such as biomass conversion, photolysis, and thermochemical water splitting [31]. This code enables the analysis of how alternative hydrogen production technologies have progressed over the observed time frame.

The table below illustrates how codes are derived from statements by identifying relevant keywords.

Statement/text	Keyword/Keywords	Code
”In 2023,the capital cost for installed electrolyser ranged between USD 2000/kW for alkaline and USD 2450/kW for PEM electrolysers.”	Capital cost	CAPEX
”Energy efficiency of ALK stood at 65% in 2023.”	Energy efficiency	Electrolyser efficiency
”Manufacturing capacity for electrolyser systems had reached 25GW/yr by the end of 2023, based on the nominal facility size from company announcements.”	Capacity of electrolyser systems	Electrolyser capacity
”Biological and electrochemical processes have the dual challenge of a low TRL and higher production cost.”	TRL	Technology readiness levels
”The latest data on global hydrogen patenting, as measured by international patent families, shows a jump in applications of 47% globally in 2022.”	Global hydrogen patenting	Patent activity
”The learning rate of electrolyser stack is assumed at 18%.”	Learning rate	Learning rate
”Globally China lead in electrolyser manufacturing especially alkaline electrolyser.”	Globally	Share per region
”Alkaline technology continues to make up the largest share, accounting for more than 60% of the installed capacity.”	Largest Share	Electrolyzer share
”Thyssenkrupp nucera has expanded its product range by signing partnership with German research center for commercialisation of SOEC technology”.	Commercialisation on SOEC	Commercialization stage
”Research within PEM electrolysers focuses on minimising the use of expensive platinum group metal components in catalysts.”	Research within PEM electrolysers	Incremental innovations
”By 2030,large-scale deployment as in the NZE Scenario could bring down the cost of electrolysers.”	By 2030	Cost prediction
”Researches on other technologies for low-emissions hydrogen production, such as photocatalytic water splitting is growing rapidly.”	Growing rapidly	Emerging technologies

Table 4.2: Statements and their associated keywords and classification codes

4.3.4. Thematic analysis

A qualitative technique used to identify, examine and interpret patterns or themes in a data set is thematic analysis. By combining similar codes into broad groups (themes) that encompass important facets of the study, it offers a methodical way to arrange complicated data. Researchers may extract valuable insights from vast volumes of qualitative data by using thematic analysis, which also helps to uncover links, trends, and dynamics across time or between instances [52].

Review of Codes: To ensure comprehensiveness, both pre-defined (deductive) codes derived from the research framework and literature (e.g., TRL levels, electrolyser efficiency, learning rate) and codes that emerged (inductive) codes identified during data analysis (e.g., emerging technologies, commercialisation of non-electrolyzer technologies) were thoroughly reviewed.

Grouping into Themes: Based on conceptual similarities, the examined codes were subsequently arranged into themes. For example, codes pertaining to manufacturing share, capacity, and efficiency were classified under the performance theme, whereas the innovation activity theme was used to aggregate patent activity and emerging technologies. A better comprehension of the fundamental aspects of technology dynamics was made possible by this step.

Contextual Interpretation: Each theme was organized along a timeline (2020–2024) to address the sub-question of how green hydrogen production technologies have evolved and exhibited dynamics over time.

4.3.5. Themes

The thematic framework used to examine the qualitative data pertaining to green hydrogen production methods is summarized in the table below. Aspects including cost evolution, performance, innovation activity, market scalability, and industrial scaling and market influenced the data interpretation. This methodical technique made it possible to comprehend the dynamics of technology from 2020 to 2024 in detail.

The themes and their corresponding codes have been organised to reflect a logical progression, beginning with technological maturity and moving through innovation, performance, cost evolution, and finally, market scaling. Starting with technological maturity, it provides a clear understanding of the development stage of each technology between 2020 and 2024. Following this, innovation activity highlights the key drivers of technological advancement, which are then reflected in measurable improvements in performance indicators such as efficiency and capacity. These performance enhancements contribute to declining costs over time, as outlined under the cost evolution theme. Ultimately, reduced costs facilitate broader deployment and influence the pace and extent of market adoption.

Theme	Related Codes	Explanation
Technological maturity	TRL levels, Commericialisation status	The TRL levels and commercialisation status together assess the stage of development of both electrolysers and non-electrolyser technologies in each year.
Innovation Activity	Patent Activity,Incremental Innovation,Emerging Technologies	Highlights the role of technological advancements and patent trends in driving efficiency and performance improvements.
Performance	Capacity of electrolysers, Efficiency of each electrolyser.	This theme evaluates how the performance of the electrolyser has evolved from 2020-2025
Cost Evolution	Cost predictions, CAPEX, Learning rate	Analyses cost patterns over time and reflects how cost dynamics influence the competitiveness and adoption of green hydrogen technologies.
Industrial scaling and Market	Share of each electrolyser manufacturing,share per region	Indicates how manufacturing capacity and deployment scale impact commercialization and global diffusion.

Table 4.3: Themes and their relevant codes

4.4. Results

The findings from the thematic analysis are arranged in chronological order to depict how technologies developed from 2020 to 2024. Each theme illustrates the emergence, development, or transformation of specific technologies over time within that thematic context.

Technological Maturity

The theme technological maturity of green hydrogen production technologies were analyzed using the codes Technological Readiness Levels (TRL) and commercialization for both electrolyser as well as non-electrolyser technologies. Among electrolyser technologies, Alkaline (ALK) and Proton Exchange Membrane (PEM) electrolysers are the most commercially established and widely used for producing green hydrogen.

From 2020 onward, ALK electrolysers consistently held a TRL 9 status, signifying their complete commercial deployment and technological maturity. PEM electrolysers, in contrast, began at TRL 8, indicating they were shown to work in operational settings but progressed to TRL 9 by 2021, highlighting full maturity and commercialisation equivalent to that of the ALK electrolyser. At the same time, technologies like Anion Exchange Membrane (AEM) and Solid Oxide Electrolyser Cells (SOEC) advanced quickly during this period. AEM electrolysers began at TRL 3–4 in 2020 (indicating initial development and laboratory validation), progressed to TRL 5 by 2022, and swiftly moved to TRL 7 in 2023, signifying that a system prototype was demonstrated in an operational setting. In that same year, the German company Enapter AG introduced the first commercial-scale AEM electrolyser system, which represented a significant milestone. In 2024, additional advancements occurred as the U.S. based startup Power to Hydrogen launched its first industrial-scale commercial AEM electrolysis stack. Although AEM electrolysers have made progress, they are still in the nascent phase of market adoption and account for under 1% of the overall electrolysis market.

Conversely, Solid Oxide Electrolyser Cells (SOEC) showed consistent technological progress throughout the period. SOEC technology attained TRL 6 in 2021, signifying that the system was demonstrated in a relevant environment. It reached TRL 8 by 2022, indicating that a complete system had undergone testing and qualification in its operational environment. SOEC technology was first commercially deployed in 2020 by the MULTIPLHY project in the Netherlands when it was integrated into a biofuel refinery, marking its entry into practical applications. SOEC electrolysers represented an estimated 5% of the commercial electrolysis market in 2024, indicating a burgeoning interest and initial adoption in the realm of hydrogen production.

Other methods of producing green hydrogen that do not involve electrolysis were analyzed as well, utilizing the same codes, i.e., technological readiness levels (TRLs) and commercialisation status. For instance, between 2020 and 2021, biomass gasification was mainly in the research and small-scale pilot phase, having a TRL of 5. Between 2022 and 2024, the technology progressed to commercial-scale projects reaching TRL 7, indicating system prototype demonstration in an operational environment. In 2020, photo catalytic water splitting was still confined to laboratory research, centering on the creation of effective photo catalysts. By 2024, this technology had progressed to the stage beyond lab scale testing, with its TRL rising from 2 to 5, indicating a shift from fundamental research to early application. Photo electrochemical water splitting advanced from TRL 2 in 2020 to TRL 4 in 2022, and biological hydrogen production progressed from TRL 2 in 2020 to TRL 4 by 2024, indicating ongoing research and development.

Innovation activity

Innovation activities in green hydrogen technologies were analyzed using codes such as patent activity, incremental innovation, and emerging technologies. The innovation landscape in 2020 was characterized as relatively linear, with established technologies such as PEM and alkaline electrolysers taking precedence, while only foundational research was being conducted in fields like AEM, SOEC, and biomass gasification. In 2021, patent applications related to hydrogen rose by 5%, with a main focus in Europe, and initial research and development started looking into seawater electrolysis categorized under emerging technologies. China accomplished the first demonstration of direct seawater electrolysis in 2022, and global patent growth persisted at 5%, driven significantly by Japan (24%) and the EU (28%). SOEC demonstrated a more robust increase in patent activity compared to PEM, whereas the number of filings for alkaline electrolysers remained constant. AEM saw the emergence of moderate international patent filings. Noteworthy incremental innovations in 2023 encompassed iridium-free PEM electrolysis, initiatives aimed at prolonging the lifespan of SOECs, high-pressure electrolysis, and simplifications of balance-of-plant processes to minimize compression requirements.

There was a shift in focus to offshore hydrogen production, and the identification of the first natural hydrogen well represented an important milestone in resource discovery. Additionally, automation was recognized as a key area under emerging technologies. From 2020 to 2024, there were significant developments in the automation of green hydrogen production, particularly in relation to the incorporation of digital tools and control systems aimed at enhancing electrolyser performance and optimizing plant operations. At the outset of 2020, automation was confined to fundamental control systems in pilot plants. In 2021 and 2022, the use of industrial IoT (Internet of Things) and SCADA systems became more prevalent, facilitating real-time monitoring of hydrogen purity, pressure, and system health. In 2023, especially in large-scale plants, there was a growing adoption of AI-driven predictive maintenance and automated load balancing. By 2024, it became possible to produce decentralized systems with minimal human intervention using fully automated modular electrolyser systems, including containerized units.

Performance

Two key codes, electrolyser capacity and efficiency, were used to evaluate the performance of electrolysers from 2020 to 2024. These metrics demonstrate the progression and uptake of green hydrogen technologies through time.

The capacity of electrolysers grew considerably in this time frame. It rose from around 290 MW in 2020 to 510 MW in 2021, then reached 700 MW in 2022. The capacity experienced a significant increase to 1.4 GW in 2023, and this upward trend persisted into 2024, with preliminary data pointing to another considerable rise (exact percentage pending), indicating a faster global uptake of green hydrogen technologies.

At the same time, the efficiencies of electrolyser technologies have also improved:

- The efficiency of alkaline (ALK) electrolysers increased modestly from 62% in 2020 to 64% in 2022, and it remained relatively stable thereafter, with minor fluctuations of 1–2 percentage each year.
- The efficiency of Proton Exchange Membrane (PEM) electrolysers showed notable increases, climbing from 81% in 2020 to 83% in 2022 and reaching 86% by 2024, reflecting consistent technological advancements.
- The efficiency of Solid Oxide Electrolyzer Cells (SOEC) rose from 76% in 2020 to 79% in 2022, and then to 81% in 2024, demonstrating progress in high-temperature electrolysis performance.

These trends underscore the growing use of electrolysers and the continuous technological advancements, especially in PEM and SOEC systems, that are improving energy conversion efficiency and increasing their competitiveness for commercial-scale green hydrogen production. Because of their limited commercial use and early development, it was not possible to evaluate the efficiency and capacity of non-electrolyzer methods for producing green hydrogen. These technologies, in contrast to electrolysers, do not have standardized reporting and are primarily limited to laboratory settings or small-scale pilot projects. Consequently, performance data that is consistent and in comparable units (such as MW or % efficiency) is not widely accessible.

Cost evolution

Between 2020 and 2023, the capital expenditure (CAPEX) for electrolysers showed considerable variation depending on the type and region. In 2020, the average cost of PEM electrolysers was approximately USD 1,750 per kW. In contrast, alkaline (ALK) electrolysers had a global price range of USD 1,000 to 1,400 per kW, which fell to USD 500 to 750 per kW in certain regions of China as a result of large-scale domestic production. Due to inflation, global ALK costs reached approximately USD 1,700/kW and PEM costs reached around USD 2,000/kW by 2022, while China kept its ALK costs at a lower range of USD 750–1,300/kW. In 2023, the costs of ALK and PEM globally reached USD 2,000/kW and USD 2,400/kW respectively, whereas China persisted in providing ALK systems at prices as low as USD 750/kW, underscoring regional cost differences. Although most reports do not explicitly provide the cost of ALK and PEM electrolysers for 2025, available data suggests that PEM electrolyser costs are expected to decline to between USD 700 and 1,500 per kW, while ALK electrolyser costs are estimated to range from USD 800 to 1,000 per kW.

On the other hand, From 2020 to 2024, there have been significant developments in the capital expenditure (CAPEX) for Solid Oxide Electrolyser Cells (SOEC) and Anion Exchange Membrane (AEM) electrolysers. SOEC, during its initial demonstration phases, had restricted commercial deployment and incurred higher costs because of the need for high-temperature materials. SOEC CAPEX was estimated to be between USD 2,800 and 5,600 per kW by 2023–2024, due to its intricate design and limited scale. On the other hand, AEM electrolysers, which utilize non-precious materials and promise reduced production costs, maintained a low level of technological readiness until 2022. With the onset of commercialisation, particularly involving firms such as Enapter and Power to Hydrogen, AEM CAPEX saw a marked reduction, falling beneath USD 200 per kW by 2024, thus positioning it as a promising low-cost option within the electrolyser market.

The IEA report provides cost predictions, and the data under that was analyzed using the code cost predictions. According to the report it indicates that due to technological advancements and greater economies of scale it might lead to a significant reduction in the costs of both PEM and alkaline electrolysers by 2030, with prices possibly falling to approximately USD 300–500 per kW. This cut would enhance the economic feasibility of producing green hydrogen.

The learning rate signifies the percentage reduction in cost for a technology each time its cumulative production doubles, reflecting cost improvements through innovation and scale.The learning rate for electrolyzers was 15% in 2020, increased to 18% in 2021, and has remained at 18% thereafter, indicating steady cost reductions with increased deployment.

Industrial scaling and market
From 2020 to 2022, the installed capacity of alkaline (ALK) electrolysers was predominant, representing about 61% in 2020 and sustaining a majority share of 60% in 2022. In contrast, PEM electrolysers accounted for roughly 31% in 2020 and 30% in 2022. Other technologies like AEM and SOEC started to appear, reaching approximately 5% combined share by 2021 and 2022. In 2020, ALK electrolysers accounted for 85% of the production share in manufacturing, while PEM contributed 15%. In 2020, Europe accounted for 60% of global manufacturing capacity, while China followed with 35%. As of 2021, the distribution of manufacturing shares changed to 70% for ALK and one-third for PEM, while AEM and SOEC started to penetrate the market.

Together, Europe and China accounted for 80% of worldwide manufacturing. As of 2022, the landscape for manufacturing and installation had become more varied, with China and Europe each making up roughly a third of global manufacturing, while the U.S. and Canada accounted for about 10%. The installed capacity in Latin America and Africa has reached 17%, signaling an increase in global distribution.The overall distribution of electrolyser technologies and geographic manufacturing has remained relatively stable, with China and alkaline (ALK) electrolysers continuing to dominate. However, the market has experienced slight shifts, notably with modest increases in the shares of Anion Exchange Membrane (AEM) and Solid Oxide Electrolyser Cell (SOEC) technologies, indicating a gradual emergence of these newer technologies.

4.5. Key Findings

The key findings of this research provide information on how green hydrogen production technologies has changed between 2020 and 2024. The key findings of the analysis are given below.

1. **Electrolysers continue to lead, while alternative technologies advance**
   Electrolysis technologies especially Alkaline(ALK) and Proton Exchange membrane electrolyser have played a leading role since 2020 . However, non-electrolyser methods such as biomass gasification and photocatalytic water splitting showed notable progress, advancing from laboratory-scale research to pilot-level demonstrations/commercialisation between 2022 to 2024. This indicates a broadening of viable pathways for green hydrogen production.

2. **Innovation trends shifted towards automation and emerging sources**
   With a steady increase in patent applications, automation and digital control systems became more and more important in green hydrogen innovation. Meanwhile, new frontiers such as seawater electrolysis, wastewater -based hydrogen production, and offshore hydrogen generation initiated research in 2021 and fulfledged projects started in 2022 gained traction which suggest that technological advancement is becoming more diverse.
3. **Manufacturing Remained Concentrated in China and Europe**
   By 2024, China and Europe still accounted for more than 65% of the world's electrolyser production capacity, despite increased interest from throughout the world and pilot projects in other areas. These regions continue to dominate due to their established supply chains, policy support, and industrial capabilities.
4. **Alkaline Electrolysers Sustain Cost Leadership While AEM Technologies Emerge as the Next Affordable Alternative.**
   Despite advancements in technologies like PEM, AEM, and SOEC over time, alkaline (ALK) electrolysers have remained the most economical option due to their high technological maturity, widespread commercial deployment, and significantly lower manufacturing costs particularly in China, where ALK systems have been available for as low as $750/kW. However, AEM electrolysers are rapidly emerging as the next cost-effective alternative, with capital costs dropping below $200/kW by 2024, making them a promising low-cost option in the evolving green hydrogen landscape.

The table 3.4 shows how the key findings have evolved over this timeline.

Year	Key developments
2020	- ALK and PEM electrolysers leading the green hydrogen landscape with high TRL levels. - Beginning of early-stage automation. - China leading in ALK electrolysers. - Alkaline electrolysers are recognized as a cost-efficient option, with capital expenditures around $1,400 per kW.
2021	- PEM reached full technological maturity (TRL 9) - Initial steps in seawater electrolysis and offshore hydrogen research were initiated. - China and Europe held a dominant share in electrolyser manufacturing (∼65%).
2022	- Biomass gasification and photocatalytic water splitting advanced to pilot-scale testing(around 5-6). - Industrial automation expanded via SCADA and IoT system. - ALK electrolysers remained the lowest-cost commercial option.
2023	- AEM and SOEC technologies reached system demonstration stages(TRL 6-7). - Offshore and waste water-based hydrogen gained increased attention.
2024	- Non-electrolyser methods like biomass gasification and photocatalytic water splitting reached higher (TRL 7) indicating commercialisation. - Fully automated modular electrolyser system became viable. - AEM Electrolyser cost dropping below $200/kW.

Table 4.4: Year-wise representation of key findings

5

Study on policy adoption

5.1. Introduction

In order to map the relationship between technology dynamics and policy adoption, the second study involved gathering relevant policy documents from various official government policy websites. For the analysis, the policy mix framework which examines the combination of policy instruments and their interactions to achieve specific policy goals, were employed. The interpretation of the analysis is discussed in the subsequent section. The primary objective of this study is to identify and gather policies relevant to the technologies outlined in the first sub-question, which addresses the sub-question:

What were the various policy instruments that collectively shaped the development of green hydrogen production technologies in India?

5.2. Data collection

5.2.1. Data sources

The Ministry of New and Renewable Energy (MNRE), Ministry of Power (MoP), Press Information Bureau (PIB), and Department of Science and Technology (DST) were among the official government websites that were used to gather data on policy adoption pertaining to green hydrogen production technologies. These platforms are all administered by the government. The study focuses on the period from 2020 to 2024, during which policy documents relevant to green hydrogen were gathered and analysed. Below is a list of the selected websites along with the rationale for their inclusion.

Source	Selection Rationale	Focus area
MNRE (Ministry of New and Renewable energy)	Key authority for renewable energy policy and green hydrogen initiatives and it is the implementing agency of the National Green hydrogen mission (NGHM).	- Schemes under NGHM implementation - Policies with respect to NGHM.
MoP (Ministry of Power)	Provides supporting renewable energy policies that are implemented for green hydrogen development.	- Supporting renewable energy policies which aligns with NGHM.
DST (Department of Science and Technology)	Provides information on R&D and innovation activity related to green hydrogen technologies.	- R&D with respect to green hydrogen development. -Information on international collaborations.
PIB (Press Information Bureau)	Comprises official updates and press releases on green hydrogen policies.	- Updates and announcements on G.H policy actions. - International collaborations

Table 5.1: Sources of Policy Documents and their rationale

5.2.2. Collection strategy

A keyword-based search technique was used to make sure that only appropriate documents were gathered for the study. The search results were filtered using keywords like ”Green hydrogen production,” ”Electrolysers,” and ”Green hydrogen AND production technologies.” This method made it easier to find papers that were especially about green hydrogen and the technology used to produce it. Policies pertaining to other value chain segments or end-use applications of green hydrogen were not included for the analysis in order to maintain the scope. A specialized National Green Hydrogen Portal that compiles extensive information about green hydrogen was found on the MNRE website. Furthermore, the majority of pertinent government websites had portals specifically for green hydrogen. For the analysis, documents from these specialized sections as well as other pertinent areas of the websites, were examined and evaluated. The policy documents which were obtained as a part of this search strategy is given below.

Source/Minstry	Policy name/Document
MNRE	- Scheme Guidelines for Hydrogen Hubs under NGHM. -SIGHT Program-Component I. - Scheme to support pilot projects on innovative GH production techniques. - SIGHT Program – Component II . - R&D Scheme under NGHM.
MoP	-Interstate Transmission Fee Waiver for GH producers. - Green Open Access Rules for RE (including GH).
DST	-DST–Fraunhofer ISE Collaboration. - India–Denmark Joint R&D Call on Green Fuels and Green Hydrogen. - Call for proposals on Hydrogen Valley Platform in India.

Table 5.2: Data sources

5.3. Data analysis

Data analysis is as important as data collection. A hybrid coding approach that integrates both inductive and deductive methods was employed in order to efficiently analyze the data. A predetermined set of codes derived from theory or past knowledge serves as the starting point for the analysis i.e. deductive coding. On the other hand, inductive coding lets codes emerge naturally from the data as it is being analyzed. Both strategies are used in hybrid coding, which begins with a starting code set but is adaptable enough to accommodate new themes and codes as the analysis progresses.

The predefined codes were developed on the basis of policy mix framework. The Policy Mix Framework provides an organized approach to examine how a combination of policies together influence the creation, spread, and uptake of technologies through their integrated strategies, tools, and interactions. Examining intricate socio-technical changes in energy systems, innovation ecosystems, and sustainability initiatives is made easier with the help of this approach.

Three essential elements forms the framework's core. The first component, policy strategies, relates to the general direction and vision established by the government or relevant institutions. These strategies usually include long-term objectives, road maps, and a time horizon that direct the desired course of systemic and technical change. The second component consists of policy instruments, which are the concrete tools deployed to realize the strategies. The characteristics of the policies themselves make up the third part of the policy mix framework. This covers operational aspects like the duration of implementation (short, medium, or long-term), the type and extent of financial and institutional resource allocation, the agencies or bodies in charge of carrying out the policy, and the particular sectoral focus (e.g., manufacturing, transportation, or energy).

The evaluation of the interactions between these different policies is the last component of policy mix analysis. Determining whether the policies are redundant (overlapping without significantly adding value), contradictory (operating at cross-purposes), or complimentary (reinforcing each other) requires an understanding of the nature of these relationships.

From this list of elements, I selected only the once which are relevant to the study topic. The codes selected for the study along description, is given below.

Codes	**Description**
Policy goals	Long-term,strategic objective that a policy or set of policies aims to achieve.
Year	Point of time when a specific policy was introduced.
Technology push	It refers to the instruments that supports knowledge creation(e.g. R&D fundings,demonstration projects).
Demand pull	It refers to the instrumens that stimulates market uptake and create demand(e.g. Mandates,subsidies).
Systematic instruments	Measures that improve system-level functioning (e.g., actor coordination, skills development, standards)
Implementing group	The organizations or institutions responsible for executing, managing, and enforcing the policy instrument
Target group	Actors or stakeholders a policy is intended to influence or support.

Table 5.3: Codes which were derived from the framework.

Two other codes also surfaced during data analysis. Because these codes directly relate to characteristics that are centered on technology, they were incorporated into the coding process. They provide valuable insights into how the policy landscape surrounding the technologies have evolved over time, contributing to a deeper understanding of the temporal dynamics and shifting priorities in technology governance.

Code	Description
Technology focused	Identifies which specific technologies are prioritized in policies at different points in time to trace shift in focus.
Technology stage targeted	Captures the stage of the technology lifecycle a policy supports such as R&D, demonstration, or deployment to assess coverage and continuity.

Table 5.4: Emerged codes

The table below shows an example of how the result of analysis of a particular policy looks like.The policy analyzed here is implementation of R& D scheme under NGHM.

Code	Example
Policy Goals	Increase the affordability of green hydrogen value chain technologies, build industry-academia government partnerships , facilitating the scaling up and commercialization of technological advancements by providing policy and regulatory support.
Year	2024
Technology push	Funding for R&D for various hydrogen valuechain technologies.
Systematic instruments	Facilitate Public private partnership.
Implementing group	MNRE
Target group	Academic institutions,Universities, Government/Non profit research organizations.
Technology focused	Indigenous Modular electrolysers, PEM based fuel cells, Biomass based hydrogen generation, electrocatalysts, SOECs electrolysers, Sea water electrolysis.
Technology stage targeted	Both R&D and commercial .

Table 5.5: Example of coding

5.4. Results

The findings of the analysis are shown below. It begins with a general review of the National Green Hydrogen Mission (NGHM), as the majority of the measures covered were implemented under this program. NGHM provides a significant step forward in the adoption of green hydrogen. Following that, each key policy is described using predetermined codes, such as goals, year, technology-push, demand-pull, systemic instruments, implementing body, target group, technological focus, and targeted technology stage.

The following major steps were found to be the main activities and policy measures during the data collecting phase that are intended to facilitate the deployment of green hydrogen in India and reach the objective of producing 5 million metric tonnes (MMT) of green hydrogen by 2030.These main actions/policy measures are presented in the order based on the policy lifecycle and deployment pathway starting from early-stage enablers,moving through research and development,then to infrastructure and scale-up,and finally to market creation and regulation.

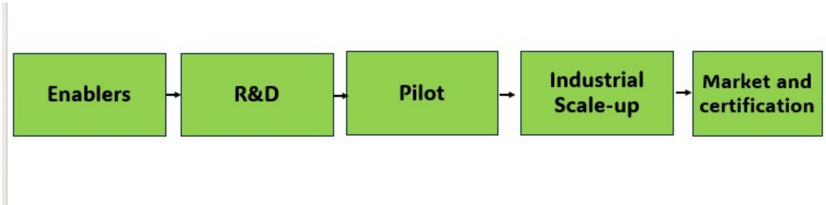

Figure 5.1: Logical flow of Policy measures cross green hydrogen development lifecycle.

5.4.1. National green hydrogen mission

Launched in 2023, the National Green Hydrogen Mission (NGHM) is spearheaded by the Ministry of New and Renewable Energy (MNRE), with collaborative involvement from the Ministry of Power, the Ministry of Petroleum and Natural Gas, and the Ministry of Heavy Industries.The main objective of the mission is to establish India as a global center for the production and export of green hydrogen, therefore bolstering the nation's energy security and climate pledges. In addition to encouraging widespread use of green hydrogen and its byproducts, such as green ammonia and methanol, NGHM seeks to facilitate thorough decarbonization in hard-to-abate industries, including steel, cement, fertilizers, and refineries.

Key stakeholders include state governments, export markets, producers of technology and electrolysers, industrial consumers, and developers of renewable energy. The mission's primary objectives include increasing domestic electrolyser manufacturing capacity, creating skilled labor through training and capacity development, creating hydrogen production hubs and specialized storage and distribution networks, and developing renewable energy infrastructure. NGHM is the main national framework propelling India's transition to a green hydrogen economy and strengthening its position in the global clean energy landscape. It does this by combining technology-push policies like R&D support and manufacturing incentives, demand-pull measures like procurement mandates and portfolio standards, and systemic instruments like standards and workforce development.

The majority of the policies described below are tied to the National Green Hydrogen Mission (NGHM). For example, the Interstate Transmission Fee Waiver and the Green Open Access Policy facilitate the availability of clean, renewable energy, which is crucial for green hydrogen generation. Meanwhile, efforts such as SIGHT Components I and II, the R&D scheme, the scheme for developing hydrogen hubs, and pilot projects on innovative green hydrogen production are being carried out directly within the NGHM framework.

However, international collaborations, such as the DST-Fraunhofer ISE partnership with Germany, the India-Denmark Joint R&D Call, and the Call for Proposals for the Hydrogen Valley platform in India, are not formally launched under the National Green Hydrogen Mission (NGHM), but they are closely aligned with its goals. These efforts are primarily carried out through the Department of Science and Technology (DST) and other bilateral or international cooperation frameworks, and they contribute considerably to the NGHM's objectives by advancing research, development, and demonstration activities in green hydrogen technology.

Below each major policies are discussed, which are aimed for green hydrogen production technologies in India.

1. **Interstate transmission fee waiver and Green open access for renewable energy:**

   The waiver of the interstate transmission fee eliminates additional expenses associated with utilizing grid infrastructure to transfer renewable energy, which makes it feasible for hydrogen plants to purchase affordable solar or wind energy from far-off places. The open access policy promotes flexible, affordable procurement by enabling developers to directly purchase renewable power across state boundaries without going through utilities. The inter-state transmission fee waiver aims to reduce the cost of renewable electricity for green hydrogen production by eliminating transmission charges, thereby enabling large-scale and geographically flexible projects. Similarly, the open access policy for renewable energy seeks to facilitate direct and affordable procurement of renewable power by green hydrogen producers, promoting broader participation and improving cost-efficiency in hydrogen production. The interstate transmission fee waiver was introduced in 2021 which was later extended in 2023 and open access was introduced in 2022.

   These instruments come under demand-side instruments because they lower the cost of renewable electricity and easily accessible, which is green hydrogen's main input, making projects more financially attractive. By improving affordability for developers and end-users, they stimulate market demand without direct production subsidies. Both of these policies are implemented by MNRE(Ministry of New and Renewable Energy) and regulated by CERC (Central Electricity Regulatory Commission), and these policies are targeted at renewable energy generators and industrial users, which helps in scaling the sector without direct subsidies. Both interstate transmission fee waivers and open access target green hydrogen production via electrolysis, since these rely heavily on electricity, typically from renewable sources like solar or wind. It primarily supports commercial-scale deployment and scale-up stages as the policy is designed to reduce operational costs for mature or near-commercial technologies, i.e., electrolysers.

2. **DST-Fraunhofer ISE Collaboration and India-Denmark Joint R&D call on green fuels and green hydrogen**

   Both partnerships seek to advance green hydrogen innovation by encouraging electrolyser production, research and development. Launched in 2023, the India-Germany joint call aims to advance high-temperature electrolyser research and open the door for large-scale manufacturing. Through improved technological readiness and mass production, this program supports R&D and early-stage innovation as a supply-push tool. The Department of Science and Technology (DST) is in charge of the collaboration on the Indian side, which is aimed at university partners, research institutes, and start-ups that collaborate with Fraunhofer ISE (Germany). With an emphasis on electrolyser technologies this collaraboration aims to research on high-temperature ALK and PEM electrolysers, and advance the research on AEM electrolysers. Targets TRL level 5-8.

The India-Denmark collaborative R&D call, which was announced in 2024, intends to promote cutting-edge electrolyser technology research in order to spur innovation in green hydrogen generation. Serving as a systematic policy tool as well as a supply-push, the initiative not only promotes technological development but also improves industry-academia cooperation. It is being carried out by the Department of Science and Technology (DST) and is aimed at research institutes, industrial partners, academic institutions, and joint consortia. In addition to promoting research into digital solutions like AI- and ML-based optimization tools and intelligent control systems for green hydrogen generation, the initiative aims to lower CAPEX and increase the efficiency of high-temperature electrolysis (for ALK,PEM and SOEC electrolysers) . With the goal of advancing ideas to commercial readiness across Technology Readiness Levels (TRL 4), it assists initiatives in the technological development phase.

3. **Scheme to support Pilot projects on Innovative Green hydrogen production methods.**

   The goal of this scheme is to accelerate the development and demonstration of non-conventional green hydrogen technologies.This scheme was introduced in 2024 as a part of National Green hydrogen mission. This scheme is supply-side instrument as it directly supports the development and scaling of hydrogen production by providing financial assistance for pilot projects, equipment procurement, infrastructure setup, and technology validation. It is implemented by Ministry of New and Renewable Energy (MNRE) and targets key stakeholders including research institutions, startups,
   public-private partnerships R&D labs and industry innovators. This scheme targets green hydrogen production technologies such as biomass gasification, wastewater electrolysis, seawater electrolysis, modular electrolyser connected to rooftop solar or other decentralized RE plants like small hydro etc. This scheme focuses on technologies at TRL 4 to 7, aiming to bridge the gap between early-stage research and commercialisation, and contribute to a more diverse and cost-effective green hydrogen ecosystem in India.

4. **Guideline for implementation of R&D scheme under NGHM**

   The effort, which was started in 2024, intends to create an innovation ecosystem and solid industry-academia relationships in order to lower the cost of producing green hydrogen. By providing targeted policy assistance, it aims to make it easier for technology innovations to be commercialised. The initiative prioritizes research and development to speed up green hydrogen technology, acting as a supply-push tool. The program, which is run by the Ministry of New and Renewable Energy (MNRE), targets a variety of stakeholders, such as private universities, industry players, academic and research institutions, and cooperative consortia. The program covers Technology Readiness Levels (TRL 5 to 8) and supports initiatives at different levels of technical maturity, especially those in the R&D and commercialization phases.

   There are three primary components to the scheme, which also gives information about the technologies targeted:
   Projects in mission mode (short-term: 0–5 years): These emphasize expanding the commercialization of biomass-based green hydrogen production, encouraging domestic development of modular electrolysers and PEM fuel cells, and working with industry to produce end-use products.

Mid-term Grand Challenge Projects: Focusing on enhancing the transportation infrastructure and green hydrogen supply chain.

Long-term Blue Sky Projects: Committed to the advancement and demonstration of innovative technologies, including seawater electrolysis and reversible solid oxide electrolysis cells (SOECs).

The initiative's overall goal is to assist technical innovations as they go into commercialization.

5. **Call for proposal on hydrogen valley platform in India**

   The goal of this initiative is to enhance the cost-effectiveness, efficiency, and reliability of clean hydrogen across the value chain through advanced R&D, strengthen industrial and scientific capabilities, demonstrate scalable hydrogen solutions for widespread deployment, and boost public and private awareness and adoption. This initiative was launched in 2022. This instrument supports infrastructure and production by funding research and development as well as demonstrations to develop hydrogen technologies across TRL levels, making it a supply-push tool. It is also systematic as it encourages cooperation between government, business, and academia in order to create a strong innovation ecosystem. Department of Science and Technology (DST) is the implementing agency.The hydrogen valley platform initiative targets a diverse group of stakeholders such as public-private partnership, academic institutions and R&D organizations, industry consortia and infrastructure providers, regional and local planners across the hydrogen value chain. The platform supports a pluralistic mix of technologies, prioritizing electrolysis like ALK, PEM, SOEC, AEM and also non-electrolysis routes such as biomass, biological and photo catalytic hydrogen production. It targets a wide range of technological stage i.e. from TRL stage 5-9, which means it supports technologies that have been validated in relevant environment as well as technologies which are ready for large-scale demonstration, system integration and pre-commercial deployment.

6. **Call for proposals for setting up of green hydrogen hubs in India.**

   The objective of the green hydrogen hubs scheme in India is to identify and develop areas for large-scale production and use of green hydrogen, promote integrated project development for scaling and resource pooling, and enhance cost competitiveness in comparison to fossil fuel-based alternatives. It also targets maximizing domestic production and exports, improving asset viability across the value chain. The scheme is launched under NGHM in 2024, and has a combination of supply-push and systematic instruments. It acts as a supply-push instrument by providing infrastructure and financial support to scale up green hydrogen production capacity, fostering domestic manufacturing, and enabling integrated project development.

   On the other hand, this scheme acts as systematic instrument as it promotes coordination among stakeholders such as industry, government, and technology providers through shared infrastructure, regional clustering, and ecosystem based planning to support the entire hydrogen value chain. The Ministry of New and Renewable Energy (MNRE) is the implementing agency for this scheme. This scheme targets stakeholders such as central and state PSUs, private enterprises, joint ventures, and consortium's capable of project execution and commercialisation. Although the scheme does not explicitly specify the technologies it supports, it does emphasize green hydrogen production alongside the broader value chain. This implies a flexible, technology-neutral approach. However, it can be inferred that the scheme primarily focuses on the commercialization of already established and mature technologies that are ready for large-scale deployment.

7. **SIGHT - Component 1 (Electrolyser manufacturing Incentive)**

   The strategic interventions for green hydrogen transition (SIGHT) programme - component I has key goals to maximise electrolyser manufacturing and reduce the leverized cost of green hydrogen production. The policy also aims to support both established and emerging electrolyser technologies, gradually raise domestic value addition, and guarantee performance and quality that are competitive on a worldwide scale. The SIGHT program was launched in 2023, with subsequent announcements and implementation details unfolding in 2024. This program's instrument type is supply-side as it reinforces domestic electrolyser production by providing manufacturers with financial assistance. The implementing agency is Solar Energy Corporation of India (SECI) and targets Indian electrolyser manufacturers, including firms and new entrants.The scheme covers a wide range of electrolyser technologies, including solid oxide electrolyser cells (SOEC), proton exchange membranes (PEM), anion exchange membranes (AEM), and alkaline (ALK). As the main goal of this initiative is to promote local production of electrol ysers it focuses on technologies that are already well-established in the market.

8. **SIGHT-Component II Incentive Scheme for green hydrogen production (under mode 1)**
   The SIGHT Component II consistent of mode I and mode II. The three sub-modes of the SIGHT Component II are mode I, mode 2A, and mode 2B. Of these, mode 2A concentrates on green ammonia, whereas mode I and mode 2B are devoted to the production of green hydrogen. As a result, mode I and mode 2B are analyzed in this study. The first paragraph discusses mode I, while the second paragraph discusses mode 2B.

   The goal of mode 1 is to boost the amount of green hydrogen and its derivatives produced in India, encourage widespread use, and make locally produced green hydrogen more affordable. By providing green hydrogen producers with production-linked incentives (PLI), it seeks to establish a strong local market, guarantee affordability and scale, and lessen reliance on fossil fuels. This scheme was announced in 2023 with supporting guidelines continuing in 2024. By providing production-based financial incentives (Rupee/kg) for green hydrogen, mode 1 is a demand-pull instrument designed to increase market demand and promote both production and consumption. Targeting a broad spectrum of green hydrogen producers, including private entrepreneurs, public sector businesses, consortia, and industrial consumers, the program is being carried out by the Solar Energy Corporation of India (SECI) under the Ministry of New and Renewable Energy (MNRE). For SIGHT Component II the technology targeted includes two distinct buckets. Bucket 1 supports technology-agnostic electrolyser pathways, while Bucket 2 specifically focuses on biomass-based hydrogen production technologies. As the plan aims to facilitate widespread implementation and quicken the shift to a competitive green hydrogen economy, it concentrates on near-commercial and commercial technologies (TRL 8–9).

   Announced in 2024, Mode 2B shares a similar overarching objective with Mode 1, i.e. to accelerate the production and adoption of green hydrogen in India. However, while Mode 1 aims to provide uniform financial incentives per kilogram of green hydrogen produced to stimulate the general supply, Mode 2B specifically aims to promote sectoral integration by linking hydrogen production with committed industrial end-use sectors such as steel, refining, and fertilizers. It functions as a demand-pull tool, intended to increase market demand by providing financial assistance for each kilogram of green hydrogen generated, thereby promoting industry adoption. It is implemented by SECI and target group as such as private developers, public sector undertakings, and industrial consortia.The scheme is technology-agnostic,allowing participation from any green hydrogen production method and targets commercial and near-commercial technologies.

5.4.2. Timeline analysis

If we arrange the policies chronologically and analyze them accordingly, it is evident how the focus of technologies has changed. For instance, in 2021 and 2022, the policies were on providing the basis for green hydrogen production.The Interstate transmission fee waiver and green open access policies served as enabling measures for the future hydrogen economy by providing renewable energy which is needed for producing green hydrogen. The hydrogen valley call focused on a diverse set of electrolysis (ALK, PEM, SOEC , AEM) as well as non-electrolysis routes (Biomass gasification, biological and photocatalytic hydrogen production) for green hydrogen production. promoting R&D , demo, as well as commercialisation of technologies.

By 2023, the emphasis shifted to increasing and broadening R&D activities. SIGHT Component I was introduced to facilitate the production of several electrolyser technologies, such as Anion Exchange Membrane (AEM), Solid Oxide Electrolysis Cells (SOEC), Proton Exchange Membrane (PEM), and Alkaline (ALK) electrolysers, in order to increase domestic manufacturing. In the meanwhile, SIGHT Component II- mode 1 provided incentives for the generation of green hydrogen via biomass gasification and electrolysis. The India-Germany partnership worked concurrently to develop high-pressure electrolysis for ALK and PEM electrolysers in order to get them ready for scalable production. Additionally, it aided in the ongoing advancement of AEM electrolyser technology.

A major shift in policy orientation and technical advancement occurred in 2024, when commercialisation, collaboration, and innovation in advanced hydrogen technologies were prioritized. Notably, the creation of hydrogen hubs and SIGHT Mode 2B took a technology-agnostic stance, giving industrial and regional significance precedence over particular technology type.At the same time, the National Green Hydrogen Mission's (NGHM) R&D Scheme and Pilot Project Scheme focused on novel and innovative approaches. The pilot projects investigated topics such improving grid stability for electrolysis operations, modular electrolyser systems, biomass gasification, and wastewater and seawater electrolysis. The R&D plan supported the commercialisation of biomass gasification technologies while simultaneously focusing on innovation in modular electrolysers, PEM fuel cells, seawater electrolysis, and reversible solid oxide electrolysis cells (r-SOECs).

Furthermore, in order to increase efficiency and reduce CAPEX, the India-Denmark collaborative R&D call concentrated on developing high-temperature electrolysis technologies, such as Alkaline (ALK), PEM, and SOEC electrolysers. In order to improve green hydrogen production, it also underlined the integration of digital solutions, such as intelligent control systems and optimization tools powered by AI and ML.

The table below shows how the technology focus have evolved.

Year	Policy instruments	Technology focus	Approach
2021	- Interstate tranmission fee waiver	Enabling electrolysis using RE	Setting up enablers for electrolysis
2022	- Hydrogen valley call - Green open access	Focus on PEM,AEM for R&D , Mix of electrolysis and non-electrolysis for hydrogen valley	Promoting R&D for electrolysis and demos.
2023	- SIGHT Component I &II(Mode I) - India-Germany R&D call	Domestic manufacturing of electrolysers (ALK, PEM, SOEC, AEM) , R&D for ALK , PEM, and research for AEM.	Scale-up and broader R&D , Commercialisation
2024	- SIGHT Mode 2B - Hydrogen Hubs - Pilot projects for innovative GH production methods - R&D scheme under NGHM India Denmark joint R&D call	Shift towards a more technology- agnostic approach, Focused on the commercialisation of biomass gasification, R&D towards seawater and wastewater electrolysis, modular electrolysers, PEM/SOEC- based fuel cells, Digital pathways (AI/ML-based optimisation for GH production).	Sector coupling, Innovation and regional suitability.

5.5. Key Takeaways

Overall, it is evident how India's green hydrogen policies have changed over time by examining the chronology and contents of significant policy changes. At first, electrolysis was the main emphasis, both in terms of domestic manufacturing and research and development activities. This was indicative of a focused attempt to make electrolysis the mainstay of green hydrogen generation.

Moreover, by 2023, the term ”indigenous” began to appear frequently in policy language, indicating a growing emphasis on strengthening domestic manufacturing capabilities.

But there was a discernible change by 2024. With governmental frameworks starting to accept a greater range of green hydrogen generation techniques than only electrolysis, the technological scope greatly expanded. This broader focus started to show in both research funding and commercialisation initiatives, such as production and end-use application subsidies. This shift is highlighted by the introduction of the term ”technology-agnostic” into policy discourse after 2024, which denotes a conscious effort to encourage a variety of production methods, including alternatives to electrolysis, such as biomass gasification.

Now that this background has been provided, the following chapter will explore the mechanisms behind this policy evolution and its linkage with technology dynamics. The next chapter aims to explain how the policy emphasis changed from prioritizing electrolysers to concentrating on biomass and then shifting to a more technology-agnostic approach. It also explains how this change may be understood in relation to technology dynamics.

6

Linking technology dynamics and policy adoption

6.1. Introduction

The literature review indicated that the relationship between technology and policy adoption is often shaped by underlying mechanisms that evolve alongside emerging technologies. These mechanisms, in turn, influence the development and adoption of new policies. Therefore, this study seeks to investigate whether such a link exists and how it can be explained. A quick recap of the literature review, the third subquestion is :

How could the link between technology dynamics and policy adoption be described?

This study is divided into three parts: data collection, data analysis, and interpretation of the results.

6.2. Data collection

The sources used, the reasoning behind their selection, and the method utilized to effectively filter and compile a vast number of articles are described in this collection strategy section.

6.2.1. Data sources

Real-time resources like news articles and think-tank websites were used as data sources. These sources were employed to gather data because they represent current stakeholder viewpoints, policy announcements, and industry perspectives. Based on this, I selected two newspaper portals for this research. Energy News and The Hindu, because they are among India's most widely circulated newspapers, with a broad nationwide readership [53]. Insights from think tanks like TERI were also included since they offer in-depth research and expert analysis on India's energy and environmental policy, providing important context beyond standard news coverage.The following table presents an overview of the data sources along with the reasons for their selection.

Data source	Description
Energy world	Energy world is a dedicated platform that focuses specially on energy - related news,making it highly relevant for tracking developments in green hydrogen.
The Hindu Business line	Offers credible , in-depth reporting on India's policy developments, energy reforms, and government announcements.
TERI - The energy and resource Institute	Provides expert-backed policy analysis, scenario-modelling and technology forecasts specific to energy transitions.

Table 6.1: Articles selected and their description

6.3. Collection strategy

Appropriate search terms were applied to retrieve articles from the selected data sources. Two board search terms were used:"Green hydrogen" and "Renewable hydrogen" which refer to the same concept but are expressed using different terminologies. The use of both terms is to ensure that the search remains comprehensive and inclusive, capturing all potentially relevant articles. The inclusion of "Renewable hydrogen" specifically aimed to account for sources that might prefer this terminology while referring to hydrogen produced from renewable energy sources.

6.3.1. Scoping strategy

The initial search yielded a large number of results. Therefore, it was necessary to filter out unrelated articles and to focus only on those relevant to this research topic. The first step involved reviewing the articles' publication dates and excluding those published before 2020 and after 2024. Since the first two subquestions looked at the same time period, this chronology was also used in this subquestion to maintain consistency. Almost one-fourth of the total articles were eliminated in this phase alone, as many of them were published after 2024. After that, additional exclusions were made after skimming the remaining articles. In this phase, articles were eliminated if they (1) focused solely on other technologies like storage or end-use unrelated to green hydrogen production technologies, (2) The one's examined state-level policies, as this thesis focuses on national-level policies.

After this initial screening, the selected articles were read thoroughly. During this stage keywords associated with predefined codes those which were relevant to technology dynamics and policy adoption, were applied. Certain patterns were noticed as a result of this. While some publications did not discuss technological dynamics and policy adoption together, others merely gave a broad summary of the policies that were put into place. In particular, publications that lacked the necessary keywords tended to concentrate on the adoption of technology or policies separately rather than the connection between the two. Hence, they were not considered for the analysis.

Afterwards, duplicate articles containing the same content but sourced from different databases were removed. Following this thorough filtering process, almost 86 articles remained, which were further analyzed and were included in the findings.

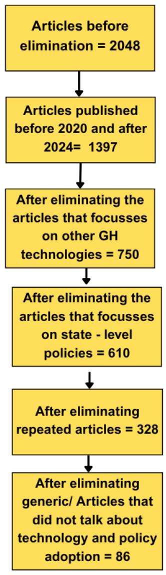

Figure 6.1: Scoping strategy

6.4. Data analysis

A set of predefined codes were used to guide the data analysis process. These codes were also applied during the final stage of selecting newspaper articles to ensure that only articles that describe about technology and policy were selected. This process of using a pre-defined coding strategy is known as deductive coding. Deductive coding is a process of applying a predefined set of codes or themes to the data, based on existing theories or prior knowledge [54].To explore the link between technology and policy, the same set of predefined codes used in sub-questions 1 and 2 were applied. This is to see how the link between technology and policy is described.

As mentioned earlier, this sub-question utilized the identical set of codes that were used in sub-questions one and two. Not every code, though, was precisely aligned in the data. Capturing the intersection of codes from sub-question one and sub-question two was the aim. As a result, only newspaper items for which these sets of codes were pertinent were considered.

A quick recap of the codes used for sub questions one and two, and their small description is given below.

Type	Codes	Description
Technology	CAPEX	Initial investments costs associalted with the electrolyser systems.
	Electrolyser efficiency	Tracks how effectively electricity is converted into hydrogen.
	Electrolyser capacity	Indicates the maximum hydrogen output capacity of an electrolyser.
	TRL Levels	Assess the technological maturity of hydrogen production technologies.
	Patent activity	Reflects innovation intensity via international hydrogen-related patents.
	Learning rate	Captures cost reduction trends due to experience and production scale-up.
	Share per region	Maps geographical distribution and adoption trends of electrolyser technologies.
	Electrolyser share	Shows the market share of each electrolyser type over time.
	Commericialisation	Indicates which technology has started commercialisation or became close to commercialisation in a particular year.
	Incremental innovation	Represents continuous, small-scale improvements in technologies.
	Cost predictions	Analysis future capital and operational cost trends of electrolysers.
	Emerging Technologies	Identifies hydrogen technologies still in early or pilot stages of development.
Policy	Policy goals	Long-term, strategic objective that a policy or set of policies aims to achieve.
	Year	Point of time when a specific policy was introduced.
	Technology-push	It refers to the instruments that supports knowledge creation (e.g. R&D fundings, demonstration projects).
	Demand-pull	It refers to the instruments that stimulate market uptake and create demand (e.g. Mandates,subsidies).
	Systematic instruments	Measures that improve system-level functioning (e.g., actor coordination, skills development, standards).
	Implementing group	The organizations or institutions responsible for executing, managing, and enforcing the policy instrument.
	Target group	Actors or stakeholders a policy is intended to influence or support.

Table 6.2: Quick recap into codes used for sub-questions one and two

These codes were applied systematically to identify instances where specific policies or related initiatives were implemented with the aim of promoting specific aspects of technological development which were identified through the technology dynamics study. For example, the analysis focused on tracing how certain policy measures were intended to improve the electrolyser efficiency of least efficient or reduce the CAPEX of the most expensive electrolyser etc. And how external forces have contributed for these policy adoption (e.g. industry lobbying). This explains the reasoning behind the selection of these specific codes.

6.5. Findings

This section presents the findings in two ways: first, by mapping the combinations of technology and policy-related codes and their link to policy adoption; and second, by comparing these findings with potential underlying mechanisms.

6.5.1. Combination of codes

Several recurring patterns were observed where technical and policy-related codes occurred together. While other countries made swift progress on their green hydrogen agendas, India was cautious and observant in the early stages, around 2020. But growing pressure from industry experts and other stakeholders made it seem urgent for India to step up its efforts. Prime Minister Narendra Modi's announcement of the National Hydrogen Policy, which positioned India as a potential global hub and signaled a strategic commitment to green production of hydrogen, codified this urgency. Building on this foundation, the following list of recurrent code combinations was found.

Electrolyser efficiency & Supply-push instruments:
The importance of improving electrolyser efficiency to reduce CAPEX and lower the overall cost of green hydrogen was strongly advocated by the Ministry of New and Renewable Energy (MNRE) and the Ministry of Power (MoP). Following the rollout of India's Green Hydrogen policy, which included provisions like waiving interstate transmission fee charges and green open access for renewable energy, the advocacy for supply-push instruments such as production-linked incentives and viability gap funding gained momentum. Furthermore, the Senior President of ICRA supported these measures, who emphasized that enhancing electrolyser efficiency is key to improving cost competitiveness. Industry stakeholders, including Ernest & Young and Engie India's CEO, further reinforced the need for focused supply-push policies to drive down capital costs and spur innovation in electrolyser technologies.

Innovation and R&D instruments:

The link between innovation and research and development, which comes under the supply-push instrument, was also seen. For instance, A researcher at CSTEP pointed out that the high cost of securing critical minerals such as platinum, iridium, and ruthenium, which are used as catalyst for electrolysers and are essential for domestic electrolyser manufacturing, poses a challenge. This could be alleviated by advancing recycling technologies and exploring alternative materials to support green hydrogen development. The research organization ICRA also supports this viewpoint, emphasizing the necessity of government intervention through suitable policy measures and the need for metal prices to decline in order to lessen the capital expenditure burden of electrolysers.

Learning rate and demand pull instruments:

Researchers and analysts pointed to the critical role of demand-pull instruments like the Green hydrogen Portfolio Standard (HPS) and dedicated procurement mechanisms which help lock in scale, which in turns triggers the learning-by-doing, reducing the overall cost of green hydrogen and related technologies. On top of that, Bernstein's study underscores persistent worries regarding the high capital costs (CAPEX) of electrolysers in relation to stressing demand-pull forces. Demand segmentation is essential to addressing this. The study predicts that by 2070, the price of green hydrogen may drop to about $1.70 per kilogram due to a combination of rising demand and falling prices for renewable energy.

Additionally, GE Gas Power South Asia CEO Deepesh Nanda stressed that building a strong local value chain and boosting demand should be the top priorities of India's second phase of green hydrogen implementation. Over time, this strategy would help the learning by doing process, which inturn helps to reduce the overall cost of producing green hydrogen and electrolyser prices.

Innovation and systematic instrument:

A connection between innovation and systematic instruments was also evident. The Minister of New and Renewable Energy emphasized the significance of emerging technologies like sea-water electrolysis and stressed the need for collaborative efforts across research domains and institutions to strengthen hydrogen production capabilities. Several examples mirrored the focus on the role of systematic instruments. Industry experts strongly supported having a skilled and competent workforce as a requirement for increasing green hydrogen capacity, according to insights from the International Conference on Green Hydrogen. While the majority of the instruments under the National Green Hydrogen Mission (NGHM) are focused on technological advancements, such as pilot projects and commercial-scale production, there is still a critical gap in the availability of trained manpower, the Ministry of New and Renewable Energy (MNRE) acknowledged this concern. One of the main obstacles to accomplishing the mission's objectives is addressing this labor shortage. Furthermore, firms such as Ernst & Young (E&Y) have emphasized that reducing the capital expenditure (CAPEX) associated with electrolysers requires the establishment of effective public–private partnerships. Such collaborations are seen as essential for fostering innovation and accelerating the development of cost-effective green hydrogen technologies. Prime Minister Narendra Modi shared this opinion, stressing the value of cooperation, R&D, and industry-academia partnerships to spur innovation, especially in fields like wastewater and seawater electrolysis. In order to advance green hydrogen generation, he also emphasized the necessity of critically analyzing and enhancing electrolyser efficiency.

Automation and R&D:

Additionally, the potential of digitalization and automation in the production of green hydrogen is becoming more widely acknowledged. Industry participants agree that there may be substantial advantages to using digital technology into green hydrogen systems. To achieve the goal of 5 million metric tonnes (MMT) of green hydrogen capacity by 2030, for instance, the CEO of a US-based construction company noted that depending just on electrolysers would not be enough. He emphasized how critical it is to promote innovation in this field. Furthermore, he pointed out that electrolyser technologies are quite energy-intensive, which significantly raises the cost of manufacturing as a whole. He recommended that India can investigate the combination of digitalization and green hydrogen technologies by means of focused research and development.

CAPEX, Innovation and PPP partnership:

The interplay between capital investment, technological innovation, and public-private partnerships, which also comes under systematic instruments has become increasingly evident. According to industry experts, one of the biggest obstacles to enabling domestic production of electrolysers is the high capital expenditure (CAPEX) required. Concerns about the environment and society are also raised by the significant amount of electricity and fresh water needed to create hydrogen on a large scale. This problem is made much more urgent by the fact that groundwater levels are already dropping and that water stress is getting worse all throughout India. In response, various industry experts have suggested looking into using treated wastewater for the electrolysis process as an alternative to freshwater. The experts suggest creating pilot projects and public-private partnership (PPP) models to support this approach, which aims to maximize resource use and reduce related risks. In order to improve efficiency and scalability, it has also suggested funding research into artificial intelligence (AI), grid infrastructure, and other cutting-edge technologies.

Biomass-based green hydrogen:

The results show that the production of green hydrogen from biomass is becoming an economically feasible approach. The MNRE Minister stated that valuable resources for green hydrogen production may be produced from agricultural wastes, animal waste, sugarcane bagasse, and municipal solid waste. In order to promote the efficient utilization of these waste streams, the National Bio-Energy Programme (NBP) was established in November 2022. As a result, biomass is becoming acknowledged as a promising source for producing green hydrogen. Sarangi (MNRE Minister) also highlighted the method's potential, pointing out that the National Green Hydrogen Mission's (NGHM) research and development activities are concentrated on determining its feasibility.

Leaders in the industry also support this viewpoint. For example, according to the CEO of Femto Green Hydrogen, electrolysis alone may not be sufficient to reach the NGHM's goal of 5 million tonnes of green hydrogen since it requires a lot of solar power and, thus, a lot of land. He underlined the necessity of R&D activities for alternative production technologies, such as biomass-based and thermochemical processes. The Chairman of Indian Oil has proposed the use of biomass for green hydrogen production and emphasized the need for establishing more facilities that employ biomass gasification technology to support this initiative.

6.5.2. Linking the findings with policy proposals

The evolution of concerns can be outlined along a timeline, showing how these concerns have shifted over time.This timeline of evolving concerns can also be mapped against the policies adopted, enabling a comparative view of how stakeholder priorities and policy actions might have progressed in parallel. However, it is challenging to state with certainty that such concerns and discussions directly prompted policymakers to make firm decisions, due to the time required for policy development from drafting to public announcement. While our findings do not provide explicit evidence of this causal link, it remains a plausible possibility. The two timelines, however, can still be compared to observe how both evolved in parallel.

For instance, in the early stage around 2020, when other countries were in the forefront of green hydrogen implementation, India was still in its "Wait and Watch " phase. Concerns emerged with respect to the cost of renewable energy, which is almost (50%-70%) of the total cost of electrolysis and the supply of R.E as well. Experts also emphasized the need of infrastructure for G.H. production. Concurrently in 2021, the announcement of the green hydrogen policy introduced measures such as the interstate transmission fee waiver and green open access(which was later introduced in 2022) , aimed at creating an enabling environment for green hydrogen production. Following the announcement of the green hydrogen policy, news articles reflected a growing emphasis on concerns related to the infrastructure needed for the production of green hydrogen. Later, in order to provide the necessary infrastructure, the government called for proposals for the hydrogen valley, with a wide range of technologies, incorporating electrolysis as well as non-electrolysis technologies and covering everything from research to commercialisation.

Around 2022/2023, after the introduction of these policies, worries were raised concerning the high CAPEX cost of electrolysers. Stakeholder feedback at the time stressed the importance of promoting local electrolyser manufacturing and improving their efficiency. In parallel, research and development activities, such as the India-Germany joint call, were initiated to investigate high-temperature electrolyser technologies such as ALK and PEM, as well as to move AEM electrolysers closer to commercialization. The National Green Hydrogen Mission (NGHM) was launched in 2023, with the SIGHT Component-I focused solely on the local manufacture of electrolyser technologies such as ALK, PEM, SOEC, and AEM.

Later, around late 2023/2024, the launch of SIGHT Component-I sparked extensive discussions and concerns regarding the requirement for local electrolyser manufacturing. These included the necessity for land and solar capacity for electrolysis, as well as the difficulty of sourcing expensive catalysts needed to produce green hydrogen via electrolysis. The introduction of extending research into biomass gasification and moving it to commercialisation might have been a response to these concerns. Similarly, significant concerns arose over the substantial freshwater requirements for electrolysis, a matter still uncertain in the Indian context. This issue has been widely acknowledged, notably by India's Prime Minister, who has underlined the necessity for more collaboration to overcome such technical issues. Furthermore, the lack of suitable demand-pull instruments, which are required to enable "learning by doing," was acknowledged.

In a similar vein, various initiatives were announced in 2024. These included pilot projects which focused researching on innovative green hydrogen production methods such as seawater and wastewater electrolysis, modular electrolysers, grid-stability research, and further advancements in biomass gasification, all of which facilitated public-private partnerships. Another important element was the research and development program, which focused on technologies such as PEM and SOEC-based fuel cells, seawater and wastewater electrolysis, and modular electrolyser development.

Furthermore, in 2024, concerns regarding market creation through demand-pull instruments gained prominence, and the importance of incorporating digitalization and AI into green hydrogen production became increasingly evident.The same year, SIGHT Component-II (Mode 1) was announced, for production of G.H. with two categories: electrolyser technologies and non-electrolysis technologies. Furthermore, SIGHT Component-II (Mode 2B) emphasized industry integration and market development, which might have been in reaction to worries about a lack of demand-pull instruments.

Moreover, in the same year, multiple stakeholder feedback highlighted the need for public–private partnerships, collaborations, and workforce development. In parallel, initiatives such as the India–Denmark collaboration and innovative pilot projects were designed to promote and incorporate public–private partnerships.

Finally, the India–Denmark joint R&D call concentrated on enhancing the efficiency of electrolysis technologies such as ALK, PEM, and SOEC electrolysers. It also emphasized research on the application of digital technologies in green hydrogen production, potentially addressing stakeholder feedback and suggestions regarding the use of digitalization in this sector. The table below provides a summary of the discussion and highlights the comparison.

Year	Key technological discussions / Concerns	Policy introduced
2020 & 2021	- Need for enabling environment for electrolysis using RE - Cost of renewables need to be reduced	-Interstate transmission fee waiver.
2022	- High CAPEX for electrolysers, - Need for domestic manufacturing, - Efficiency improvements, - Focus on PEM electrolyser as the most efficient.	- Green open access policy - Hydrogen valley call.
2023	- Push for domestic manufacturing, - Freshwater scarcity for electrolysis , - High land and solar requirement, - Concerns that electrolysis alone won't meet targets, - Need for R&D and incentives for biomass gasification.	- SIGHT Component - I - India-Germany R&D Call (High temperature ALK,PEM &AEM) efficiency improvement. - SIGHT Component -II - Mode 1
2024	- Need for demand-pull incentives, - Emphasis on partnerships skilled workforce, - Collaboration in order to explore alternative methods: - Seawater and wastewater electrolysis. Modular electrolysers , biomass gasification. - Sector coupling and flexibility in production methods.	- SIGHT Component II-Mode 2B, -Hydrogen Hubs (Technology agnostic), -Innovative GH production pilot projects. Scheme for R&D under NGHM. - India-Denmark Joint R&D call.

Table 6.3: Mapping concerns with policy adopted

Although we do not have enough evidence to prove that the concerns led to the introduction of policies, they are compared with respect to the timeline in which they were introduced. However, it is important to note that they are just causable claims.

6.5.3. Comparing the findings with potential mechanisms

The literature review highlighted mechanisms that explain the relationship between technological developments and policy adoption. To quickly recap, the mechanisms identified in the literature includes compulsive policy learning, policy mix co-evolution, the advocacy coalition framework, and the use of multiple frameworks to describe the relationship between them. Below, the findings are discussed in relation to these theoretical perspectives, with only the mechanisms that align with our results being described.

Advocacy coalitions:

Patterns of advocacy coalition can be observed in the findings. An advocacy coalition, as defined in the Advocacy Coalition Framework (ACF), is a group of actors from various organizations that share core beliefs about a policy issue and coordinate their efforts across time within a given policy subsystem. In this study, six distinct advocacy coalitions can be identified. The coalition for electrolyser efficiency and supply-push support, which includes the MNRE, MoP, the Senior President of ICRA, E&Y, and Engie India's CEO, believes that improving electrolyser efficiency and deploying supply-push instruments such as PLI and viability gap funding are critical in lowering CAPEX and increasing cost competitiveness. Another significant coalition can be observed for innovation in essential minerals and recycling, which includes advocacy from CSTEP researchers and ICRA, who pushes for the advancement of recycling technology, the exploration of alternative materials, and the implementation of government-funded efforts to solve essential minerals' high cost and scarcity. Furthermore, another coalition can be noticed for demand-pull and learning-by-doing, which includes researchers, Bernstein study authors, and Deepesh Nanda, CEO of GE Gas Power South Asia, who all advocates for scaling demand through mechanisms like as HPS and specialized procurement to promote learning-by-doing and lower costs. The coalition for innovation, PPPs, and systematic instruments, includes the MNRE Minister, industry experts, E&Y, and Prime Minister Modi, promotes public-private partnerships, skilled workforce development, and R&D collaborations, particularly in seawater and wastewater electrolysis, to spur innovation and reduce CAPEX. Another coalition can be noticed for CAPEX reduction and use of alternative water sources, comprised of diverse industry professionals, focuses on using treated wastewater for electrolysis, developing PPP-backed pilot projects, and utilizing AI and grid infrastructure enhancements to improve scalability. Finally, the coalition for Biomass-based green hydrogen, which includes MNRE Minister Sarangi, the CEO of Femto Green Hydrogen, and the chairman of Indian Oil, advocates for investing in biomass-based hydrogen technologies and establishing biomass gasification facilities as a complementary to electrolysis in meeting NGHM targets.

Despite their thematic differences, we can observe that these coalitions share common goals of accelerating the deployment of green hydrogen technologies, reducing production costs, and supporting the targets outlined under NGHM.

Compulsive policy making:

The findings also reveal patterns of compulsive or reactive policy making, where stakeholder pressures and external circumstances prompted rapid policy response to accelerate India's green hydrogen development. Although not explicitly evident, a subtle pattern of compulsive policymaking may be discerned. India first took a cautious ”wait-and-watch” approach to green hydrogen, whilst other countries moved more quickly in their adoption efforts. This discrepancy has raised worries among industry professionals and policy analysts about the dangers of falling behind on global energy and climate trends. The government might have adopted the green hydrogen policy, which established an ideal environment for expanding renewable energy supply, a critical component of green hydrogen generation in response to this urgency. Experts described this policy as a ”quantum leap” towards meeting India’s energy and climate goals. Furthermore, according to reports in the TERI think tank portal, industry players and energy analysts have repeatedly pushed India to speed green hydrogen adoption by leveraging on its rising energy capacity, citing the need for a defined roadmap and strategy. These factors most likely would have influenced the government’s decision to formally launch the National Green Hydrogen Mission (NGHM), signaling a significant shift toward proactive policy action.

Policy co-evolution:

There are causal claims pointing to the existence of policy co-evolution in India’s green hydrogen industry, however these are not yet backed by strong data. The initial phase focused on enabling infrastructure, such as transmission fee exemptions, which eventually evolved to more targeted initiatives supporting local electrolyser manufacturing, support for alternative production technologies (e.g., biomass gasification), R&D, and workforce development. A close temporal trend can be seen: stakeholder complaints frequently developed within a single year, and relevant policy actions were implemented either that year or the next year. However, policy acceptance still takes a long time from formulation to implementation, and there is little evidence to support a tight chronological order between concerns stated and policy adoption.

For example, stakeholders and industry experts noted that relying solely on solar-powered electrolysis would require extensive land and energy, making it challenging to meet India’s green hydrogen targets. The support for biomass-based hydrogen production through initiatives like the National Bio-Energy Programme and R&D under the National Green Hydrogen Mission would have been a response. This demonstrates a possibility of the existence of a feedback loop where technological and practical constraints would have prompted targeted policy measures, reflecting the adaptive, co-evolutionary relationship between technology and policy.

Stakeholder feedback:

Although this mechanism was not identified in the literature review (Section 2.2.1), the findings of this study reveal a clear pattern, which justifies its inclusion in the analysis. A clear pattern of stakeholder feedback evolving throughout the timeline is given below. For instance, in the early phase, concerns centered on the availability of renewable energy sources, a critical prerequisite for green hydrogen production. This later shifted towards the high CAPEX of electrolysers, with calls for promoting local manufacturing. By 2023, attention turned to the availability of critical materials needed for domestic electrolyser production, prompting interest in alternative pathways such as biomass gasification. Subsequently, environmental concerns gained prominence, particularly regarding freshwater availability, leading to suggestions for advancing research on seawater and wastewater electrolysis. Most recently, discussions have focused on the potential of digitalization and AI in green hydrogen production and the importance of incorporating these technologies. Taken together, this reflects a clear pattern of evolving stakeholder feedback that has guided the direction of policy considerations over time. It can also be observed that with each advancement in technology, stakeholders often revisit and question the suitability of the previously used technology, subsequently proposing policies to support the adoption of the newer one.

Although the mechanisms outlined in Section 2.2.1 of the literature review were observed, evidence for the presence of the Multiple Streams Framework remains absent.

6.5.4. Exploring the link between technology dynamics and policy adoption

This section provides a comparative analysis integrating all three parts of the research, aimed at examining the relationship between technology dynamics and policy adoption.

For instance, electrolysis specifically, the deployment of ALK and PEM electrolysers was the most popular technique for producing green hydrogen in the first few years, i.e., in 2020 and 2021. In the meantime, research and development was still ongoing for AEM and SOEC technologies. India had not yet formally started any green hydrogen-related policy initiatives in 2020. The availability of renewable energy needed for electrolysis, and the lack of infrastructure needed for G.H. production were the main topics of discussion. An important enabler was the interstate transmission fee waiver that India implemented as a first step in 2021, making it easier to obtain renewable energy for the production of green hydrogen.

By 2022, technology dynamics revealed that although biomass-based hydrogen production had advanced to pilot-scale projects, SOEC technologies had started to enter the commercialisation phase. Non-electrolysis techniques were still scarce. Research on AEM and SOEC technologies began to pick up steam. In the meantime, the CAPEX for ALK and PEM electrolysers increased little as a result of inflation. For ALK, PEM, and SOEC, the reported efficiencies were 64%, 83%, and 79%, respectively. The high CAPEX of electrolysers has been a growing source of concern. PEM was recognized as the most effective technology, which led to requests for more study and assistance for local production in order to reduce prices. On the policy side, the Green Open Access policy, the Hydrogen Valley project for infrastructural assistance were announced.

In 2023, SOEC and biomass gasification technologies entered the commercialization phase and AEM entered pilot project stage. Incremental innovations emerged, such as iridium-free PEM electrolysers, along with growing interest in seawater and wastewater electrolysis. R&D into AI and automation for green hydrogen production also gained momentum. Due to inflation, CAPEX rose significantly. ALK reached $2,000/kW, PEM reached $2,400/kW, and SOEC reached $2,800/kW. At the same time, discussions intensified around the need for domestic manufacturing of electrolysers, the high cost and limited availability of catalysts like iridium and platinum, and the land and solar power requirements for electrolysis. Concerns were also raised about the feasibility of meeting hydrogen targets using electrolysis alone, which pushed biomass gasification into the spotlight. On the policy side, initiatives like SIGHT Component I (Domestic manufacturing) , the India-Germany R&D call (For high temperature ALK, PEM, SOEC, and research for AEM electrolysers), and SIGHT Component II (For both electrolysis and biomass based production) were introduced.

In contrast, 2024 signaled a change away from the creation of completely new technology and toward the commercialisation of already-existing ones. Research on technologies like photocatalysis and biological hydrogen generation has progressed. Digitalization became increasingly important, and fully automated modular electrolyser units appeared. Commercial use of biomass-based production of hydrogen started to expand. At the same time, there was an increasing push for more robust cross-sector cooperation, public-private partnerships, and international collaborations in order to research on more innovations. Alternative manufacturing techniques, such as electrolysis of wastewater and seawater, continued to attract interest. Digital technologies for green hydrogen generation gained prominence as the year went on. Initiatives such as SIGHT Component II (Mode 2B), emphasizing electrolysis as well as technology agnostic G.H production and pilot projects centered on novel hydrogen generation routes focusing on innovative technologies like wastewater and sea water electrolysis, biomass, and photo catalytic water splitting and modular electrolyser, provided assistance for this phase from a policy standpoint. Coupled with the India-Denmark joint R&D call was announced in a way that enables international collaboration and research on digital technologies.

A recurring pattern emerges: whenever a policy is introduced, stakeholders frequently question its suitability for the Indian context or its cost implications. In response, they often encourage the government to promote alternative technologies through supportive measures. It is also possible to notice that stakeholder concerns frequently point toward researching or promoting emerging alternative technologies, as reflected in the results of the technology dynamics study. Notably, the policies proposed in the same year tend to align with these emerging technologies or cost trends highlighted in the concerns. While a chronological relationship can be suggested, there is insufficient evidence to definitively establish causality or make firm claims regarding this linkage.

6.6. Key Takeaways

The entire research makes it clear that there is a potential linkage between technology dynamics and policy adoption. Existing technologies are scrutinized when new alternatives hit the market and technology advances, frequently raising questions about their scalability in the context of India, cost trends, or regional applicability. Stakeholders are then prompted by these worries to suggest more recent technology developments. Furthermore, the evolution of policies can be noted in which the policy focus has changed from supporting electrolyser manufacturing to a more technology-agnostic support.

A tangible example may be used to demonstrate this pattern. India responded to the increase in electrolyser capital expenditure (CAPEX) by encouraging indigenous production. This, however, sparked additional worries about the availability of resources and the need for catalysts for large-scale manufacturing. Green hydrogen production using biomass gasification methods started to gain commercial momentum around this period. Although it is not explicitly evident, the SIGHT component-II might have been a response to this concern.

Hence, the observed pattern is as follows: a specific technology is initially supported through policy adoption; subsequently, a new technology enters the market or changes occur in the price of the existing technology. The stakeholders recommend government or policymakers to consider implementing measures for alternative, more recent technologies.

When comparing them with policy adoption, the technologies targeted in policies within a given year broadly align with technological dynamics and stakeholder concerns. However, the current evidence is insufficient to definitively establish a causal link between technology dynamics and policy adoption, which is the focus of the final study of this thesis. It is important to note that policy adoption involves a time lag from drafting to implementation. Nevertheless, the chronological alignment suggests a possible existence of such a link, even if it cannot be conclusively proven with the available data.

7

Discussion

The examination of green hydrogen technologies from 2020 to 2024 reveals a changing landscape of technological maturity, innovation, and market dynamics. Alkaline (ALK) electrolysers have maintained cost leadership due to their technological maturity, widespread commercial deployment, and established manufacturing infrastructure, particularly in China, whereas emerging technologies such as Anion Exchange Membrane (AEM) electrolysers are rapidly lowering their costs, with capital expenditures falling below USD 200/kW by 2024.This interplay between existing and developing technologies highlights that there might be possibilities of critical issues for future scaling, indicating that although ALK may maintain dominance due to infrastructure and operational familiarity, AEM may disrupt the industry if its technological preparedness continues to improve. Manufacturing remains heavily concentrated in China and Europe, accounting for more than 65% of global electrolyser production capacity by 2024, exposing possibilities for supply chain vulnerabilities for countries like as India and emphasizing the importance of indigenous manufacturing growth. Concurrently, research and innovation are expanding into new frontiers, such as seawater electrolysis, wastewater-based hydrogen, offshore generation, and biomass gasification, transitioning from laboratory research to pilot demonstrations and indicating the potential for localized adaptation in India's resource landscape. Automation and digitalization have also emerged as significant drivers. Overall, these technological trends lay the groundwork for understanding the relationship between technology dynamics and policy adoption, which will be explored further in this discussion.

The trajectory of policy adoption between 2020 and 2024 demonstrates a close alignment with the technological advances discussed earlier, particularly in the case of electrolyser development. Most of the major policy instruments, ranging from subsidies and grant-based schemes to pilot project funding, were designed to incentivize technologies that had already gained momentum in the innovation space, especially alkaline and PEM electrolysers, while also cautiously extending support to emerging concepts such as AEM and SOEC. This suggests that, rather than actively steering technological change, policymakers were responding to existing innovation dynamics and reinforcing directions already set by industry and research communities. At the same time, the analysis highlights the inherent time lag between technological breakthroughs and policy implementation. Policy adoption processes, which involve drafting, consultation, and coordination across multiple stakeholders, often mean that by the time supportive measures are announced, the underlying technologies are already several steps ahead in development or demonstration. Nevertheless, when viewed chronologically, India's hydrogen policy framework shows a striking degree of synchronization with technological trends: enabling policies in the early years coincided with the initial scaling of electrolysers, while more recent measures have converged with the commercialisation and diversification of advanced hydrogen production routes.

However, there required further elaboration to determine whether there are potential driving mechanisms that can describe the link between technology dynamics and policy adoption. Study 3 was driven by this justification. Study 3 revealed patterns of mechanisms as described in the literature, such as advocacy coalitions and compulsive policy-making, as well as a significant effect of feedback from stakeholders. The data suggest a repeated pattern: an initial policy promotes a certain technology; thereafter, either a new technology enters the market or the cost of the present technology changes. This transition encourages stakeholders to push for alternative, more modern technology, which might have lead to policy changes. The implementing body, in this case the Ministry of New and Renewable Energy (MNRE), often acknowledges such multi-layered concerns and suggestions. This observed pattern indicates a likely mechanism: to tackle the technical challenges and issues posed by the existing technology, policymakers implement new measures to facilitate its advancement or create policies for the latest technologies that may address the problems associated with the current technology. This process becomes cyclical, molded by the changing technology landscape. In this setting, achieving both cost-effectiveness and technological efficiency is vital. Furthermore, the results of this analysis show that numerous governmental measures were purposefully targeted at lowering manufacturing costs, decreasing the overall cost of green hydrogen. This establishes cost reduction as a key policy driver. Unlike previous studies, which frequently focused on technological maturity or alignment with global trends, this study emphasizes cost reduction as a deliberate and major goal in policy formation in an emerging market scenario. Additionally, developing international partnerships with top nations and being globally competitive are crucial in determining the direction of India's green hydrogen strategy. The results also revealed a number of significant disclosures. Notably, stakeholder participation increased dramatically in 2023 and 2024, which corresponded with times when green hydrogen technology was developing quickly. This pattern suggests that stakeholder involvement might serve as a stimulus for policy change as well as a reaction to new technical developments. Furthermore, persistent issues with high capital costs and limited resources continuously led to a reassessment of current technical options. These issues underscore the significance of social conditions and the economic viability of green hydrogen technologies, highlighting them as key factors in understanding the relationship between technology and policy. Additionally, a more flexible and forward-thinking strategy is reflected in the noted shift in policy objectives from core infrastructure to research, development, and support for specialist technologies. It implies that Indian officials are actively setting up the industry for long-term innovation and worldwide competitiveness in addition to addressing current issues.

The coding-based methodology in this thesis provided a structured and replicable way to analyze policy adoption alongside technological trends. While this approach highlighted clear patterns, it also carried limitations since the chosen codes and reliance on secondary sources may have left out nuances such as informal negotiations or industry-specific data. If the same codes were applied by another researcher, the results would likely be similar, but future work could strengthen the analysis by adding interviews or bibliometric studies. Such mixed methods would offer a more comprehensive view of how policy and technology co-evolve.

The coding-based method used in this thesis provided a systematic and transparent approach to linking policy adoption with technology dynamics, guaranteeing that the findings are repeatable and consistent. At the same time, the methodology leaves room for enriching the analysis in future work. Such additions would not replace but rather complement the current framework, making it even stronger in capturing the co-evolution of policy and technology.

While this study focuses on India, the alignment between policy adoption and technology dynamics for green hydrogen may look very different in more developed contexts such as the EU or the US. These regions already have relatively advanced hydrogen ecosystems, with mature R&D pipelines, stronger industrial capacity, and established policy frameworks, which means policies may be more proactive or better synchronized with technological advances.

7.0.1. Comparing with existing literature

Early phases and compulsive policy

Firstly, the early phases of India's green hydrogen strategy resembles compulsive policymaking [9]. In the findings of study 3, we noticed that India initially adopted a cautious "wait-and-watch" approach to green hydrogen, while other countries advanced more rapidly, raising concerns about falling behind in global energy and climate trends. In response, the government introduced the green hydrogen policy to create a supportive environment for renewable energy, a key input for green hydrogen production. Experts have called this a "quantum leap" toward India's energy and climate goals. Reports from TERI indicate that industry players and energy analysts repeatedly urged faster adoption, highlighting the need for a clear roadmap, which likely influenced the launch of the National Green Hydrogen Mission (NGHM) and a shift toward proactive policy action.

However, it is possible to observe patterns of compulsive policymaking only in this phase; as the evolution continued, policy responses became more dynamic and strategically planned.

We are unable to identify a clearer or consistently continuous pattern. Only subtle signs of patterns are observable. This difference may be due to the fact that the previous study considered a longer timeline of 12 years, whereas our research focuses on a four-year period. Additionally, the earlier study i.e. [9] analyzed a more developed country, Germany, while our research examines India, a developing country. Moreover, the previous study combined interviews with secondary document analysis, unlike our study which relied on secondary sources.

Transition to adaptive and co-evolutionary policy

Around 2023-2024, a shift can be noticed toward a more adaptive,co-evolutionary form of policymaking. During this period, priorities expanded from enabling infrastructure to domestic electrolyser manufacturing, incentives for GH production using alternative production routes such as biomass gasification, and R&D for niche technologies. On the other hand, a growth in stakeholder feedback can be noticed. This has a resemblance to the literature on policy co-evolution, particularly the idea that policy mixes evolve alongside socio-technical systems. We do have evidence from this study that shows feedback loops where technological challenges, such as high capital costs or environmental concerns, requesting consideration of policies. On the other hand, we can notice changes in the policy. However, a explicit link cannot be observed here as well.

[55] were able to find clear and ongoing co-evolutionary trends by analyzing numerous policy cycles and providing well-documented feedback. They used interviews and secondary document research to capture intricate processes and actor perspectives that demonstrated how policy mixtures interact

with socio-technical systems. In contrast, our investigation only found minor signs of interaction. The shorter time range, India's developing-country environment, and dependence on secondary sources made it more difficult to discern softer, actor-driven feedback processes, avoiding the establishment of unambiguous, repeating cycles.

Comparison with advocacy coalition framework

As discussed in the findings, six distinct patterns of advocacy coalitions can be found. However, these are merely activities advocating for the consideration of policy proposals; there is no concrete evidence that such advocacy directly caused the observed policy changes.

The ACF posits that policy change emerges from coordinated action by coalitions of actors who share core beliefs, engage in long-term policy-oriented learning, and respond collectively to external events [20]. In contrast, our study's restricted duration of 4 years focuses on early contacts and feedback, making it difficult to see fully evolved advocacy coalitions or long-term policy effects. Furthermore, the concentration on a specific sector and dependence on secondary sources hampered the identification of belief systems, resource exchanges, and coordinated activities, all of which are essential to the ACF. These distinctions show that, while early signals of coalition activity are present, the longer-term, organized effect of advocacy coalitions for policy change, as characterized by the ACF, is not yet visible within the current research time and setting.

The Multiple Streams Framework is not clearly observable in the findings because India's green hydrogen policy evolved gradually and cautiously. The analysis shows feedback-driven interactions between technology and policy rather than a sudden convergence of problem, policy, and political streams. In this emerging sector, policy changes have been iterative and technology-centered, making the typical MSF pattern less evident.

Although the findings are inconclusive, this study represents a fresh endeavor, particularly in the Indian environment. During the literature review, it became clear that research on green hydrogen in India is mostly focused on broad policy evaluations or suggestions. The dynamics of the technologies themselves were underexplored, with most available research focusing on lifecycle assessments or techno-economic evaluations of green hydrogen.

8 Conclusion

The research question and objectives stated in Chapter 1 are addressed in this section to ensure that the study's objectives are met.

This research aimed to examine the evolution of green hydrogen production technologies and analyze how these technological developments have influenced the development and transformation of relevant policy tools in India. This thesis also aimed to look at how different actors have shaped and modified these policy instruments.

For this, the research question developed was,

How did technology dynamics influence policy adoption of production technologies for green hydrogen in India from 2020 to 2024?
To address the main research question, it was further broken down into three guiding sub-questions:

1. What were the technology dynamics surrounding green hydrogen production technologies in this timeframe?
2. What were the various policy instruments that collectively shape the development of green hydrogen production technologies in India?
3. How could the link between technology dynamics and policy adoption be described?

To answer the study questions and subquestions, I used a qualitative data analysis approach. To gain a better understanding, the primary research was split into three sub-studies. The first focused on the technological dynamics of green hydrogen production technologies. The second created a list of important policy instruments enacted within the chosen time period, while the third looked into their descriptive linkages. The research focused on the timeframe 2020-2024.

According to the findings of Study 1, electrolysis technologies, notably alkaline (ALK) and proton exchange membrane (PEM) electrolyzers, were the primary drivers of green hydrogen generation between 2020 and 2024. While these technologies remained dominant, non-electrolyser methods such as biomass gasification and photocatalytic water splitting moved from laboratory-scale research to pilot-level demonstrations and early commercialization, indicating a diversification of viable production pathways.

Automation and digital control systems were increasingly at the center of innovation trends, which are being fueled by a constant growth in patent activity. New technical avenues, such as seawater electrolysis, wastewater-based hydrogen production, and offshore hydrogen generation, advanced from preliminary research in 2021 to full-scale projects by 2022, suggesting a broadening of technological opportunities.Alkaline electrolysers remained cost-competitive due to their technological maturity and affordable production costs, notably in China, where prices fell to roughly $750/kW. However, anion exchange membrane (AEM) electrolysers have quickly emerged as a viable low-cost alternative, with capital costs decreasing below $200/kW by 2024, making them a competitive choice in the growing green hydrogen environment.

On a global scale, the findings found that, while China and the European Union originally led the way, by 2023, Saudi Arabia, sections of Africa, and India had achieved significant breakthroughs in the green hydrogen industry.

Building on the key takeaways and findings from Study 1, Study 2 aimed to identify the policy instruments adopted during the same timeframe and to examine whether there are any similarities between the results of Study 1 and the set of policy measures identified in Study 2.

In order to answer subquestion 2, Data was collected from official government websites containing policy documents, and the analysis was conducted using the policy mix framework. The findings from Study 2 demonstrated how India's green hydrogen policies have evolved over time. Initially, policy focused primarily on electrolysis, promoting both local manufacture and research and development, indicating a desire to establish electrolysis as the principal technique for green hydrogen generation.

By 2023, policy language had become more focused on ”indigenous” skills, indicating a greater emphasis on promoting domestic industry. By 2024, there was a notable change, with government frameworks expanding their technological scope beyond electrolysis. This was mirrored in research funding, commercialization activities, and subsidies for manufacturing and end-use applications. The use of the word ”technology-agnostic” in policy papers after 2024 shows a conscious attempt to encourage a wide range of production techniques, including alternatives like biomass gasification.These findings highlighted the progression toward a more flexible and inclusive policy approach, encompassing both traditional electrolysis and emerging technologies.

While Study 1 gave insights into the technology dynamics of green hydrogen generation, and Study 2 highlighted changes in policy instruments over time, Study 3 investigated the relationship between the two. This study entailed gathering newspaper articles and analyzing them using predetermined codes. The study revealed tendencies that are consistent with the mechanisms mentioned in the literature review, including compulsive policymaking, advocacy coalitions, and stakeholder feedback.

Study 3 demonstrated a link between technology dynamics and policy adoption for green hydrogen production technologies. The findings indicated that when new technologies enter the market, stakeholders often assess their costs and suitability for the Indian context, leading them to recommend alternative options. While such patterns were evident in the literature, policy changes were not always clearly traceable in this study.

Previous research has mostly studied technology-policy interactions in developed economies, notably in Europe. Using India as a case study, this thesis fills a vacuum by investigating the way technological developments impact policy adoption in a developing country. The findings show a mixed pattern, with parts of early compulsive policymaking motivated by external demands and a progressive change toward a more organized, feedback-oriented approach.

This paper increases theoretical knowledge of technology-policy linkages in developing countries while also providing empirical evidence that India is transitioning to a more sustainable, innovation-driven environment.It further highlights the country's growing ability to balance domestic technological progress with global competitiveness, supported by strategic international collaborations, active stakeholder engagement, and targeted government interventions.

8.1. Implications

8.1.1. Theoretical Implications

This thesis contributes to the literature on sustainable transitions, particularly studies examining the influence of technology dynamics on policy adoption [9] [55] [23].While the findings did not yield extensive empirical evidence, the research demonstrates how mechanisms such as compulsive policymaking, policy co-evolution, and advocacy coalitions develop in the context of green hydrogen.This study revealed a previously unknown theoretical pattern about the role of stakeholder feedback in shaping policy. The findings indicates that such feedback exists between the processes of compulsive policymaking and policy co-evolution, constituting a separate interaction channel.

This research advances existing theory by examining the technology policy interplay for an emerging technology in a developing country, contrasting with prior studies focused on mature technologies in developed economies.

The findings reveal that policy dynamics, stakeholder influence, and adoption pathways differ significantly under resource and institutional constraints, indicating the need to adapt existing theoretical models to such contexts.This research demonstrates a combination of multiple mechanisms influencing policy, with a particularly strong emphasis on the role of advocacy coalitions. Within the Advocacy Coalition Framework (ACF), policy subsystems are composed of diverse stakeholders including government agencies, industry actors, researchers, and interest groups who coordinate around shared objectives to shape policy outcomes.The findings highlight a sequence of advocacy priorities: initially emphasizing renewable energy availability for hydrogen production, followed by efforts to reduce electrolyser CAPEX through domestic manufacturing, and later focusing on water resource limitations and the feasibility of achieving scale-up targets. These trends illustrate that advocacy coalitions adapt dynamically to technological, economic, and resource-related challenges rather than following fixed agendas.

8.1.2. Practical implications

The findings of this research have a few practical implications for India's G.H. sector. This thesis provides a detailed and organized account of how green hydrogen production technologies have evolved over the 2020–2024 timeline. At the start of this research, the technological dynamics were scattered across various sources and lacked a systematic analysis. As this research presents technology dynamics of green hydrogen production technologies in a more systematic and structured way policymakers can now gain a clearer understanding of technology trends and maturity, enabling them to propose policies that align with technological growth and development.

The report also provides practical insights for stakeholders, such as industrial groups and government bodies. Recognizing that stakeholder input is a critical driver of policy change, these actors can boost their involvement by offering more structured feedback or building collaborative forums for group participation. While forums like IH2A exist, the availability of resources and formal mechanisms for input remains restricted, indicating a potential opportunity to increase stakeholder engagement. Another practical implication is the need for more study in this fast expanding area. The study found that research into technology-policy linkages in the Indian green hydrogen industry is inadequate. Encouraging more research initiatives by students, academic institutions, and research organizations can help to improve policymaking and accelerate the sector's long-term growth.

8.2. Limitations and future research

This section outlines the limitations of the study, which in turn highlight opportunities for future research.

8.2.1. Limitations

There are a few limitations in this study. First, secondary data sources were used for analysis in this study. This method presented some difficulties for the third sub-question, even though it was suitable for answering the first two, when pertinent information was easily available. In this instance, interviewing a wide range of stakeholders may have yielded deeper, more complex insights, particularly by obtaining viewpoints not found in publicly available sources. Including primary data from stakeholder interviews could have improved the study's validity and provided a more thorough grasp of dynamics and new perspectives on the ground. Another problem is that the study does not give a clear evidence of how technological dynamics and associated concerns directly influence policy responses. Concrete evidence that particular concerns motivated policy action, such as written ministerial acknowledgment, is still absent. Instead, the study focuses on observable patterns rather than giving definite, direct proof of a link.The causal relationship could not be adequately investigated, due in part to the short time frame studied. Green hydrogen was not much of a priority in India prior to 2020, and obtaining reports published after 2024 was difficult, making it impossible to explore this link in depth or develop a clearer correlation.

8.2.2. Future research

I have some suggestions for someone who want to research more about this topic. First, as was already indicated, in order to obtain information for the third sub-question, researchers may think about conducting interviews, since this could yield more in-depth information. Second, future research may broaden its scope to cover additional facets of green hydrogen technology, such as end-use applications, storage, and transportation. Another aspect to consider is that if the same research were performed after 10-20 years, it might give more explicit data to better clarify causal linkages. A longer time frame would allow for a more in-depth examination of whether the cyclical patterns between technology and policy remain over time, offering more confidence in the mechanisms' consistency. The green hydrogen industry was still in its early stages in 2020 and 2021, hence the trends found are more for the period 2023-2024. Examining a decade-long chronology may provide more in-depth observations and stronger conclusions.

8.2.3. Reflection

When I think back on this master's thesis's scientific path, I realize that it required some time to properly understand the study issue and define the scope. For me, doing research was an entirely new experience, and although there were many difficulties along the way, I am very pleased with the results produced. There were times of advancement and clarity over the six-month study period, as well as times when the data were sparse or unclear. It was quite of a roller coaster ride. However, my supervisor's constant direction and assistance were crucial throughout the procedure. A solid basis that I could use in practice was also given by the Management of Technology program's courses, especially Research Methods and Emerging and Breakthrough Technologies. I never would have thought that the theoretical knowledge I learned in class would be so immediately applicable and helpful in forming my analytical and research strategy.

Upon reflection of the results, I am confident that India is making progress in embracing and advancing green hydrogen technology. Since this is still a potential subject for additional research, if I had more time, I would have travelLed to India to interview stakeholders, which could have provided more clearer evidence.

References

[1] G. C. Khilnani and P. Tiwari, "Air pollution in india and related adverse respiratory health effects: Past, present, and future directions," *Current Opinion in Pulmonary Medicine*, vol. 24, no. 2, pp. 108–116, 2018. DOI: 10.1097/MCP.0000000000000463. [Online]. Available: https://doi.org/10.1097/MCP.0000000000000463.

[2] Natural Resources Defense Council, *Paris climate agreement: Everything you need to know*, Accessed: 2025-04-23, 2023. [Online]. Available: https://www.nrdc.org/stories/paris-climate-agreement-everything-you-need-know.

[3] A. Piebalgs and Y. Popkostova. "The ukraine war and the energy transition." Accessed: 2025-04-23. (2022), [Online]. Available: https://geopolitique.eu/en/articles/the-ukraine-war-and-the-energy-transition/.

[4] Iberdrola. "What is green hydrogen and its importance." Accessed: 2025-04-23. (2025), [Online]. Available: https://www.iberdrola.com/sustainability/green-hydrogen.

[5] Vajiram & Ravi. "Green hydrogen, meaning, benefits, production, applications." Accessed: 2025-04-23. (2025), [Online]. Available: https://vajiramandravi.com/upsc-exam/green-hydrogen/.

[6] National Grid. "The hydrogen colour spectrum." Accessed: 2025-04-24. (2023), [Online]. Available: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum.

[7] R. V. Vardhan, R. Mahalakshmi, R. Anand, and A. Mohanty, "A review on green hydrogen: Future of green hydrogen in india," in *2022 6th International Conference on Devices, Circuits and Systems (ICDCS)*, IEEE, 2022, pp. 303–309. DOI: 10.1109/ICDCS54290.2022.9780805. [Online]. Available: https://doi.org/10.1109/ICDCS54290.2022.9780805.

[8] Financial Times, "Heat pump champions call for more support as sales stutter," 2024, Accessed: 2025-06-18. [Online]. Available: https://www.ft.com/content/0c054c45-a59a-4b98-ac7b-404046c7182d.

[9] J. Hoppmann, J. Huenteler, and B. Girod, "Compulsive policy-making—the evolution of the german feed-in tariff system for solar photovoltaic power," *Research Policy*, vol. 43, no. 8, pp. 1422–1441, 2014. DOI: 10.1016/j.respol.2014.01.014. [Online]. Available: https://doi.org/10.1016/j.respol.2014.01.014.

[10] M. P. Hekkert, R. A. Suurs, S. O. Negro, S. Kuhlmann, and R. E. Smits, "Functions of innovation systems: A new approach for analysing technological change," *Technological Forecasting and Social Change*, vol. 74, no. 4, pp. 413–432, 2007. DOI: 10.1016/j.techfore.2006.03.002.

[11] B. Turnheim, F. Berkhout, F. Geels, *et al.*, "Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges," *Global Environmental Change*, vol. 35, pp. 239–253, 2015. DOI: 10.1016/j.gloenvcha.2015.08.010.

[12] K. Reichardt and K. S. Rogge, "How the policy mix impacts innovation: Findings from company case studies on offshore wind in germany," *Environmental Innovation and Societal Transitions*, vol. 18, pp. 62–81, 2016. DOI: 10.1016/j.eist.2015.08.001.

[13] C. E. Lindblom, "The science of "muddling through"," *Public Administration Review*, vol. 19, no. 2, pp. 79–88, 1959.

[14] F. Kern and M. Howlett, "Implementing transition management as policy reforms: A case study of the dutch energy sector," *Policy Sciences*, vol. 42, no. 4, pp. 391–408, 2009. DOI: 10.1007/s11077-009-9099-x. [Online]. Available: https://link.springer.com/article/10.1007/s11077-009-9099-x.

[15] T. J. Foxon and P. J. Pearson, "Overcoming barriers to innovation and diffusion of cleaner technologies: Some features of a sustainable innovation policy regime," *Technological Forecasting and Social Change*, vol. 77, no. 6, pp. 882–895, 2009. DOI: 10.1016/j.techfore.2009.01.004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0040162509000195.

[16] F. W. Geels, "Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study," *Research Policy*, vol. 31, no. 8–9, pp. 1257–1274, 2002. DOI: 10.1016/S0048-7333(02)00062-8. [Online]. Available: https://doi.org/10.1016/S0048-7333(02)00062-8.

[17] V. Lauber and L. Mez, "Renewable energy policies in germany and the uk: A comparative analysis," *Energy Policy*, vol. 32, no. 7, pp. 843–851, 2004. DOI: 10.1016/S0301-4215(03)00173-7.

[18] [. N. Zhou *et al.*, "[full title of the article]," *[Journal Name]*, vol. [Volume Number], no. [Issue Number], [Page Range], 2019. DOI: [DOI]. [Online]. Available: %5BURL%5D.

[19] H. L. Breetz, M. Mildenberger, and L. C. Stokes, "The political logics of clean energy transitions," *Business and Politics*, vol. 20, no. 4, pp. 588–613, 2018. DOI: 10.1017/bap.2018.12. [Online]. Available: https://doi.org/10.1017/bap.2018.12.

[20] P. A. Sabatier, *Theories of the Policy Process*, 2nd, P. A. Sabatier and C. M. Weible, Eds. New York: Routledge, 2007, ISBN: 978-0-367-27468-9. DOI: 10.4324/9780367274689.

[21] D. L. Edmondson, F. Kern, and K. S. Rogge, "The co□evolution of policy mixes and socio□technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions," *Research Policy*, vol. 48, no. 10, pp. —, 2019. DOI: 10.1016/j.respol.2018.03.010.

[22] J. P. Wesche, E. Dütschke, S. O. Negro, and M. P. Hekkert, "Coalitions, coordination, and contestation: A systematic review of the advocacy coalition framework and its implications for sustainability transitions research," *Frontiers in Political Science*, vol. 6, p. 1 497 731, 2025. DOI: 10.3389/fpos.2024.1497731. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpos.2024.1497731/full.

[23] N. Goyal, M. Howlett, and A. Taeihagh, "Why and how does the regulation of emerging technologies occur? explaining the adoption of the eu general data protection regulation using the multiple streams framework," *Regulation & Governance*, vol. 15, no. 4, pp. 1020–1034, 2021. DOI: 10.1111/rego.12371. [Online]. Available: https://doi.org/10.1111/rego.12371.

[24] Á. M. Morán, "Diversifying clean hydrogen: Regulatory barriers for a circular hydrogen economy," *Journal for European Environmental & Planning Law*, vol. 21, no. 3-4, pp. 167–190, 2024. DOI: 10.1163/18760104-21030003. [Online]. Available: https://brill.com/view/journals/jeep/21/3-4/article-p167_003.xml.

[25] A. Desai, K. Joshi, and H. Shah, “Next generation energy green hydrogen: Critical review,” *Medicon Engineering Themes*, vol. 4, no. 6, p. 141, 2023. DOI: 10.55162/MCET.04.141. [Online]. Available: https://themedicon.com/journals/engineeringthemes/MCET-04-141.

[26] Y. Yuan and M. Tan-Mullins, “An innovative approach for energy transition in china? chinese national hydrogen policies from 2001 to 2020,” *Sustainability*, vol. 15, no. 2, p. 1265, 2023. DOI: 10.3390/su15021265. [Online]. Available: https://www.mdpi.com/2071-1050/15/2/1265.

[27] B. Zhu and C. Wei, “A green hydrogen era: Hope or hype?” *Environmental Science & Technology*, vol. 56, no. 16, pp. 11 107–11 110, 2022. DOI: 10.1021/acs.est.2c04149. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.est.2c04149.

[28] T. Daniel, L. Xing, Q. Cai, and L. Liu, “Potential of progressive and disruptive innovation-driven cost reductions of green hydrogen production,” *Energy & Fuels*, vol. 38, no. 11, pp. 10 370–10 380, 2024. DOI: 10.1021/acs.energyfuels.4c01247. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.energyfuels.4c01247.

[29] A. Acharya, “Scaling-up green hydrogen development with effective policy interventions,” *Journal of Sustainable Development*, vol. 15, no. 5, pp. 135–135, 2022. DOI: 10.5539/jsd.v15n5p135. [Online]. Available: https://doi.org/10.5539/jsd.v15n5p135.

[30] P. Cunningham, “Demand-side innovation policies, policy brief no. 1,” Pro Inno Europe, Inno Policy Trendchart, Tech. Rep., 2009. [Online]. Available: https://wbc-inco.net/object/document/7210/attach/TrendChart_demandside_policies_innovation_needs.pdf.

[31] International Energy Agency, “Global hydrogen review 2021,” International Energy Agency, 2021, Accessed: 2025-05-23. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2021.

[32] International Renewable Energy Agency, “Green hydrogen: A guide to policy making,” IRENA, Tech. Rep., 2020. [Online]. Available: https://www.irena.org/publications/2020/Nov/Green-hydrogen-A-guide-to-policy-making.

[33] S. Bhide and P. K. Mohanty, “Policy roadmap for green hydrogen in india,” The Energy and Resources Institute (TERI), Tech. Rep., 2022.

[34] A. Sharma, R. Agarwal, and V. Jain, “India’s green hydrogen strategy: Opportunities and challenges,” *Journal of Energy Policy Studies*, vol. 42, no. 1, pp. 55–72, 2023.

[35] N. Farrell, “Policy design for green hydrogen,” *Renewable and Sustainable Energy Reviews*, vol. 178, p. 113 216, 2023, ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2023.113216. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032123000722.

[36] M. Jaradat, S. Almashaileh, C. Bendea, A. Juaidi, G. Bendea, and T. Bungau, “Green hydrogen in focus: A review of production technologies, policy impact, and market developments,” *Energies*, vol. 17, no. 16, 2024. DOI: 10.3390/en17163992. [Online]. Available: https://www.mdpi.com/1996-1073/17/16/3992.

[37] N. Athia, M. Pandey, M. Sen, and S. Saxena, “Techno-economic potential assessment of green hydrogen production system,” in *Advances in Clean Energy Technologies. ICET 2023*, ser. Springer Proceedings in Energy, G. Dwivedi, P. Verma, and V. Shende, Eds., Springer, Singapore, 2025, pp. 45–60. DOI: 10.1007/978-981-97-6548-5_4. [Online]. Available: https://doi.org/10.1007/978-981-97-6548-5_4.

[38] A. Singh, "Assessment of india's green hydrogen mission and environmental impact," *Renewable and Sustainable Energy Reviews*, vol. 203, p. 114 758, 2024. DOI: 10.1016/j.rser.2024.114758. [Online]. Available: https://doi.org/10.1016/j.rser.2024.114758.

[39] P. Nikolaidis and A. Poullikkas, "A comparative overview of hydrogen production processes," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 597–611, 2017. DOI: 10.1016/j.rser.2016.09.044. [Online]. Available: https://doi.org/10.1016/j.rser.2016.09.044.

[40] S. Mukherjee, A. Ghosh, D. Khastgir, and S. Sarkar, "An overview of the green hydrogen value chain technologies and their challenges for a net-zero future," *Hydrogen*, vol. 6, no. 2, p. 26, 2024. DOI: 10.3390/hydrogen6020026. [Online]. Available: https://www.mdpi.com/2673-4141/6/2/26.

[41] S. A. Sherif *et al.*, "Hydrogen storage technologies: A review," *International Journal of Hydrogen Energy*, 2021. DOI: 10.1016/j.ijhydene.2021.06.132. [Online]. Available: https://doi.org/10.1016/j.ijhydene.2021.06.132.

[42] International Energy Agency, "Global hydrogen review 2021," International Energy Agency, Tech. Rep., 2021. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2021.

[43] L. Rosén, M. de Heer, E. Özdemir, H. Hellsmark, and B. A. Sandén, "Modeling of a "hydrogen valley" to investigate the impact of a regional pipeline for hydrogen supply," *Frontiers in Energy Research*, vol. 12, p. 1 420 224, 2024. DOI: 10.3389/fenrg.2024.1420224. [Online]. Available: https://doi.org/10.3389/fenrg.2024.1420224.

[44] M. Tomai, G. Papachristos, and S. V. Ramani, "The dynamics of change towards sustainability in developing countries: Evidence from ghana's waste-to-energy transition," *Environmental Innovation and Societal Transitions*, vol. 53, p. 100 928, 2024, Open access under CC BY license. DOI: 10.1016/j.eist.2024.100928. [Online]. Available: https://doi.org/10.1016/j.eist.2024.100928.

[45] Y. Pleshivtseva, M. Derevyanov, A. Pimenov, and A. Rapoport, "Comparative analysis of global trends in low carbon hydrogen production towards the decarbonization pathway," *International Journal of Hydrogen Energy*, vol. 48, no. 83, pp. 32 191–32 240, 2023. DOI: 10.1016/j.ijhydene.2023.04.264. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0360319923020943.

[46] A. Tuluhong, Q. Chang, L. Xie, Z. Xu, and T. Song, "Current status of green hydrogen production technology: A review," *Sustainability*, vol. 16, no. 20, p. 9070, 2024. DOI: 10.3390/su16209070. [Online]. Available: https://www.mdpi.com/2071-1050/16/20/9070.

[47] E. M. Rogers, *Diffusion of Innovations*, 5th. New York: Free Press, 2003, ISBN: 978-0743222099.

[48] M. P. Hekkert and S. O. Negro, "Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims," *Technological Forecasting and Social Change*, vol. 76, no. 4, pp. 584–594, 2009. DOI: 10.1016/j.techfore.2009.07.001.

[49] M. A. Nemitallah, A. A. Alnazha, U. Ahmed, M. El-Adawy, and M. A. Habib, "Review on techno-economics of hydrogen production using current technologies: Recent advancements and future directions," *Current Opinion in Green and Sustainable Chemistry*, vol. 42, p. 100 889, 2024. DOI: 10.1016/j.cogsc.2024.100889. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2590123024001439.

[50] Y. Wang and J. J. Wu, “Thermochemical conversion of biomass: Potential future prospects,” *Renewable and Sustainable Energy Reviews*, vol. 187, p. 113 754, 2023. DOI: 10.1016/j.rser.2023.113754. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032123006111.

[51] Unknown, “Incremental innovation: Long-term impetus for design business creativity,” *Sustainability*, vol. 14, no. 22, p. 14 697, 2022. DOI: 10.3390/su142214697. [Online]. Available: https://www.mdpi.com/2071-1050/14/22/14697.

[52] M. Naeem, W. Ozuem, K. Howell, and S. Ranfagni, “A step-by-step process of thematic analysis to develop a conceptual model in qualitative research,” *International Journal of Qualitative Methods*, vol. 22, pp. 1–18, 2023, ISSN: 1609-4069. DOI: 10.1177/16094069231205789. [Online]. Available: https://journals.sagepub.com/doi/10.1177/16094069231205789.

[53] S. Boora and M. T. Karakunnel, “Media framing of indian green fiscal policy: A survey of environmental policies across online news portals,” *Environment and Ecology Research*, vol. 11, no. 5, pp. 712–726, 2023. DOI: 10.13189/eer.2023.110502. [Online]. Available: https://www.hrpub.org/journals/article_info.php?aid=13590.

[54] R. Streefkerk. “Inductive vs. deductive research approach | steps & examples.” Accessed: 2025-06-19. (2023), [Online]. Available: https://www.scribbr.com/methodology/inductive-deductive-reasoning/.

[55] K. S. Rogge and K. Reichardt, “Policy mixes for sustainability transitions: An extended concept and framework for analysis,” *Research Policy*, vol. 45, no. 8, pp. 1620–1635, 2016. DOI: 10.1016/j.respol.2016.04.004.