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Hydrogen in the Urban Setting

Understanding the role of hydrogen in the energy transition of Berlin through the lens of the Multi-Level-Perspective

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Abstract

Climate action can be seen in economic, political, cultural and social processes around the globe. Rarely are these processes more visible than in the context of sustainable urban transition. With a growing population, especially in urban areas, the question of how to sustain this growth in terms of energy production and resource use is becoming more apparent. It is clear that a sustainable transition is becoming a task for multiple actors involved in urban development. The Multi-Level Perspective (MLP) provides a transition-theoretical framework in which socio-technical processes are explored at three levels - the landscape, the regime, and the niche. The dynamics within and across these levels are described with drivers and barriers to understand a transition over time. In the context of a city-state like Berlin, the MLP faces limitations that are addressed through a multi-actor approach while also acknowledging the involvement of a multi-level governance structure through local and national policy-making processes. This thesis unpacks the role of hydrogen in Berlin's energy transition by operationalizing the MLP framework and analyzing the key conditions under which hydrogen has evolved in the past. Through expert interviews complemented by document analysis I describe the conditions necessary for its diffusion into a broader implementation of the energy system. Finally, the feasibility of the theoretical framework used, to understand past and future transition processes, is discussed. My empirical analysis shows that a successful hydrogen breakthrough in Berlin requires political legislation (landscape changes) to drive additional technical advances in production, storage, and infrastructure (regime adjustments). These findings confirm the dynamic nature of the MLP framework and demonstrate its practicality when applied in an urban context, allowing exploration of future opportunities for niche technologies.

Foreword

First and foremost, I would especially like to thank Per Ove Eikeland for his continuous support throughout the entire process of writing this thesis. Your counsel and supervision has kept up my spirits and motivated me to keep pushing and explore new ways of conducting a research project such as this. Your regular calls and checkups on my progress has profoundly impacted the way I approached this thesis and I cannot thank you enough for the time and contiuous effort you've invested in me personally. Thank you!

Furthermore, I'd like to thankt the Fridtjof Nansens Institut for inviting me to Oslo and giving me a scholarship for working on my thesis amongst other scholars. I have wonderful memories from my time there, especially from the Nansens Expedition and spending the night outside in the mountains at minus 10 degrees Celsius. I enjoyed every conversation with all the collegues, and reading out loud the lunch questions in Norwegian. Thank you for providing me with my own office and that cool table that goes up and down. I had a wonderful time playing with it. I'll definitely get one myself, if I ever work from home.

Also, special thanks to Christian von Hammerstein for providing essential resource access through avoiding paywalls and Andrea Edland for sticking around throughout this entire process. You've had some epiphanies for me which carried me through the downs of this thesis. Thank you!

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List of Abbreviations

MLP	Multi-Level-Perspective
MLGP	Multi-Level-Governance-Perspective
TIS	Technological Innovation System
SNM	Strategic Niche Management
TM	Transition Management
UN	United Nations
EU	European Union
ST	Sustainable Transition(s)
SUT	Sustainable Urban Transition
BEK	Berlin Energy and Climate Protection Program
R&D	Research & Development
GDP	Gross Domestic Product
CHP	Combines Heat and Power
GDR	German Democratic Republic
EKB	VEB Energiekombinat Berlin
EBAG	Energieversorgung Berlin Aktiengesellschaft
UNFCCC	United Nations Framework Convention on Climate Change
ETS	Emission Trading System
KSG	Federal Climate Protection Act
EEG	Renewable Energy Act
PV	Solar Photovolatic
EWGBln	Berlin Climate Protection and Energy Transition Act
GHG	Greenhouse Gas
SDG	Sustainable Development Goals
CEP	Clean Energy Partnership
NIP	National Hydrogen and Fuel Cell Technology Innovation Programme
VES	Transport Energy Strategy
MoU	Memorandum of Understanding
SME	Small and Medium Enterprises
AKA	Also Known As
SESTA	Fuel Emissions Trading Act
NHS	National Hydrogen Strategy
EHB	European Hydrogen Backbone
BAU	Business as usual
H_2	Hydrogen
BEnSpG	Berlin Energy Savings Act

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I. Introduction

One of the most pressing challenges facing our society today is climate change. It can easily be placed in the context of any major political, economic, social, or technological decision-making process. Individuals and consumers are beginning to become more aware of their choices, and technology is constantly advancing and striving for greater efficiency. Governments are considering the climate more than ever when implementing new policies. Economies are transitioning towards sustainability and looking for ways to decouple their growth from their impact on the climate. A recent example is the EU's Green New Deal, which aims to reduce the EU's carbon footprint through complex systemic changes. At the same time, population growth threatens to offset some of these gains, as more people benefit from resource access. This development towards sustainability and population growth can be seen in political, economic, social, and technological processes coming together in the environment of a city.

For the first time, the world is home to more than 8 billion people. Nowhere is this population growth more evident than in urban areas. The UN predicts that by 2050, more than 68% of the world's population will live in cities (UN News, 2018). In Germany, this phenomenon is known as "*Landflucht*", which literally means fleeing the countryside. The fact that so many people want to live in cities is an ode to urban life, but it also means that urbanization must become sustainable in the face of growing concerns about climate change. *Landflucht* thus brings along opportunities for a sustainable urban transition but also new challenges.

One challenge on the road to sustainable urbanization is energy consumption and its consequences. Cities consume enormous amounts of energy producing millions of tonnes of CO_2 worldwide each year. The 2014 IPCC report calculated that about 67-76% of global energy is consumed by cities and that this consumption accounts for about 75% of greenhouse gas emissions (IPCC, 2014). Major contributors include the energy sector, industry, agriculture, transportation, and heating and cooling of residential and commercial buildings. Sustainable urbanization must therefore be supported by a transition of the urban energy system towards the use of clean technologies and renewable energy resources.

The electrification of cities is an important step towards reducing carbon emissions. The rise of electric mobility in private and commercial transportation methods is just one example. Electrification the transport sector, and even the heating and cooling sectors is a hot topic in many cities. However, renewable electricity alone cannot meet the challenge of sustainable urban transformation. It must be combined with non-intermittent, storable and flexible energy sources. In addition, there are economic sectors where the direct use of renewable electricity is not sufficient to decarbonize - e.g., the metal smelting industry, which uses carbon (coke) as a medium to purify iron ore through the smelting process, with CO_2 as an output. For such hard-to-abate sectors and as a medium for energy storage, there is a new focus on developing clean hydrogen (H_2) as part of the energy system.

This thesis analyzes the ongoing urban energy transition in the city of Berlin, and the role of hydrogen in this transition. With the Paris Agreement in place, Berlin has set the goal to become climate neutral by including hydrogen in its roadmap. The city has been working for decades to transition from coal and lignite to natural gas and renewable energy production, with a more recent goal of achieving climate neutrality by 2040. As the capital of Europe's strongest economy, Germany, it has now set out to prove that sustainable urban living is not just a concept but can be achieved with the help of hydrogen. Together with the surrounding state of Brandenburg, Berlin has developed a hydrogen strategy with 63 measures, including research and development, production, industrial use, mobility applications, heat and power generation, storage and international cooperation, inter alia (MWAE & SenWEB, 2021). This roadmap is based on the results of feasibility studies such as 'Hydrogen Potential in Berlin 2025' and regulatory frameworks such as 'Berlin Energy and Climate Protection Program" (H2Berlin, 2020; BEK2030, 2023). Several hydrogen start-ups are being funded in the city, while incumbent actors in the energy system are committing to reduce their emissions with the help of clean hydrogen. Hydrogen is thus experiencing high and growing political momentum.

But transitioning an energy system with the aid of hydrogen is not an easy task. Although hydrogen is already an integral part of industrial and chemical processes, its current production comes from the reforming of natural gas, generating significant emissions. To support a clean and sustainable urban energy transition, hydrogen production must therefore be decarbonized, i.e., based on electrolysis of water using renewable electricity (green hydrogen) or by combining continued reformation of natural gas with carbon capture and storage (blue hydrogen)[1]. The commercial breakthrough of such clean hydrogen production technologies,

[1] There are other ways to produce hydrogen as well, such as using nuclear power as an energy source (pink hydrogen), lignite or coal (black hydrogen) or methane through the pyrolysis process (turquoise hydrogen).

not only in the city of Berlin but in general, will require regulations, rules and standards on how hydrogen can be produced sustainably. Next, demand for hydrogen must be secured through the development and deployment of hydrogen-ready consumer technologies. Such demand can be accelerated not only by a bottom-up approach, but also by a top-down approach, where government policies and regulations provide a framework for cost-reducing technological development and innovation to make hydrogen technologies competitive. Finally, to match the supply of clean hydrogen with demand, it will be necessary to develop a hydrogen transport infrastructure, including safe distribution and storage, will be needed.
In summary, solving these interrelated challenges will require a systemic transformation process of the energy system of Berlin that precedes any breakthrough for a wide deployment of hydrogen.

To understand the evolving role of hydrogen in the sustainability transition of Berlin’s energy system, I will apply a transition theory framework, specifically the Multi-Level-Perspective (MLP). This framework provides a template for descriptively exploring how the transition of an energy system follows from various reconfiguration processes that take place over time at different levels: the niche level (where new transition ideas and technologies emerge), the regime level (representing the existing incumbent energy system), and the landscape level (external factors impacting regime and niche levels). In this thesis, hydrogen is considered as a niche trying to diffuse into the Berlin energy system (regime) under the influence of various factors that constitute the landscape of Berlin's energy transition. Empirically, I will take a long-term approach to describe and explain regime change (transition of Berlin’s energy system) through niche developments (hydrogen emerging in the niche and regime) and landscape pressures.

A first purpose of the thesis is to understand the current role of hydrogen in the urban transition of Berlin. Here I will apply the MLP’s conceptualization of transition stages and typology of transition processes to characterize and explain the current status of hydrogen in Berlin’s energy system. This typology includes processual conditions for progressing a niche technology, such as hydrogen, through various stages of a transition. My second purpose is to apply the MLP framework to analyze some key conditions for hydrogen to enter new, more developed stages with wider deployment into Berlin’s energy system. The research questions that I have tried to answer are:

Q1: **Under what conditions did Berlin's energy sector change in the past?**

Q2: **Under what conditions could a successful breakthrough for hydrogen take place in Berlin?**

A 'successful breakthrough' means the integration of hydrogen as an irreplaceable technology deployed widely in Berlin's energy system. I will rely on the MLP framework for my analysis, and thus an additional purpose of the thesis is to discuss the feasibility of this framework for understanding the ongoing urban energy system transition in Berlin. Here I ask the question:

Q3: **To what extent can the MLP framework be used to understand past and future transition processes?**

The theoretical framework will be developed and presented in detail in Chapter II. An overview of the methodology of my research in which I outline how the data were collected and processed, follows in Chapter III. In Chapter IV, I provide a brief historical overview of the evolution of Berlin's energy system and how hydrogen evolved into and as a niche option for transitioning this system. In Chapter V, I discuss and answer the research questions of the thesis. Finally, I conclude my research in Chapter VI by summarizing the discussion and findings. Also, further research is being suggested from which this thesis would have benefited without the given limitations.

II. Theoretical Basis and Analytical Framework

Having established the purpose of this thesis, in this section I will elaborate on the theoretical framework of my research. To analyse the current role of hydrogen and the conditions for its further deployment in the city of Berlin, I will build on the Multi-Level Perspective (MLP) framework developed from the works of *inter alia* Frank W. Geels (Geels, 2002, 2006, 2011; Geels & Kemp, 2007). As a branch of transition theory, the MLP explores the main questions of how system change and transition occur.

The MLP developed in the context of a variety of co-evolving innovation-theoretical approaches that branched off into subfields of sustainability transition research: the Technological Innovation System (TIS), Strategic Niche Management (SNM), and Transition Management (TM) approaches (Köhler et al. 2019). Section 2.1 briefly introduces these approaches in order to contextualize the MLP within the transition theory literature and to show why this framework is specifically suitable for my thesis.

Section 2.2 elaborates on the theoretical framework of the MLP. As a sustainability transition framework, the three levels of the MLP are used as a tool to identify incumbent actors in the Berlin energy system, to pinpoint niche developments in hydrogen technology as well as to outline the socio-technical landscape in which a transition of this system takes place. The transition process will be studied by looking at the dynamics *between* and *within* the macro (landscape), meso (regime) and micro (niche) levels of Berlin's socio-technical energy system. A transition of such a system involves "major changes in technological, organizational and institutional terms for both production and consumption" (Farla et al., 2012, p. 991). The MLP is further applied to discuss how hydrogen technologies could achvieve a breakthrough for wider future deployment in the urban environment of Berlin. In describing the socio-technical landscape of Berlin's energy system transition, I will draw on the Multi-Level-Governance-Perspective (MLGP), developed in political science, to outline how this transition is embedded in the broader German and European contexts (section 2.3.). As a city-state, this excursion is necessary as Berlin's political and technological infrastructures are deeply intertwined with national and supranational structures - understanding the transformation of Berlin's energy system presupposes that levers for change at the national or supranational level are taken into account.

The MLP is designed to analyze the transition of entire national systems. (Geels, 2018). Using the MLP to understand meso or even micro transitions in subsystems (like Berlin) is nothing new, but requires case-specific adaptions which will be elaborated in section 2.4. Finally, some limitations of the MLP as tool for my analysis are briefly discussed (section 2.5).

2.1. The MLP in the context of transition theories

2.1.1. What theories exist to study transitions in general?

The literature review shows that the field of innovation studies has received increasing attention in the last ten years. It encompasses the analysis of a number of societal domains where innovation is crucial and an ongoing process, including medical, economic, political and cultural innovation, as well as innovation in development or sustainability. The field of research has expanded in response to the many challenges of today's world. Studies on innovation in sustainability deserve special attention in this thesis, as they relate to and guide the field of sustainability transition research.

Since the signing of the Paris Agreement in 2015, sustainability transition (ST) has been placed on the political agenda. Under this agreement, more than 196 countries have pledged to "pursuing efforts to limit the temperature to 1.5°C above pre-industrial levels" (United Nations, 2015, p. 3).This requires an effective and progressive response to climate change which can be seen as acting towards a new trajectory of sustainability through transformation[2]. In this context, transformation can and should involve all parts of society that are in need of sustainable transitions. There are many transition theories that try to encompass and explain the process of change of socio-technical systems, the most prevalent, besides the MLP, being the Technological Innovation System (TIS), the Strategic Niche Management (SNM), and the Transition Management (TM) frameworks.

[2] Transformation research tends to be applied when looking at large-scale changes on a local, national or global level and is often used for addressing the topic of climate change through questions of resilience and planetary boundaries (Hölscher et al., 2018). Transition on the other hand focuses on 'complex adaptive systems' and their "social, institutional or technological change in societal sub-systems" such as energy, mobility, or entire cities (ibid. p.2). Both terms, according to Hölscher et al. (2018), achieve duality with each other by addressing the same fundamental change of a system.

The TIS investigates the novelty of innovations by incorporating institutions, actors, and technology (Köhler et al., 2019). It combines the theory of innovation systems and industrial economics, with a focus on how to promote technological progress. This approach may be relevant for studying the technical aspects of hydrogen deployment within Berlin, though leaving out some important aspects of why a transition ocurrs, which is necessasry to answer the research questions of this thesis. This includes the role of the interplay between actors at different levels in initiating and guiding a transition in an urban context, which is considered in the MLP.

The SNM is a framework built around the idea that radical innovations appear in 'protected spaces' where they can be developed through the "interactions between learning processes (…), social networks, and visions and expectations" (Köhler et al., 2019, p. 4). Like the MLP, it incorporates the importance of niche technology development within sustainability transitions, but focuses only on the micro perspective of transition processes. Through these interactions developments are fostered that thrive on e.g., subsidized demonstration projects, experiments, or specialized niche actors such as the army (ibid.), from which they are diffused more broadly through 'innovation trajectories'. The trajectories will then depend e.g., on the quality of innovation or the extent of the social network. Although this framework includes niche technology development, it does not account for external forces and the influence of governing actors. Berlin as a city-state finds itself in a unique position as its transition is not only influenced by regional and local forces, but is also affected by wider national trajectories.

The TM framework picks up on the deficit of SNM by linking governance studies with complexity science (ibid.). TM investigates a transition by looking at the influence of policy and its ability to guide and shape a transition through strategic, tactical, operational, and reflexive activities (ibid.) to govern and structure a transition process. From identifying a trajectory, an idea, or a vision, to more concrete implementation and supervision or evaluative activities, policy can thus steer a transition process by instrumentalizing policy tools to support incremental developments. This meso- or even macro approach recognizes the role of policy in transitions, though expecting a more cooperative rather than competitive relationship between actors. This leaves room for criticism, as new technologies in later stages of development tend to thrive on competition, improving their cost-efficiency, which is ultimately needed to support a transition. A good example is the development of solar photovoltaic (PV) systems in Germany, where later competition from China led to global competition, ultimately driving down the price of solar PV (Quitzow, 2015).

These different transition frameworks offer various theoretical bases for understanding transitions through a technology lens and the niche and governing perspective, respectively. Each one focuses on individual and important, yet specific, aspects of system transitions. A combination of the frameworks would provide for a wide understanding of transition processes, including how various actors engage in promoting transition at multiple levels, relevant to answering the questions of this thesis. The MLP can be characterized as providing a combination of these frameworks, combining certain strengths of the TIS, SNM, and TM with a focus on both technical and social aspects of a transition. Essentially, the MLP offers insight into development of a niche technology (micro-level) (Schot & Geels, 2008), its diffusion into an incumbent regime (meso-level) through influence by co-evolving socio-technical landscape factors (macro-level) (Geels, 2002), also incorporating a multi-actor perspective (Avelino & Wittmayer, 2016).

2.1.2. The Multi-Level-Perspective

Köhler et al. (2019) show that sustainability transitions are a complex field of study, encompassing transition processes in multiple political, social, technological, or economic areas. Various transition study frameworks are based on different ontologies, impacting their structure and reasoning. Geels (2010) identifies a total of seven ontologies in different sustainability transition studies, and how they relate to the MLP. Coming from an evolutionary theoretical background, the MLP makes use of evolutionary logic by examining 'long-term patterns' (such as trajectories) and their evolution *across* three levels. Here, heterogeneous niche innovations interact with a broader environment, the socio-technical regime and landscape (Geels, 2010, p. 505), revealing an evolutionary relationship between the micro, meso and macro levels of a system.

Looking *within* each level, the MLP incorporates interpretivism into its logic by defining these long-term patterns as the "result from social (inter) actions within semi-coherent rule structures that are recursively reproduced and incrementally adjusted by interpretive actors" (ibid., p. 505). Actors are 'knowledgeable agents' capable of actively interpreting these semi-coherent rules and shaping transitions at the micro level. Ultimately, the MLP presents itself at the intersection of evolutionary theory and interpretivism/constructivism. Geels goes on to further explain the similarities of each ontological assumption in greater depth, which will not be further outlined here due to space limitations. This brief understanding of the ontological background of the MLP should give sufficient insight into the reasoning process of this thesis.

2.1.3. Why is the MLP an appropriate approach?

To capture the complexity of system innovation and transition, Geels & Kemp (2007) use the MLP to understand that "system innovations come about through the interplay between processes at different levels in different phases" (p.443). These levels and phases are presented below, along with the typology of processes through which innovation, and ultimately a transition, occurs. The MLP, a middle-range theory[3], emphasizes the interactions between the theoretical study of a system and empirical research (Merton, 1968). The exploration of these interactions will be essential in ultimately arriving at the central research questions that guide this thesis. In the following, I present the MLP in greater detail and elaborate on its application within the urban setting.

2.2. The theoretical framework of the Multi-Level-Perspective

The MLP is based on the understanding that a transition emerges from the interrelationships of multiple actors within and across multiple levels of a system. System developments are usually analyzed on a broad scale and over a long period of time. Besides specific technological innovations that are part of the transition, social aspects are given due attention, such as "policy, user practices, infrastructure, industry structures, and symbolic meaning" (Geels, 2006, p. 164). Acknowledging this, with a focus on both social and technical aspects of a system transition, Frank W. Geels, who has profoundly shaped the MLP, proposes to thus speak of broader "changes from one socio-technical system to another" (Geels, 2006, p. 164). These socio-technical changes involve dynamic processes at the niche level, within the socio-technical regime and the socio-technical landscape.

Niches are protected spaces or 'incubation rooms' in which radical innovations are developed (Geels, 2011; Geels & Kemp, 2007). They offer areas for co-evolving experimentation with

[3] Middle range theory, developed by Robert K. Merton aims at combining theory and empirical research, ultimately investigating their interactions (Merton, 1968). By addressing distinct topics and applying empirical data, middle range theory helps to understand specific interactions on different levels by multiple actors.

technology, user practices, and regulatory norms. (Schot & Geels, 2008). This co-evolutionary process allows the niche technology to change and adapt. Niche actors interact with regime-level actors and adapt to changes in the landscape, spreading acceptance of expectations and visions. When niche technologies have gained widespread acceptance, social networks have grown up around them, and when learning processes are stable enough to overtake other technology designs, this creates momentum, that is crucial to gaining legitimacy and attracting resources for further development, as well as putting pressure on the socio-technical regime and its incumbent actors (Geels, 2011,p. 28). Incumbent actors may typically provide incubation hubs themselves, since they are financially able to experiment and to provide the sufficient resources to align their innovation strategies to new niche trajectories and visions. Once a niche technology has gained momentum, incumbent actors are threatened to be replaced, thus encouraging their early-stage participation in niche technology development. Their participation is strongly dependent on regime and landscape responses, providing the seeds for major sociotechnical change (Geels, 2002, p. 1261; Smith et al., 2010).

The socio-technical landscape can be seen as the broader context in which the niche and the regime are embedded in. It typically comprises political ideologies, societal values, demographic trends, macro-economic patterns (economic growth), military conflicts, environmental problems, or resource scarcity, directly or indirectly influencing the regime and niche development levels (Geels, 2002, 2011; Geels & Kemp, 2007; Smith et al., 2010). Landscape factors tend to change slowly. Changes at the landscape level may cause pressure on the regime level, forcing it to realign its trajectories, adapt and respond to it, which gives niche technologies a ‘window of opportunity’ to spread within the regime (Smith et al., 2010). In this regard, landscape changes are an overarching force, which lays the course for sustainability transitions, especially at a time when climate change is prevalent in global policy-making processes.

The socio-technical regime is responsible for stabilizing the socio-technical system, where the system and its embedded actors ultimately shape interrelated and semi-coherent rules (Geels, 2011; Geels & Kemp, 2007, p. 442). Rules, in this context, can be cognitive, normative, and regulative, shared by social networks of regime actors such as politicians, engineers, scientists, banks, and users (ibid.). Even consumer behavior patterns and routines can be viewed as rules, as can governmental regulations, guiding principles, norms, and problem agendas (ibid.). Socio-technical change would presuppose the diffusion of new rules within the regime.

However limited and tied up to sunk investments, infrastructure, and other material aspects, actors within the socio-technical regimes can also be expected to resist change in rules. Such dynamics of rule change within the regime are crucial for a transition, which usually takes place over an extended period of time (Smith et al., 2010).

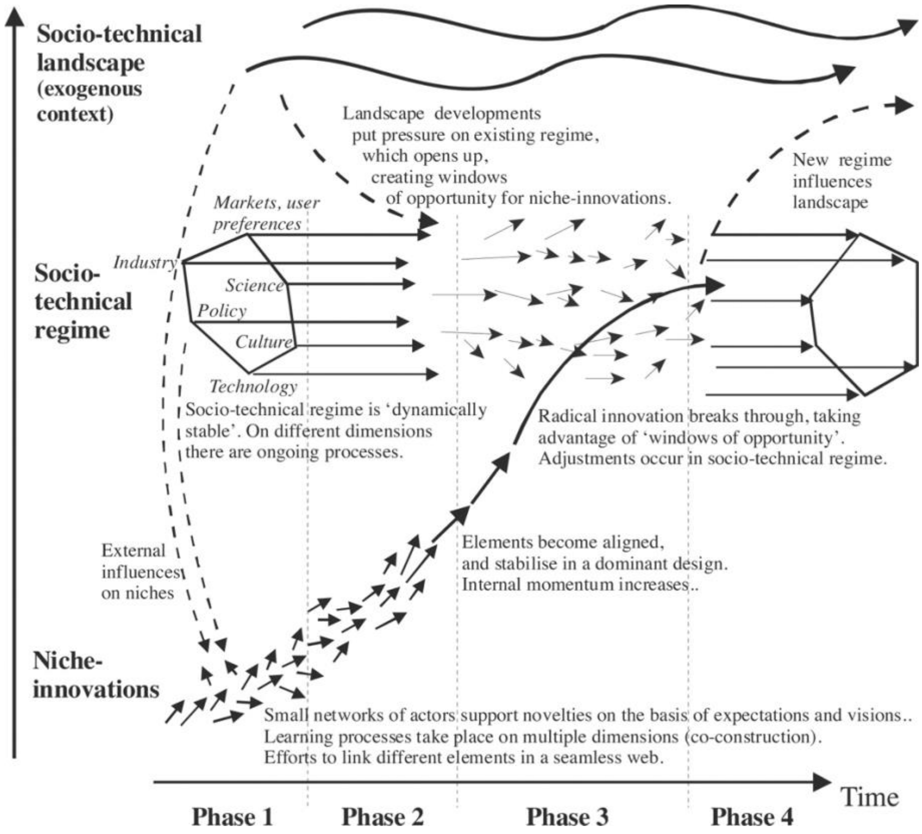

Figure 1 MLP framework. Transitions of sociotechnical systems over time (Geels, 2018)

The MLP framework is typically used to analyze how big socio-technical system transitions occur over long periods of time. Looking at the status quo of a system, the niche developments might get stuck in their niche while incumbent actors use their dominating power to develop existing infrastructures and invest in known and reliable as well as widely accepted technology. This is called a *reproduction process,* in which existing rules are reproduced by incumbent actors with incremental change of a system (Geels & Kemp, 2007). Here, dynamics only happen laterally at the regime level, leading to 'dynamic stability'. Without interconnectivity between the levels, a transition would be difficult to initiate. This interconnectivity may include pressure from the landscape on the regime and the regime's adjustment/reorientation to this external pressure (ibid.). Interconnectivity may be strengthened by the formation of social networks in which outsiders, public regulatory pressure, and new actors challenge the existing regime (ibid.). A *transition process* is the "outcome of linkages between developments at multiple levels" (Geels, 2002, p. 1262). This outcome is made possible by the landscape and niche exerting external pressure onto the regime, opening a window of opportunity for a transition (ibid.). This window may be the result of the regime's inability to adapt to landscape pressures in time, due to the 'dynamic stability' of the system, where change comes only incrementally. It ultimately opens up for a transition from one socio-technical system to another, where new trajectories are set and the incumbent regime is replaced by a technological breakthrough through a process called 'creative destruction'.

Regarding these processes, Geels and Kemp introduce four different phases (Figure 1), marking the conditions of a transition over a longer period of time, *emergence, take-off, acceleration, stabilization* (Geels, 2006, 2011, p. 29). These interlinks of the phases allow for either the reproduction, transformation or the transition of the regime, depending on each phase interconnectivity, respectively. The *reproduction process*can be placed between the first and second phase, the *transformation* between the second and third phase and the *transition* from the third to the fourth.

In the first phase, radical innovations emerge in niches. Niche actors experiment with new technologies in a dynamic, fast changing, and competitive environment. This initial development is inspired by problems or challenges at the regime or landscape level that these innovations seek to address (H2 and H1 in Figure 2) , leading to a response at the niche level (H3). Dynamics only happen *within* the niche level.
In phase 2, innovation dynamics begin to *take-off,* stimulated by networks and niche players (H6). The new technology is used in small markets for specialization purposes (start of a new technological trajectory) and a set of rules are established. Concerning sustainability transitions, this phase is crucial because of risks of discontinuation in technology developments due to mismatches appearing between the niche and the incumbent regime and the landscape (Geels & Kemp, 2007). This mismatch between the levels can be ascribed to lock-in mechanisms (H5, H4) such as sunk costs of investments in existing infrastructure, but also shared beliefs, power relations, consumer lifestyles and preferences, and political lobbying, (Geels, 2011). Lock-in mechanisms lead to path dependencies in the incumbent regime that hinder a rapid transition. To finally achieve a breakthrough for the new technology, the niche innovation must gain momentum. This momentum is built up with "articulation (and adjustment) of expectations or visions" (Geels, 2011, p. 28). In addition, social networks and

learning processes may add to create momentum. Ultimately, these aspects lead to settling a ‘dominant design’ for the new technology which can be supported by growing networks of actors, including powerful actors from the regime level) (ibid.).

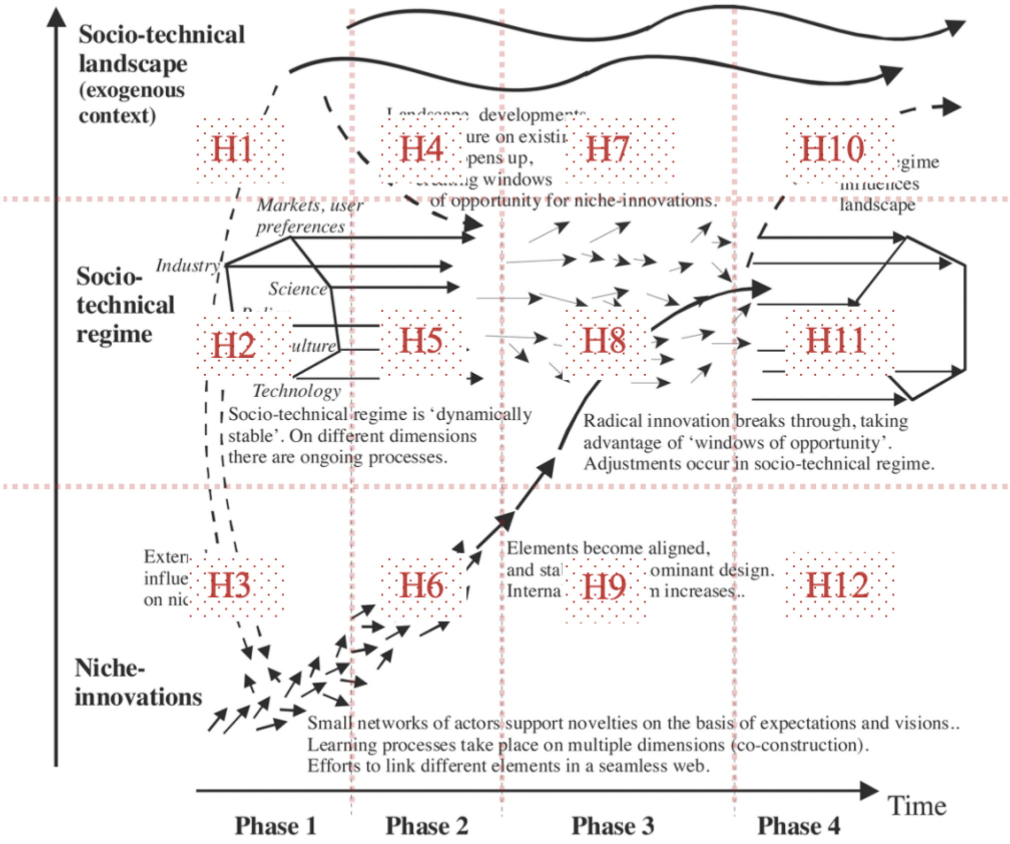

Figure 2: Phases and Change Processes in the MLP (H1-H12)

Phase 3 marks the breakthrough of the technology (H9 in Figure 2), in which its development is *accelerated* by the interplay of processes and actors (Geels, 2006; Geels & Kemp, 2007). This interplay reveals itself, inter alia, through competition within the incumbent regime and a wide diffusion of the new technology (ibid.). In this phase, landscape and niche pressures on the regime eventually open a ‘window of opportunity’ (H8) enabled by the inability of the regime to respond adequately to these pressures. There are certain internal and external drivers or barriers to this dynamic. Typical external landscape drivers widening the window of opportunity would be stricter regulations and changing user preferences (H4/H7). Internal regime drivers may be of economic, socio-technical, or social nature, while regime barriers may typically relate to solving technical problems for the niche technology (Geels, 2006). Economic drivers are typically improvements in the cost/performance ratio of the niche technology, of which the development of photovoltaic solar panels in Germany in the 2000’s is a good example (Quitzow, 2015). Socio-technical drivers can be new linkages and configurations between the niche technology and actors, spurring upgrowth of a stable infrastructure and favourable regulations needed for technology deployment (Geels, 2006). Finally, social mechanisms such as ‘hypes’ or ‘bandwagon effects[4]’, strategic games, social struggles, or the sailing ship effect[5] may push a breakthrough and cause a wider window of opportunity (ibid.). There is "no single ‘cause’ or driver", but rather a combination of internal and external drivers, of processes and linkages at multiple levels, that reinforce each other (Geels, 2011, p. 29). Geels calls this ‘circular causality’, denoting the reciprocal dynamics between actors, the technology, and the socio-technical system.

Finally, in the fourth phase, the emerging technology *stabilizes* within the the established system and eventuelly replaces the old regime and completes a transition (ibid.). In this phase, new policies, infrastructures, and lifestyles evolve over time.

2.3. Multi-Level-Perspective and Multi-Level-Governance

Given the common interest in tackling environmental problems in urban areas, cities are often confronted with specific policy-making processes and measures that depend on national or even supranational regulations[6]. This means that decisions made at the local level often have to comply with national or supranational norms, potentially impeding interests at the urban local level (van Stigt et al., 2013). The Multi-Level-Governance Perspective (MLGP) analyzes the dynamics on horizontal and vertical policy-making processes as they cross local, regional, and national borders, and is often used to discuss the governance structure of the European Union. Practitioners at multiple levels of government, involved in the same regulatory and policymaking tasks, often share these processes (Hague & Harrop, 2013). Because urban development relies not only on local planners and policy makers, but also on national standards, which are also guided by supranational standards, these interconnections reveal that urban development actors and their goals cannot be viewed as entirely independent. Rather, they must be seen and understood in relation to their hierarchical governance network.

[4] A cognitive bias resulting in peer pressure.
[5] New technology causes improvements in incumbent technology.
[6] In the case of Berlin and Germany and even the European Union, its political structure as a federation presumes dependencies on regulations and norms but also independencies when it comes to enforcing these regulations through case specific measurements.

Such a multi-level-governance perspective may thus inform and enhance our understanding of the socio-technical landscape of the MLP, e.g., the external political ideologies and macro-economic patterns that may pressure the incumbent regime into adapting new policies and regulations at the national, meso and micro levels (Geels, 2011; Smith et al., 2010).

The MLGP framework will not be outlined in depth though is mentioned briefly to enhance the theoretical understanding of the different dynamics at the landscape level. Berlin, a city state, is in a position where its policies mainly affect the urban space and thus directly influence sustainable development through local and national policy-making processes.

Berlin's laws and regulations are bound to national standards, which again are tied to EU laws. The EU is a significant driver (and barrier) of change in its member states. Its policies bind the 27 member states to include environmental investments and adapt their national strategies, for example to support renewable energy (EU, n.d.). But it could also hinder faster transitions on a micro level, which are bound to EU regulations supporting them. If these regulations are not clear, or laws and policies still neeed to be put in place, this would be a barrier to a transition. Therefore, the landscape of Berlin can be understood in the context of two landscape categories: the macro-landscape, being the wider context at the European and German level, and the micro-landscape, which is the immediate political, cultural, economic, or environmental context of Berlin. Further mentioning of the landscape level therefore presupposes the European and German dynamics with and on Berlin's local political decision-making processes. The European Green Deal or the EU Taxonomy for Sustainable Activities are examples that lie within the broader context of Berlin's influence on policy-making processes at the regime and niche levels.

Extending the landscape level understanding of the MLP framework with a multi-level governance informed perspective will be crucial in describing the specific landscape conditions under which a hydrogen breakthrough can occur in the urban setting of Berlin. Berlin's energy system is embedded not only in the local but also in the regional (Brandenburg), national (Germany) and European energy systems, with policies and governance established at each level that can influence the transition in the city of Berlin.

2.4. The MLP in an urban sustainability transition framework

The MLP is a framework for understanding transition processes of whole systems, often contextualized at the national level. When applying the MLP to a case of urban transition (the role of hydrogen in the transition of Berlin's energy system), cities can be seens as a subsystem in which multiple actors (e.g., local governments, transport, heat or energy operators, banks, institutions, businesses, public authorities, start-ups, consumers etc.) interact with each other (in e.g., innovation hubs, social networks, corporations, local and national politics and governance, etc.).

Urban sustainable development is a field that has gained interest in the innovation studies community over the last decade (Hodson & Marvin, 2010; Næss & Vogel, 2012; Hodson et al., 2017; Larbi et al., 2021). In this context, some limitations of the MLP have been identified when analyzing specific urban transitions, i.e., that the framework must be adjusted to give more attention to urban cultural norms, lifestyles, and context dependencies (ibid.). The adjustment of contextual dependencies is particularly important in the case of Berlin, as it is a city-state and thus directly affected by (also historic) national developments. Such developments, are important to understand in the context of Berlin, which has been subject to constant political, cultural, social, and economic change since World War II. To therefore identifiy the MLP phases 1 – 4 in the urban context of Berlin, its history must be explored first. Larbi et al. (2021) point out that niche innovations should not be reduced to technology per se, as social movements or consumer behavior also trigger transition processes (Larbi et al., 2021). This is particularly relevant in urban environments, where protests or movements can pressure the regime to adjust its policies. A good example is the FridaysForFuture protest movement and its impact on German policy, as well as the Berlin Climate Neutral 2030 referendum. Likewise, regional and urban governments and planners play a central role in translating international and national visions into actionable measures.

To sum up, when applying the MLP framework to study an urban energy transition, specific actors and institutional factors at this level must be given attention, while not neglecting a city energy system must be seen as an embedded subsystem of the wider national energy system. This calls for attention also to the multi-level governance structures affecting urban transformation processes. Policy-making processes, strategies, and legislation at the national and supranational levels can be considered as typical external institutional factors influencing the transition of the subsystem, and thus, part of the landscape level in the MLP framework. This does not exclude other external factors considered by (Geels, 2011, 2018; Geels & Kemp, 2007).

For Berlin's energy transition and the role of hydrogen in this transition, Germany's Hydrogen Acceleration Act represents such an external regulatory framework, accelerating the planning and implementation of infrastructure construction across the country (Collins, 2022). Berlin has already shown great ambition to become a hydrogen pioneer in Germany, and local stakeholders are already collaborating extensively to realize this ambition. As there may be conflicting policy ambitions and interests regarding hydrogen at the national and local levels, my MLP-based study will therefore consider that different dynamics of agency may emerge at different levels. In doing so, I take into account the criticism of the weak conceptualization of agency issues in the MLP (Markard et al., 2012). This means that there is a lack of understanding of conflicting interests and politics within and between levels that can significantly shape or even block transition processes. In my thesis I have tried to uncover the role of agency in the transition processes in Berlin.

2.5. Using the MLP to analyze the role of hydrogen in the transition of the Berlin energy system

A summary.

In this chapter, I have outlined the MLP transition theory framework used in this thesis. This framework will be used to analyze the conditions that brought hydrogen to its current role in the energy transition of Berlin, and to discuss the conditions for hydrogen to experience wider deployment in this system in the future.

In order to analyze Berlin's energy transition and to consider the niche development of hydrogen in the context of the city, it is necessary to divide Berlin's energy system development according to the four phases of the MLP. The analysis chapter aims to explore how hydrogen as a niche was able to penetratet and diffuse into Berlins energy system. This includes an empirical analysis of developments the historical background before 1990, providing an understanding of the conditions that led to the appearance of hydrogen in the Berlin niche. The first phase then explores the energy system of Berlin from 1990 onward, where regime dynamics remain internal and changing landscape factors trigger radical niche innovations. This is followed by a description of landscape pressures, including external institutional factors (e.g., national and supranational policies) and their impact on regime dynamics. The second phase explores the dynamics between the landscape and regime levels as niche hydrogen innovations gains momentum through pilot projects and further R&D. Further innovation at the niche level contributes to the momentum of the niche technology, which occasionally spills over into the regime through pilot projects and experiments, sparking regime participation and causing actors at the regime and landscape levels to adjust. Phases 3 and 4 are discussed on the basis of the conditional transition structures of the MLP framework. External landscape factors and the niche momentum of hydrogen in Berlin force the regime to adjust through the implementation of regulations and new policies (including visions, roadmaps, and future trajectories) supporting the niche technology. However, the 'dynamic stability' of the regime enables the niche technology to break into the regime through a window of opportunity, leaving regime actors unable to adjust in time. In the fourth phase, the new position of hydrogen technology within the Berlin energy regime will be enforced through continuous revision of regulations and adjustments, thus replacing the old regime and completing the transition. The dynamics of the third phase are discussed against the background of whether the developments of Berlin's energy system offer good conditions for opening a window of opportunity.

Based on the MLP framework and the structure of transitions described therein, I expect that in the second phase the energy system in Berlin will respond to landscape pressures by continuously implementing environmental policies that support hydrogen technology across sectors. Incumbent regime actors will be supported by subsidies and funding from government agencies, while new actors such as start-ups will be facilitated by incumbents to enter the market. Because the MLP's explanation of historical transitions tends to show causality between events, it may seem deterministic in its approach, even though it offers only a plausible exploratory description of a transition. This plausibility will be further explored in Chapter V.

III. Methodology

This chapter provides an overview of the methodology used in this study. Using the MLP framework, I aim to capture the "complexity of real-world developments", more specifically to understand and explain the developing role of hydrogen within the urban energy transition of Berlin (Geels, 2002, p. 1273). Using the MLP framework, I seek to explain the conditions in the past that brought hydrogen to its current role in Berlin's energy transition, and the conditions that may determine its wider use in the future.

The MLP framework is applied as a heuristic device to structure my empirical research aimed at understanding and explaining the the specific energy transition of Berlin. The aim of my empirical research is to "identify recurring patterns and generalizable lessons" (Geels, 2011, p. 26) that may assist me in understand the micro, meso, and macro conditions for the developing role of hydrogen in this transition. The MLP, as a middle-range theory and heuristic device, has worked well to emphasize the synergy between theory and empirical research (Geels, 2011; Merton, 1968, p. 26).

The empirical research is based on primary and secondary data. Primary data was collected through interviews with politicians in the Senate Committee, hydrogen entrepreneurs, and academics working in the field of sustainable solutions in urban development in Berlin. The interviews were prepared with an interview guide, whose questions aim to understand the fundamental concepts of the MLP and identify interactions within and between the different levels of Berlin's urban setting. The interview guide consists of three sections, with questions aimed at uncovering factors impacting the development of hydrogen at the three levels corresponding to the Multi-Level Perspective: the niche level, the socio-technical regime, and the socio-technical landscape. By using the same questionnaire approach for each target group, the method aims to provide different actor perspectives on the same phenomena within the energy transition in Berlin. This qualitative approach is seen necessary to understand the 'fairly complex perspective' of the MLP (Geels, 2002). Secondary data complements the primary sources and consists of academic articles and books, policy documents and laws, and government reports at the national and local levels. Below, I give more detail on how data were collected and used to ensure the transparency and replicability of my research.

By applying an abductive research strategy I uncover the context in which hydrogen technology evolves throughout and stands in relation to niche, regime and landscape dynamics. The exploratory nature of the MLP framework helps to understand the system in which hydrogen evolves. Abduction is a research method aiming to “discovering, or drawing conclusions from, circumstances and structures that are not given in individual empirical data”(Danermark et al., 2002, p. 89). This includes describing social phenomenas like actors and their motives and visions. Actors in this context are political as well as industrial and private actors at all levels of the MLP. In combination with primary and secondary data from the respected fields and a theoretical review of the framework, this abductive approach will help to understand the actor’s world and form a deeper, more comprehensible understanding of the questions. Abductive reasoning involves interpreting contemporary phenomena and placing them into a new context using the theoretical framework as a reference (Dey, 2004, p. 91); herein being the explorative framework of the MLP. Recontextualization is what distinguishes an abductive approach from induction and deduction, ultimately leading to an observation of a theory and resulting in a possible interpretation (Danermark et al., 2002, p. 80f). Therefore analyzing the evolutionary development of hydrogen at the niche level, incorporating pressures from landscape and regime dynamics, requires recontextualizing it using the MLP. Through this approach, I have adopted a critical realist stance in my research, opening up alternative conclusions about how and why hydrogen emerged and developed as a solution for the transition of Berlin's energy system.

The empirical data required for abduction serve as both a guide and a basis for understanding an event in its larger context. Abduction involves various approaches to explaining social phenomena by logically reinterpreting the data collected and providing for possible generalization through applied logical inference, both from induction and deduction methods. Choosing this strategy allows generalizations about the implementation of hydrogen technology for the purpose of sustainable urban development in the future. It supports the description of not only the past but also the future conditions for a hydrogen breakthrough by gathering specialized information as well as a theoretical background to support it. In doing so, I aim to arrive at a plausible conclusion using my own interpretations of the transition processes of hydrogen in Berlin’s energy system, thus presenting something that might be (Danermark et al., 2002, p. 91).

3.1. Embedded Single Case Study

Looking at Berlin to describe a hydrogen development and possible breakthrough requires the *narrative explanation* approach of the MLP framework (Geels, 2011, p. 34). By explaining the outcomes of different sequences and ultimately identifying causal processes within the case study I make use of process tracing (George & Bennett, 2005). Also, by investigating Berlin in depth through a case study, I am able to include multiple sources of data e.g., interviews, documents, observations, artifacts etc. (Yin, 2009). Implementing such a data collection approach allows for triangulation of the data, adding to the construct validity of this research.
This methodology allows me to follow the logical inference of an embedded single case study in which attention is also paid to subunits (Yin, 2003, p. 40). In other words, investigating the role of multiple actors at different levels of Berlin's energy system, describing their dynamics and interaction, and explaining the development of hydrogen can be perfectly managed within the framework of an embedded single case study. Not only is the context given, but the case is also described, understood and its specific dynamics examined, including micro-descriptive empiricism (Figure 3).

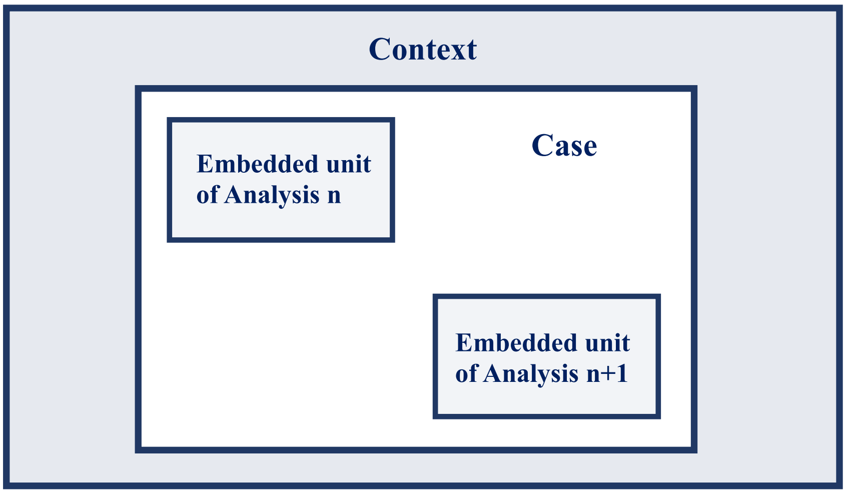

Figure 3 Embedded Single Case Study (own illustration inspired by Yin, 2003)

I will use the evolutionary development of Berlins energy system as a case study and connect the empirical data to the theoretical framework. Drawing parallels between the case and the theoretical proposition adds to the internal validity of the research. Including the MLP framework into a case study approach increases the external validity of this thesis, as shown in the research design described here. The possibility of generalization in the context of abductive reasoning addresses the external validity of this thesis.

3.2. Data Collection

The data collected consists of primary data derived from expert interviews in the political, academic, and private sectors. Initially, this data is needed to allow insight not only into the dynamics of the actors at each level, but also into their interactions across the levels. In doing so, this research aims to gather data on experts and specialists who have been involved in the policy-making processes of the Berlin hydrogen trajectory, as well as in the private and academic sectors. These different sectors are chosen to best represent the three levels within an urban setting. Following Geels and Kemp's (2007) proposition, a regime perspective and an actor perspective must be combined to understand transitions and transformations (Geels & Kemp, 2007, p. 454). Secondary data gathered in this research comes from policy documents, academic articles, and European as well as German and Berlin politics. Secondary data fills in knowledge gaps or compliments primary data through triangulation. Primary data is be gathered in the form of specialized interviews and secondary data is collected through public government websites, journals, and magazines as well as established news sources and secondary literature.

3.2.1. Interviews

Since hydrogen technology is still in the development and research phase in many areas, interviews can provide specialized knowledge about the status quo and the future pathways of the technology and its applications and supporting conditions. There are various companies and start-ups as well as research programs and governmental policies that include hydrogen development. To better understand their vision and capabilities, expertise can be very useful to also gather information that may not yet be publicly available. The interviews were all held online via Microsoft Teams and automatically transcribed by the internal transcription service. Furthermore, the interviewees were recorded, encrypted, and stored by '*nettskjema*'. A data management plan was established with '*Sikt*' and the project has been registered with the Norwegian Agency for Shared Services in Education and Research.

The interview data consists of five interviews with representatives of the Senate Department for Economics, Energy and Operations, the Senate Department for the Environment, Mobility, Consumer and Climate Protection, the H_2 Berlin Network, the Rainer-Lemoine Institute and Sunfire GmbH. Insights from the Senate Department, the political actor in Berlin providing a governance perspective, help to describe the incumbent regime, its policy making processes and the trajectories for hydrogen in the future. *H_2 Berlin's* network consists of thirty key actors in Berlin's private sector, representing both incumbent systems and niche actors on Berlin's road to climate neutrality. This network includes, inter alia, the water supplier (Berliner Wasserbetriebe), the city cleaning (BSR), the heat provider (GASAG), the electricity provider (Vattenfall) and other SMEs active in hydrogen development and deployment. The *Rainer-Lemoine Institute* has been working on the hydrogen roadmap for Berlin and Brandenburg and can be seen as an intermediary between policy makers and the private sector. Finally, Sunfire GmbH is a company that produces highly efficient industrial electrolyzers for green hydrogen production and can still be considered a niche company, although it is already involved in multilateral projects.

The interviewees were originally chosen based on their field of work. Additional interviewees were referred by primary interview partners, resulting in a snowball sample. An interview guide was prepared which separated analytical and investigative questions into three sections following the three levels of the MLP. The first section of questions aimed at the context in which hydrogen is discussed. This included political as well as technical questions to solidify the landscape level in which Berlin's hydrogen development is placed. The second section aims towards identifying Berlin actors and their dynamics as well as analytical questions about the conditions for hydrogen development. The final section asks questions more related to the city of Berlin and its role as a hydrogen pioneer in Germany. The interview guide was individually adapted to each interviewee according to their field of work. Overall, the interviewees represent the perspectives of the regime and the actors, who best understand the transition of hydrogen in Berlin city development.

3.2.2. Document Analysis

To support the primary data with the triangulation method and to verify the collected information, the document analysis of government policies, visions and roadmaps was analyzed. Together with academic articles, these policies and roadmaps will be evaluated and placed in the context of the SUT. In particular, policies and roadmaps of the EU, Germany and Berlin are relevant to answer the research questions. In addition, websites of political and private actors in Berlin are relevant to understand the hydrogen development so far.

Furthermore, feasibility studies and roadmaps help to manifest the progress of the transition and to provide future perspectives. These documents can be found on the governmental websites of the Senate departments or were provided by interviewees. Academic papers are available through the university library. Most papers were also taken from the reference lists of relevant articles in the field of hydrogen, MLP and transition theory and SUT. More data also comes from niche actors who communicate their hydrogen roadmaps on their websites and manifest them with studies conducted by academic institutions such as the Rainer-Lemoine Institute or the Fraunhofer Institute. These academic institutions play an important role in communicating hydrogen to a wider audience, but most importantly in guiding policy makers in their decision-making processes.A document analysis supports the primary data by providing a foundation and adding the same or similar information from other sources. I aim to support the validity by diversifying the sources.

3.3. Data reduction and analysis

The data were sorted according to their relevance to the topic and to answering the research questions. The choice of theoretical framework was guided by respected scholars in the field of transition theory. By broadening the understanding of MLP and recognizing the relevance of the MLG for understanding the landscape level, this research mostly looks upon political and technical conditions. The interviews also made it clear that political and technical conditions are the most pressing in supporting a wider hydrogen breakthrough in Berlin. For this reason, all gathered data will be reduced to support the conditions considered. This reduction approach aims to provide valid information and giving context without distracting from the research questions. Also, given the time and resource constraints of this research, it is reasonable to focus on a maximum of two conditions for a hydrogen breakthrough. The interviews were transcribed and manually coded. Valid information has been filtered out and triangulated for reliability. The documents were reduced to their most valuable core was achieved by highlighting relevant sections and using the search function for specific terms.

3.4. Limitations

Collecting the necessary amount of data and finding the right information has some limitations. First, choosing an abductive approach leaves room for interpretation, which the researcher must justify. Interpreting a hydrogen breakthrough in Berlin within the conceptual framework of the MLP might lead to human error e.g., misinterpretation of the data. Validating the conclusion of interpreted phenomena may also be difficult to replicate in future research, as there are no established criteria for assessing the validity of abductive research.

Furthermore, identifying the conditions for a technology's potential breakthrough using the MLP framework may appear to be a deterministic approach. Geels himself has pointed out this limitation, but stresses that "the outcomes of sequences of events and the timing and conjunctions of chains of events" are ultimately the goal of describing a transition with the MLP (Geels, 2011, p. 34). The MLP is mainly used to narratively describe past transitions. It is therefore not a tool to search for causal relationships in a transition. Having identified and described past developments and conditions for a hydrogen transition in Berlin so far does not mean that these conditions will lead to certain outcomes. They are merely a possibility, supported by theoretical frameworks and collected empirical data. Therefore, the results and conclusions of this research should be considered within the interpretive framework of the possible.

Another limitation is the selection of interviewees. Apart from not responding to interview requests, they are not always representative of an entire system or actor within a system, which reduces the reliability of generalizing any conclusions. Even though being specialized interviews, the primary data collected represents one perspective in which personal opinions may influence the answers. Throughout the process of collecting secondary data, paywalls have restricted full access to possible relevant information, possibly hindering the triangulation approach.

IV. The Evolution of the energy transition of Berlin A Case Study

The Berlin Energy and Climate Protection Program (BEK 2030) and the H2-Roadmap Berlin Brandenburg both outline ambitious deployment of hydrogen in sectors such as heating and industry for transitioning the city energy system towards 2045. Since Berlin has one of the largest district heating networks in Europe and around 40% of CO_2 emissions come from this sector alone, the potential for hydrogen here is considered immense (MWAE & SenWEB, 2021; UMVK, 2023). Berlin's energy system is closely linked regionally with that of the state of Brandenburg, calling for a common transition strategy. Most of Berlin's energy use is produced outside its borders, and imported. Today, Berlin's energy system is heavily dependent on fossil fuels. Renewable energy sources, such as solar, biomass, biofuels, wind, and environmental heat, currently covered about 12,46% of the city's primary energy use in 2020 (ibid., 2020). Combined deployment of hydrogen and renewable energy has thus become central elements of Berlin's ongoing energy transition.

The city is governed by policy-making processes affected by supranational or even global structures, such as EU regulations or UN conventions. Being embedded into such global, supranational, and national policy ambitions, Berlin has been challenged to implement climate protection measures and transition strategies. The concepts of sustainable urbanization have become more concrete through the UN seventh Sustainable Development Goal (SDG) to ensure "affordable, reliable, sustainable and modern energy for all" (UN, 2023). Tackling the energy consumption of cities worldwide by transitioning to renewable energy would significantly reduce not only the GHG emissions but also social injustice in cities, improve the wellbeing of citizens, and contribute to a sustainable urban development.

The MLP framework is used as a heuristic device to structure my empirical research in this chapter, the aim of which is to understand and explain the specific energy transition in Berlin. The chapter looks at the evolving developments of the energy system and its actors (regime), as well as the policies and external pressures on the regime (landscape) that has created a momentum for hydrogen (niche) in Berlin. The landscape, regime, and niche dynamics prior to the appearance of hydrogen are described in a brief historical excursion at the beginning. I examine the landscape (section 4.1), regime (section 4.2), and niche (section 4.3) levels independently, thus replicating the structure of the theoretical framework. A separate section (4.4) will present and analyse the planned trajectories and roadmaps aiming towards commercialization in the future. Ultimately, the results of the empirical analysis,with the main drivers and barriers for advancing deployment of hydrogen as element in Berlin's energy transition evolving at each level are briefly summarized, to set the basis for the discussion in the following chapter.

4.1. The landscape of Berlin's energy transition and institutional developments

the landscape before 2015.

Throughout the late 20th century, Germany and Berlin have seen continuous efforts to reduce the environmental impacts of its primary and secondary energy consumption, driven by legislation at the national and regional levels. National and regional legislation has in turn been influenced by EU directives, standards, and the idea of a competitive European market, while at the same time aiming for environmental improvements in response to social movements and health issues arising from high concentrations of air pollutants in the cities. Berlin's energy transition is thus embedded in a prime example of a multi-level governance system that vertically links government institutions to one or more challenges. Berlin is part of the German political system while being firmly integrated into the political, economic, and legal structures of the European Union (BLPB, n.d.). In the following, I will provide a brief chronological overview of selected EU and national legislation and landscape changes that have influenced energy development in Berlin from the post-war period until 2023.

historic excursion - prior to 1990.

In the aftermath of World War II and the advent of the Cold War, Germany was soon divided into East and West by the construction of the Berlin Wall in 1961. In 1974, West-Germany enacted the Federal Immission Control Act to protect the environment, including water, soil, air, animals, plants, the atmosphere, as well as culture and other material goods (BImSchG, 1974). This legislation laid the groundwork for a federal understanding of environmental protection and for the first time brought the issue into the midst of society by regulating, for example, traffic or noise pollution in urban areas. During the same decade and much of the next, international oil prices soared after events in the Middle East (1973 and 1979) disrupted world trade, spurring a transition to the use of cheaper alternatives such as natural gas. In the 1980s, the political atmosphere in Germany was very sensitive to external events, such as the explosion of the Chernobyl nuclear reactor in 1986 and the aftermath of the oil crisis. The environmental crisis that followed Chernobyl gave rise to social movements among the citizens of West Berlin and smaller groups in the GDR demanding a phase-out of nuclear power, putting pressure on the changing national coalition governments of the time. The Ministry of the Environment was established in 1986, and at that time it was still mandated to work for the preservation of nuclear power in Germany, since "a restart of old coal-fired power plants could cause health damage" and a nuclear phase-out was considered unrealistic until a new, more environmentally friendly, safer, and cheaper source of energy could be found (SWR2, 2021).

institutional developments post 1990.

In 1989, the fall of the Berlin Wall marks one of the greatest historical events in Germany, with consequences that are still felt today. (e.g., East-West differences in wages, pensions or political orientation). Immediately after reunification in 1990, Berlin passed an energy conservation law (BEnSpG) with the goal of using as little fossil energy as possible to ensure the well-being of its citizens, with a focus on the efficient use of waste heat (BEnSpG, 1990). This meant, for example, that non-renewable energy sources were to be conserved as far as possible, that primarily low-value forms of energy were to be used, in particular waste heat and ambient heat, and that energy was to be used in an economical, rational, socially and environmentally compatible manner and in a resource-conserving manner (ibid.).

In addition, on December 7, 1990, just two months after reunification, Germany implemented the Electricity Industry Act (StromEinspG), which legally obligated energy suppliers such as GASAG to purchase electricity generated from renewable energy sources (BGBl., 1990, p. 2633). This law also pushed the research and development (R&D) of the solar industry, which helped shaping the innovation system worldwide, especially in China (Quitzow, 2015). The costs of solar photovoltaic (PV) systems were drastically reduced, leading to competition in the market and pushed the technology out of the niche. The exemplary function of German policy was crucial for this development, although some also argue for a simultaneous development in global markets (ibid). The shift to renewables saw an increase in the production of wind and solar, but also biomass (including firewood, waste, and sewage gas) to meet final energy demand (light gray bar in Figure 4)

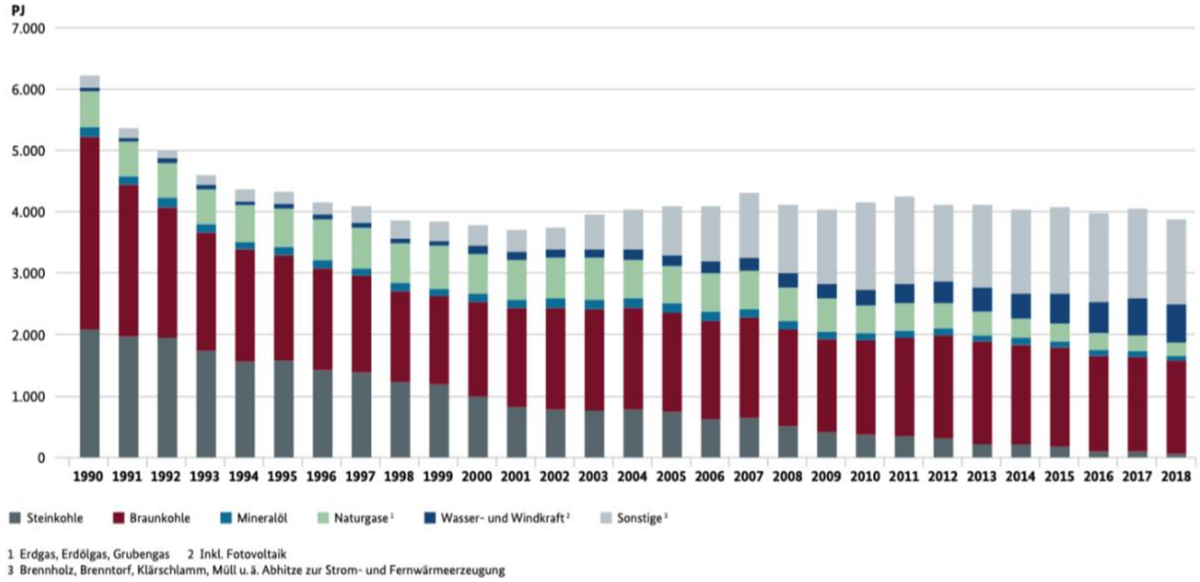

Figure 4 Primary Energy Generation in Germany (BMWi, 2019)

In 1994, the United Nations Framework Convention on Climate Change (UNFCCC) was established, bringing climate change more into the focus of its members and ratifiers. A year later, the Berlin Mandate, also known as COP1, provided critical support for the 1997 Kyoto Protocol, a climate change treaty aimed at reducing emissions from industrialized nations. The Conference of Parties (COP) have since been instrumental in promoting alternatives to fossil fuels within the legislations of nations and their sectors.

One of Germany's most important pieces of legislation is the Renewable Energy Sources Act (EEG) of 2000, building on the StromEinspG of 1990,which enabled the expansion of renewable energy and spurred development of new technologies (such as hydrogen) throughout the country. This law now lays the foundation for Germany's ambitious goal of phasing out coal and nuclear power simultaneously by 2035 at the latest[7].

Another important driver is the EU Emissions Trading System (ETS), which was adopted by

[7] As of 15th April 2023 Germany has shut down its last three remaining nuclear power plants (BASE, 2023). Cities individually have announced their goal of phasing out of coal with Berlin aiming towards 2030.

directive in 2003 as the main instrument for implementing the Kyoto Protocol and implemented in Germany in 2004. Landscape events affecting Berlin's long-term energy transition went beyond environmental legislation. In 2005, Germany signed an agreement with Russia for the construction of the Nord Stream 1 pipeline, ensuring the direct delivery of natural gas from Russia to the German coast in 2012 (Sullivan, 2022). In 2006, the ten-year National Hydrogen and Fuel Cell Technology Innovation Program (NIP I) was initiated to conduct research and development to improve the market readiness of hydrogen and fuel cell technologies, including in Berlin. The NIP I was funded by the Federal Government, together with the states, its industries and scientific institutions with a budget of 1.4 billion euros for the period 2006-2016 (NOW GmbH, n.d.). In 2008, the world was hit by a financial crisis that affected the transition both negatively and positively. Positively in the sense that demand for natural resources and energy slowed down; negatively, in that demand for and supply of international transition policies also slowed down (SYKE, 2015). In 2011, the explosion of the nuclear reactor in Fukushima accelerated concerns about the safety of nuclear energy worldwide. In Germany, this event spurred the decision to completely phase out nuclear energy and instead focus on the production of renewable energy, what has become known as the German *Energiewende* (Hasselbach, 2021). The *Energiewende* was then further supported and developed by the Paris Agreement in 2015.

The Paris Agreement as a turning point

the landscape after 2015.

The Paris Agreement of 2015, symbolizes a global breakthrough in attention to climate change and in understanding of how to tackle global warming as well as dealing with consequences of an increase of heatwaves, environmental disasters, and adaption measures. Over 196 parties have adopted the Agreement, pursuing to limit the increase of global temperature to less than 2°C as well as aiming towards 1.5°C above pre-industrial levels (United Nations, 2015). The EU has ratified the agreement, and Germany has responded by setting targets in its federal climate protection law (KSG) to reduce its greenhouse gas emissions, including hydrogen to decarbonize entire sectors. This Agreement is showing the dynamics of climate change issues within societies, which are increasingly intensified among global, national and regional actors. At the global level, this agreement has triggered carbon-neutrality targets, zero-carbon solutions, and competitiveness in all economic sectors, especially in the energy and transport sectors (UNFCCC, 2015). At a more local level, it acts as a framework upon which roadmaps and climate trajectories are built.

The Paris Agreement, and follow-up of this agreement in Germany, spurred new assessments of the role of hydrogen technology in the national *Energiewende* and at city level, for the transition of Berlin's energy system.

In 2016, the German government decided on up-scaled funding of hydrogen technology developments through the NIP II programme (continuing efforts established with the initial NIP I programme adopted in 2006). Projects under this programme, such as *Hyland,* aim to create hydrogen valleys across the country, the coupling of sectors, the boosting of R&D and enabling a commercialization of hydrogen in the transport, building and energy sector. Over 1,6 billion Euros have been allocated since 2017, with 44,2% of the funds targeting commercialization of hydrogen technology in various sectors (NOW GmbH, n.d.). The NIP II functions as a financial shield for high-risk projects implemented in regions all over Germany.

The Federal Department for Economic Affairs and Climate Protection (BMWK) in 2019 started the *"real laboratories of the energy transition"* funded under NIP II, as a national format to fund also hydrogen technology and pushing towards a wide implementation and commercialization (BMWK, n.d.). Those laboratories are especially focused on hydrogen in the energy system, energy-intensive industry and the housing industry (ibid.). Within this program, hydrogen is seen as the hinge of sector coupling, capable of storing and transporting green electricity and linking the heating, transportation and power sectors for increased energy efficiency and effectiveness.

The same year the Federal Climate Protection Act (KSG) was presented by the German government with goals of a 55% reduction in 2030 compared to 1990 encompassing lower emission targets in the energy, transport, industry, building and agricultural sectors.

Under the Paris Agreement of 2015, signatories have since 2020 submitted national climate action plans, also known as Nationally Determined Contributions (NDCs), to document climate ambitions and strategies. Part of the German national climate plan is the German National Hydrogen Strategy (2020) and the Hydrogen Roadmap for Berlin (2021), indicating a direct influence on national and regional policy-making processes. In both cases, the Paris Agreement is mentioned as the decisive factor that has set the idea of a hydrogen strategy (BMWi, 2020; MWAE & SenWEB, 2021).

The NDC's spur investments in low carbon technology, thus reducing the prices of renewables, increasing their competitiveness against fossil fuels on the energy market (IRENA, 2022). This development is important to increase renewable electricity generation, which in turn is important to ensure the production of competitive green hydrogen on the market.

The German National Hydrogen Strategy (NHS) has spurred further policy developments, and more funding of R&D in the fuel cell technology through the NIP II. Overall the NHS aims to support hydrogen along its entire value chain, from production to storage, distribution, consumption and its national and regional infrastructure (BMWi, 2020). In July 2020, the EU hydrogen strategy was adopted providing a foundational framework for national legislation towards H_2 and starting the European Hydrogen Backbone in which critical infrastructure is defined through a pan-European low carbon hydrogen market (van Rossum et al., 2022).

This same year, the world was faced with COVID-19 - a corona virus that caused a pandemic that affected global markets and development. The Corona virus led to nationwide lockdowns and a near economic shutdown in Europe. Findings from the OECD's 2022 Forum on Green Growth and Sustainable Development show that the pandemic led to a slowdown in clean energy development, although it prompted a response - a $1.2 trillion global stimulus package targeted at low-carbon technologies (Aulie et al., 2022). Investment has focused on R&D, particularly in Germany, where hydrogen has been prioritized (ibid). With 2020 experiencing the strongest economic slump since 1970, Germany introduced, in addition to a 1,1 trillion rescue package, a 130 billion economic stimulus package with over 9 billion going into the NHS and R&D on hydrogen technology (Schmid, n.d.). Also, the approval of the EU Green Deal has started a series of policy initiatives under which revision of the EU Emissions Trading System (ETS) raised the carbonprice over the years for the power sector, the industry and flight sector. National emission reduction targets had to be set for sectors outside the ETS like transport, agriculture and buildings therefore also supporting the NHS in its goals in respected areas.

In 2021, the Fuel Emissions Trading Act (SESTA) came into place on national level covering

emissions from the heating and transport sectors which were not initially affected by the EU ETS. It was implemented with the expectation of higher carbon prices for these sectors. Air transport was excluded from SESTA. The increase of carbon tax within latter industries also precedes heating strategies of energy actors such as Vattenfall and GASAG including hydrogen into their future resource portfolio.
Another important landscape factor appeared in 2021 in the context of climate protection ambitions - the constitutional court ruling on the German climate protection act (KSG). It ruled the KSG to be unfit since it did not incorporate strategies to go climate neutral after 2031 (Federal Constitutional Court, 2021) thus putting the younger generation into a disadvantaged situation – basically it was lacking ambition. Following the ruling of the constitutional court a new KSG in 2021 included more ambitious goals and concrete strategies, also leading to revised legislation of the Berlin Energy Transition Act (EWGBln). The new KSG showed new goals of climate neutrality by 2045 and interim targets. Those specific targets aim a 65% emission reduction in 2030 and 88% reduction in 2040 compared to 1990 (KSG, 2021).

Apart from the legislative factors at the landscape level, the year 2022 began with an incisive event that had an impact not only on legislation but also on economic development (energy market) and political realignment – the war between Russia and Ukraine. Russia's invasion of Ukraine started an entire chain reaction at the landscape level in form of supranational and national legislations aiming to counter the disruptions on the global energy market. The EU revealed *REPowerEU* in May – a new plan to save energy, produce clean energy and to diversify its energy supply (European Commission, 2022). It includes the acceleration of hydrogen increasing European ambitions towards a hydrogen market by 2030 as well as, inter alia, calling for a standardization of hydrogen production, infrastructure and end-use appliances, an assessment of the *IPCEI* project (Important Projects of Common European Interest) and the import of 10 Mio. tonnes of renewable hydrogen[8] by 2030 (ibid. p.7). *REPowerEU* has pushed more ambitious goals for the European Hydrogen Backbone (EHB) including about 53,000 km of hydrogen network infrastructure in 28 European countries by 2040 (ibid.). Ultimately, *REPowerEU* can also be seen as the result of industrial competition between the US and Europe. The US, through the Inflation Reduction Act (*IRA*), has created a

[8] It has yet to be decided on the terms of renewable hydrogen and whether it includes nuclear energy or natural gas in the production of renewable hydrogen. Germany is set to publish its new NHS in 2023 incorporating e.g., blue hydrogen into its strategy.

favorable environment through tax cuts and incentives for companies to invest in low-carbon technologies, threatening the European market with the departure of profitable investment and development at home.
In 2022 the German LNG Acceleration Act is also a reaction to the war. It supports a national gas supply with independency from Russia. This Act limits the use of gas-powered power plants to the 31st of December 2043 where further operation of the plants could only be approved for climate-neutral hydrogen and its derivatives. It also provides for the increased use of hydrogen in the hard-to-abate sectorsThis law has led to the construction of terminals in northern Germany within a short period of time, demonstrating the potential for rapid deployment of energy infrastructure within months through shortened permitting processes and political will.
With Russia invading Ukraine they have also cut natural gas supply to western countries thus causing an energy crisis and rising prices. Germany was forced to reorient their energy portfolio in favor of energy independence and resilience, since they relied on energy imports from Russia through Nord Stream I and II. Both pipelines were involved in an act of sabotage at the end of the year, which led to a complete interruption in gas supply. Germany has since then increased its use of coal and nuclear in the power generation thus pushing the phase out of nuclear energy to the following year. These developments followed an energy crisis with a rise of prices of fossil fuels also leading to higher prices of blue hydrogen. Despite these developments, solar and wind installations have increased simultaneously leading to an increase of coal (33,3%), wind (24,1%), solar (10,6%) in the energy mix (tagesschau.de, 2023).

The EEG has been revised several times, including in 2023, and represents "the biggest change in energy policy for decades" (Bundesregierung, 2023). 2023 is set out to include new legislation such as the Building Energy Act and the revised National Hydrogen Strategy. Prior legislation aims to ban fossil fuels from all heating systems from 2045 starting with a regulation that all newly installed heating systems must run on at least 65% renewable energy in 2024. However, its use is being critically discussed because it means that gas heating systems must be hydrogen-compatible, which at present seems uncertain for the energy actors without an existing infrastructure and supply. Latter is targeting the inclusion of blue hydrogen in the NHS, thus widening the market for hydrogen production and aiming to speed up commercialization processes.

4.2. Berlin’s energy system development and its actors

the regime before 2015.

To understand the evolving role of hydrogen in Berlin's energy transition, this part describes the long-term evolution of Berlin's energy system, its configuration of actors, and links to the landscape factors that shaped its development. This historical excursion provides a background for understanding the emergence and development of hydrogen as niche technology since 1990 as product of the dynamics of regime actors and legislation. From 1990, I will look at how the transformation of the energy system in Berlin unfolded over time until the year 2023, when the city staged its intention to become the first hydrogen pioneer city in Germany. By exploring the reconfiguration processes, the actors involved, and the context in which Berlin's energy system (regime) has developed, I aim to describe why and how hydrogen appeared as a niche technology and has evolved to the present.

Political regime actors are typically the Berlin Senate, led by the mayor and further divided into 10 senate departments each focusing on e.g., finances, health, environment etc. The Senate’s trajectories are influenced by the election which in return influences the policies put into place. Laws in Berlin are made by the House of Representatives which includes all elected parties reaching 5% or higher. Those laws are enforced by the Senate departments through individual policymaking. (Senate Chancellery, 2023b) The Senate departments are crucial in pushing legislation in sector specific areas and help building a regulative framework in which a niche technology can thrive. The Senate departments rely on national policies made by the *Bundestag*, whose policies are also enforced by the federal ministries. The Federal Department for Economic Affairs and Climate Protection (BMWK), the Senate Department for Mobility, Transport, Climate Protection and the Environment (SenMVKU) and the Senate Department for the Economy, Energy and Operations (SenWEB) are essential political actors in Berlin supporting hydrogen technology through subsidies and research programs. The policy framework in which hydrogen can thrive in Berlin is governed by various national and supranational legislation. Political actors provide planning security which incentivizes another actor group to become active in the transition process – **investors**. Incumbents of the energy system, but also Ministries, public institutions and private actors can act as inverstors in new technology. Hydrogen developments need investments to push the technology out of the niche and into the regime. It is not uncommon for incumbent actors of the energy regime to act as investors in niche technologies. After all, **industrial actors** such as Vattenfall and GASAG are key actors in Berlin's energy system (the regime) and its transition towards renewable energy and hydrogen. As main actors of the energy regime they emit a significant amount of CO_2 and therefore play a vital role in the energy transition. A closer look at their historical developments over time and visions for the future will be described further below. For niche technology to diffuse into the regime, knowledge generation through R&D is important and mostly done by **research institutes** providing the necessary technical innovation. This innovation in hydrogen technology, such as lowering of the cost-efficiency ratio, ultimately leads to the opening window of opportunity. Further pressure on the regime is enacted through s**ocial movements** like the anti-nuclear movement, the Friday For Future (FFF) movement in Germany, or referendums in Berlin.

West-Berlin before 1990

In 1948, for political reasons and as a result of the Berlin Blockade (1948-1949), the grid operation was divided into East and West, which also resulted in the division of the energy companies. The Soviets had taken over most technical facilities in the city. To secure supply of food and energy to isolated West Berlin, the Allied organized the "Candy Bomber" airlift, including construction materials and over 416,835 tons of coal for a new power plant (Bewag, n.d.). A major player in the West-Berlin energy sector was GASAG, which had supplied gas to Berlin for more than 125 years. Bewag-West was another energy provider, supplying heat and electricity. During the "blockade" of West Berlin, GASAG and Bewag-West were forced to produce their own city gas, which was produced by gasifying coal. Interestingly, city gas is mostly a hydrogenous gas, consisting of up to 51% hydrogen. By-products were coke, coal tar, benzene precursors, ammonium sulfate for fertilizer, and sulfuric acid sold to industry (Landesarchiv Berlin, n.d.). Black hydrogen was another byproduct, not desired for its poor environment properties. In the 1950s, mineral oil was added to the production process, and in the 1960s, light petroleum and methane slowly replaced coal and mineral oil in the production of city gas in West Berlin (GASAG, n.d.). This development was initiated by the Marshall Plan or the European Recovery Program (ERP) in 1948 (ibid.). In the years leading up to the fall of the Berlin Wall, natural gas replaced city gas, leading to the closure of the last coal gasification plant in 1980. As a result, West Berlin had to look for new suppliers, which it found in Ruhrgas AG and also in the Soviet company V/O Soyuz Gas Export (Bärthel, 1997; Landesarchiv Berlin, n.d.). The "new eastern policy" of the German government and the normalization of relations with the GDR made cooperation possible, leading to the construction of new infrastructure such as a pipeline from Czechoslovakia and a storage tank in West Berlin. In 1985, West Berlin received natural gas from the Soviet Union for the first time(Landesarchiv Berlin, n.d.). This development preceded political action and cooperation among the actors of the energy regime. This development, although not directly related to the emergence of hydrogen, set the stage for future developments that supported the emergence of hydrogen in Berlin.

East-Berlin before 1990

Meanwhile, in East Germany, the government took over energy supply after the war, and Bewag, which had supplied Berlin with energy since 1884, was forced to move its headquarters to the West. In the East, the state created its own energy company of the same name - Bewag-East, later renamed VEB Energiekombinat Berlin (EKB) (Vattenfall, n.d.-a). Until well into the 1970s, town gas was produced from lignite deposits in the GDR (Table 1) and used in East Berlin for heating and electricity generation. In 1977, government legislation led to the decision to convert East Berlin's energy supply to natural gas. This decision was preceded by the completion of the Soyuz natural gas pipeline from Siberia to Western Europe (2750 km), which provided a supply infrastructure (Bundesarchiv, 1981). The full supply of natural gas to East-Berlin was completed in 1990 having established a pipeline network of over 518 km in the GDR (Eggers et al., 1978). The energy regime and political regime in Berlin were strongly interconnected showing the dependency on the political will and cooperation of the Soviet Union. This pipline network later supports the emergence of hydrogen in Berlin’s energy system.

Table 1 Share of the most important energy sources in the primary energy consumption of the GDR (in percent)

Energy Source	Jahr				
	1950	1960	1970	1980	1984
Brown Coal/Lignite	zusammen	87,5	75,9	63,3	69,4
Stone Coal	über 99	9,1	10,6	6,4	6,1
Mineral Oil	—	2,5	12,6	17,3	10,7
Natural Gas	—	0,2	0,6	9,1	10,3
Nuclear	—	—	0,2	3,4	3,3
Other *(import, biomass, water)*	o. Angabe	0,7	0,1	0,5	0,2

The merged Berliner energy system

As a result of the political changes in Germany, Berlin was reunited with the fall of the Berlin Wall in 1990, which led to very dynamic reconfiguration processes among the energy actors in East and West. After German reunification, East and West German energy companies were reunited, and in 1991 natural gas supplies were extended to West Berlin. The EKB, renamed Berliner Erdgas AG (BEAG), was merged with the western Bewag in 1993, becoming the largest municipal gas supplier in Western Europe by partially incorporating GASAG into its operations (GASAG, n.d.). A chronic financial crisis in Berlin forced the government to partially sell its shares in GASAG to Bewag between 1993 and 1998 (Schuster, 2010). Since then, GASAG has been in private hands. The state of Berlin finally sold its Bewag shares in 1997, paving the way for privatization (Vattenfall, n.d.-a). The state-owned company was taken over and privatized by E.ON in 1997, shifting ownership from the Senate to private hands. E.ON sold its entire stake to Vattenfall Europe in 2003 (ibid., n.d.). In 2006, Vattenfall Europe completed its takeover by renaming Bewag Vattenfall Europe Berlin AG, under which name it still exists today. In October 2013, Berlin established a state-owned energy provider, Berliner Stadtwerke, which produces exclusively renewable energy from wind and solar. Its creation was decided by the House of Representatives, which initiated a years-long process of remunicipalization of Berlin's energy sector, as it was forced to sell its shares due to the financial crisis in 1997. The reason for this process is the concerns of the citizens and their demands for a self-determined, social and environmentally friendly energy supply, which were expressed in a referendum in 2013 (Berliner Stadtwerke, 2023).

It is clear that the reunification of Germany and Berlin was accompanied by entangled relationships and reconfiguration processes that are sometimes difficult to understand. Energy companies changed names and ownership quite often during these turbulent times. Reconfigurations had to be organized on all levels: political, economic, cultural, structural, and sociological, and were also initiated by social movements. Within these areas, certain actors play a significant role in the development of the energy system.

Developments in Berlin's energy mix until 2015

In 1990, Berlin obtained its primary energy from various sources, resulting in an energy mix of mineral oil (42.3%), coal (23.3%), natural gas (16.5%), lignite (13.5%), and renewable energy (0.6%) (Amt für Statistik Berlin-Brandenburg, 2022). Table 2 visualizes Berlin's primary energy consumption until 2015. Over the years, Berlin has increased its reliance on natural gas and drastically reduced its use of lignite. Hydrogen was used by industrial actors (e.g. fertilizer production), but remained a niche resource and technology due to its expensive production process. Compared to 1990, Berlin's energy consumption was 25.6% lower in 2015, demonstrating improvements in energy efficiency and technological innovation. The use of natural gas has increased (30%), while the use of mineral oil has decreased (36.3%). The increase in renewable energies can be seen in their energy production. In 1990, only 2251 TJ came from renewable energy and increased more than 5 times in 2015 showing an increase of 397.4%. Berlin has undergone electrification of the energy sector showing an increase of 129.7% compared to 1990. The plan of phasing out coal can also be observed in the figures with brown coal or lignite reduced almost 75% and black coal almost 50% of their primary use in 2015 compared to 1990.

Table 2 Primary Energy Consumption in Berlin 1990-2015 by Energy Source (Amt für Statistik Berlin-Brandenburg, 2022)

Year	Total	From that						
		Coal	Brown Coal	Mineral Oil	Natural Gas	Renewable Energy	Electricity	Others
Terajoule (TJ)								
1990	356 208	82 829	47 961	150 757	58 873	2 251	12 632	904,00
2000	331 518	83 968	13 072	132 802	85 639	2 455	12 060	1 522
2010	309 270	45 085	14 364	101 632	113 942	9 677	22 481	2 089
2015	264 998	39 810	12 173	96 021	79 418	11 200	24 300	2 076
Share of total PEC in percent								
1990	*100,0%*	23,3%	13,5%	42,3%	16,5%	0,6%	3,5%	0,3%
2000	*100,0%*	25,3%	3,9%	40,1%	25,8%	0,7%	3,6%	0,5%
2010	*100,0%*	14,6%	4,6%	32,9%	36,8%	3,1%	7,3%	0,7%
2015	*100,0%*	15,0%	4,6%	36,2%	30,0%	4,2%	9,2%	0,8%
Change compared to 1990 in percent								
2000	-6,9%	1,4%	-72,7%	-11,9%	45,5%	9,0%	-4,5%	68,4%
2010	-13,2%	-45,6%	-70,1%	-32,6%	93,5%	329,8%	78,0%	131,2%
2015	-25,6%	-51,9%	-74,6%	-36,3%	34,9%	397,5%	92,4%	129,7%

the regime after 2015.

The following description is intended to understand the more recent H_2 involvement of regime actors in Berlin. Several incumbent actors of the regime are influencing a hydrogen development through political, economic or social dynamics that also support new actors to join in the transition of Berlin's energy system.

National legislation such as the NHS lays the foundation for regional policy-making processes. For example, Berlin passed the Climate Protection and Energy Transition Act (EWGBln) in 2016 in which the city aims towards climate neutrality by 2050. The Berlin Energy Savings Act (BEnSpG) from 1990 laid the groundwork for the EWGBln legally binding the state to define trajectories, and targets to protect the climate and implement adaption measures in accordance with the Paris Agreement of 2015 (EWG Bln, 2016). Building on this law and a feasibility study the Energy and Climate Protection Program (BEK2030) was implemented in 2018 with measurements and strategies towards climate mitigation and adaption. In an interview with an employer of the Senate Department for the Environment, Mobility, Consumer and Climate Protection it has become clear that the sectors transport and private households are the most pressing ones to mitigate in terms of CO_2 reduction apart from the energy sector. Figure 5 shows that the energy sector is culpable of 40,8% of overall CO_2 emissions, followed by traffic (30,4%) and households and trade and services each around 13% (Amt für Statistik Berlin-Brandenburg, 2022).

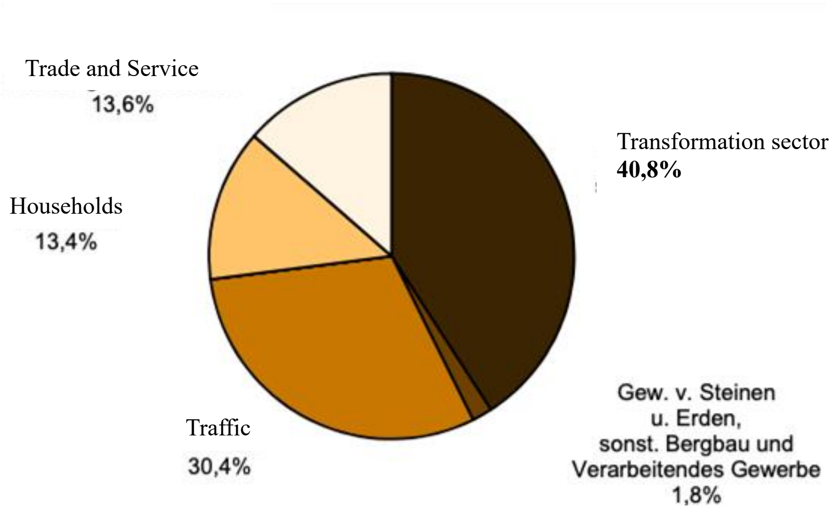

Figure 5 Share of Berlin CO_2 Emissions by Sector in 2020 (source balance) (Amt für Statistik Berlin-Brandenburg, 2022)

Even though a national program, Berlin benefits of the NIP II acting as a sponsor for the BEK2030 and enabling multiple subsidy programs carried out by the Senate Department for the Mobility, Transport, Climate and Environmental Protection (SenMVKU). Throughout the city hydrogen projects regarding energy storage, heating and electrification are supported (SenMVKU, 2023). In 2019, the now called innoBB2025 has been revised to fit national and regional climate goals as well as following EU guidelines that have been set since the Paris Agreement in 2015. The innoBB2025 strategy pushes topics such as digitalization and cooperation though specifically supports e.g., *Reallabore* and *Cluster Energietechnik* in the field of hydrogen. Since 2020 multiple legislation Acts related to energy saving, efficiency, dual use of heat and electricity, and the burning of waste have been renewed. This process has been sped up by external factors such as the Corona Pandemic in 2020 and the Russian invasion to Ukraine in 2022, former leading to energy efficiency measures and later to energy saving strategies. The EWGBln has been revised in 2021 with stricter goals now aiming at climate neutrality by 2045. In 2022 the BEK2030 has been extensively revised with a climate neutral goal by 2045 and a ramping up of the use of renewable energy, also including hydrogen into its plans. Political actors are dependent on and shaped by the voter. It has become clear that with climate change being a deeply political topic, political institutions seek out to reduce GHG emissions, create jobs and create trajectories leading to economic growth, prosperity, and social health. For this reason, it is in the interest of governmental institutions to look for clean energy alternatives that creates financial stability and provides social security to the citizens.

Berlin's **industry** makes the city a leader in energy, life sciences, information and communication technologies, microsystems technology and clean technologies (SenWEB, 2020). Companies such as *Vattenfall*, *GASAG* and *Berliner Stadtwerke* supply Berlin with electricity and heat. *Siemens Energy,* an energy technology company, produces steam gas turbines in Berlin and providing Vattenfall with Europe’s most modern combined heat and power plant (CHP) in 2020 (SenMVKU, 2023).

Compared to 1990, Berlins primary energy consumption in 2020 has shifted drastically away from coal (-73,2%), lignite (-98,9%) and mineral oil (-53,4%) towards an increased use of natural gas (74%) and renewable energy (543,7%) (Table 3). Exciting to see is the landscape pressure of the Corona Pandemic in 2020 as overall energy use has decreased due to the lockdown and its consequences on air travel and commuting[9]. The lockdown as well as phasing out of coal contributed to Berlin reaching its climate goals of the EWGBln reducing their emissions more than 40% in 2020 compared to 1990 (SenWEB, 2020b).

[9] Air travel also has been identified in the EWGBln as key component on the way of decarbonizing the transport sector. In 2020 Berlin’s air travel was responsible for around 397.000 tons showing a decrease compared to the year before with almost 1,5 mil. tons of CO_2 (Amt für Statistik Berlin-Brandenburg, 2022).

Table 3 Primary energy consumption by energy source in the state of Berlin (adopted from Amt für Statistik Berlin-Brandenburg, 2022a)

Year	Total	From that						
		Coal	Brown Coal	Mineral Oil	Natural Gas	Renewable Energy	Electricity	Others[10]
Terajoule (TJ)								
2016	272 123	36 894	12 412	97 315	88 557	11 221	23 386	2 337
2017	270 557	37 167	6 047	96 234	94 794	11 570	22 298	2 447
2018	266 504	30 494	553	93 865	100 536	13 928	24 567	2 561
2019	264 307	20 744	445	94 044	104 748	14 796	26 389	3 140
2020	233 208	22 229	551	70 313	102 423	14 493	20 717	2 482
Share of total PEC in percent								
2016	*100,0%*	13,6%	4,6%	35,8%	32,5%	4,1%	8,6%	0,9%
2017	*100,0%*	13,7%	2,2%	35,6%	35,0%	4,3%	8,2%	0,9%
2018	*100,0%*	11,4%	0,2%	35,2%	37,7%	5,2%	9,2%	1,0%
2019	*100,0%*	7,8%	0,2%	35,6%	39,6%	5,6%	10,0%	1,2%
2020	*100,0%*	9,5%	0,2%	30,2%	43,9%	6,2%	8,9%	1,1%
Change compared to 1990 in percent								
2016	-23,6%	-55,5%	-74,1%	-35,4%	50,4%	398,4%	85,1%	158,7%
2017	-24,0%	-55,1%	-87,4%	-36,2%	61,0%	413,9%	76,5%	170,9%
2018	-25,2%	-63,2%	-98,8%	-37,7%	70,8%	518,7%	94,5%	183,4%
2019	-25,8%	-75,0%	-99,1%	-37,6%	77,9%	557,2%	108,9%	247,5%
2020	-34,5%	-73,2%	-98,9%	-53,4%	74,0%	543,7%	64,0%	174,7%

Berlins energy sector has already significantly shifted most of its primary energy consumption to natural gas and renewable energy over the past decades. As of 24th May 2017, Berlin has phased out of brown coal/lignite completely with Vattenfall shutting down its last coal powered plant and shifting towards natural gas (Vattenfall, n.d.b). The same year Vattenfall completed a new CHP plant able to use hydrogen for energy production. To reach the goal of the EWGBln of becoming climate neutral by 2050 Vattenfall conducted a feasibility study in 2019 of phasing out of coal by 2030 and found hydrogen to be included in their hybrid CHP as a substitute for natural gas (BET, 2019). Vattenfall, as Berlin's primary energy provider, has reduced its GHG emissions by half in 2020 compared to 1990 with efficient CHP-plants in the city. With the revision of the EWGBln in 2021 hydrogen received a revitalized role in the heating sector.

The same year Berlin's heat has been sourced from 77.1% natural gas showing the theoretical potential for emission reduction using clean hydrogen and by 2040 they plan to provide Berlin with climate neutral heat (Vattenfall, 2022 in Figure 6). Vattenfall have sold the electric grid

[10] heat, fossil waste

operations back to the state of Berlin thus focusing on heat production and hot water. Other energy companies in Berlin have similar plans though all acknowledging challenges such as a missing hydrogen infrastructure, its expensive production process and sufficient storage options (ibid.). The main actors of the energy regime in Berlin (Vattenfall, GASAG) both see hydrogen as a key resource in decarbonizing the energy sector in the future and have published their ambitions on their website to include H_2 into their energy strategy. The SenMVKU has come to a similar conclusion and calling for a rapid electrification of the heat supply through the integration of renewable energy and feed-in of H_2 into the existing gas network.

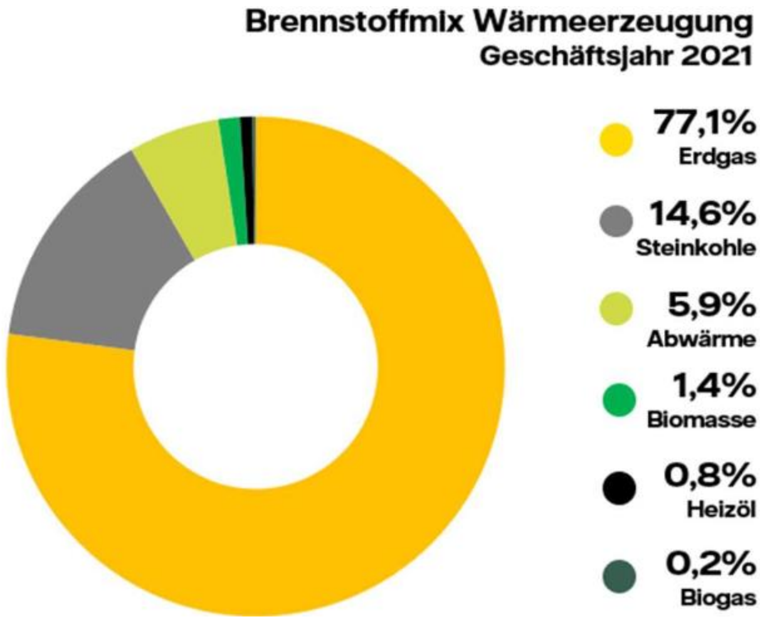

Figure 6 Vattenfall Fuel Mix Heat Generation Berlin 2021 (Vattenfall, 2022)

In 2022 Vattenfall has published that all CHP plants will be made "hydrogen-ready" in which a mix of natural gas and hydrogen will enable a successive reduction in GHG emissions. This shift to hydrogen seems convenient as Vattenfall's main energy source has been natural gas[11].

The ministries are funding hydrogen projects in Berlin to the tune of billions of euros through NIP II acting as political **investors**. Scientific institutions receive grants for research into fuel cell technology, for example, while the implementation of hydrogen refueling stations or the production of electrolyzers is supported (NOW GmbH, n.d.). In the big picture, in 2023 the

[11] Both hydrogen and natural gas having similar properties when it comes to the application in the energy sector. The NHS mentions the combined use of clean H2 and natural gas for district heating as with a 20% hydrogen share only minor changes would have to be made.

foundation H2Global has started their work with the aim to protect the environment through the planning, coordination and distribution of green hydrogen. Over 50 actors in the transport, energy and banking industry (e.g., Deutsche Bank, thyssenkrupp, DaimlerTruck, bp etc.) are acting as donors as well as the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The purpose is to overcome a so-called "chicken and egg dilemma" in which a lack of investment and availability of green hydrogen leads to market failure resulting in a slow-moving ramp-up of hydrogen. The idea is to purchase long-term contracts on the supply side and short-term sales contracts on the demand side. The difference of supply and demand prices will be backed by donors of public or philanthropic nature (H2Global, n.d.).

Further investments solidify in forms of policies like the EWGBln and the BEK2030, paving the way for a hydrogen roadmap in which green hydrogen is seen as an opportunity for climate protection through economic prosperity, political cooperation and technological progress. Hydrogen is seen as a resource that can be used in sectors that are hard to abate, as an interview with Sunfire GmbH shows. Sunfire, one of Europe's largest manufacturers of industrial electrolyzers and funded through and important investor, the EU with 'Important Projects of Common European Interest' (IPCEI), sees the potential of hydrogen in industrial applications such as steel and concrete production. Since the production of green hydrogen is still expensive, its main application is foreseen in niche sectors that cannot be electrified. Therefore, the transportation sector, and especially residential heating, is not seen as a driver for green hydrogen in the future, as it would be an inefficient and expensive use of green electricity (Endres, 2022). Despite such predictions, clean hydrogen is still planned for the heating and transport sectors once a breakthrough is achieved in the Berlin Hydrogen Roadmap.

With hydrogen receiving attention for being and becoming the fuel of the future, it has also led to increased research into its application and storage possibilities (Tarhan & Çil, 2021). **Research institutes** like the *Rainer-Lemoine-Institute* act as intermediary between politics and the industry by conducting feasibility studies for hydrogen in Berlin and provide scientific research on innovative clean technology. The *Fraunhofer Institute for Production Systems and Design Engineering* in Berlin is researching on fuel cell electric vehicles (FCEV) having received a grant of over 80 mil. from the ministry of transport (Fraunhofer IPK, 2022). The *TU Berlin* is also an example of a scientific actor pushing innovation in clean technologies. Public and private universities and independent research institutes benefit from the second largest

share of the city's gross domestic product (GDP) devoted to research and development (R&D). Such investments in R&D enable cooperation among the actors. (SenWEB, 2020a)
In 2018 the Rainer-Lemoine-Institute founded a digital '*H2-marketplace'* with help of the Senate Departments in which the supply and demand of hydrogen in Berlin and Brandenburg is coordinated. This cooperation derives from the hydrogen roadmap of Berlin and Brandenburg and aims at coordinating a sustainable hydrogen value chain amongst private and public actors. Research institutes are an intermediary for pushing hydrogen innovation in the transport and energy sectors as they conduct feasibility studies that show the potential of H_2 in Berlin.

Public actors like **social movements** have had immense influence since the success of *Fridays for Future (FFF)*. In 2019 the FFF movement has gained momentum in Germany ultimately pressuring the government to implement stricter regulations and more ambitious climate change goals. They are now considered a loud voice for the concerns of the young generation. Social movements are an important factor in pushing referendums such as "Berlin 2030 climate neutral". This referendum was pushed by a citizens initiative called *Klimaneustart (*engl. Climate start-up) showing public engagement. Even though the referendum failed in 2023, it shows that stricter climate protection measures are wanted by the citizens and thus acting out pressure on the political regime.

The dynamic of regional actors in Berlin is deeply intertwined with national actors such as the Federal Ministries. Based on national laws and programs such as the NIP II, the National Hydrogen Strategy (NHS), the Renewable Energy Act (EEG) or the Federal Climate Protection Law (KSG), the Berlin Senate administrations create policies that integrate the national goals into regional legislations. These legislations, inter alia, the Berlin Energy and Climate Protection Program (BEK2030) and the Berlin Energy Transition Act (EWGBln), in turn enable regional programs that support and monitor the funding and progress of hydrogen technology across sectors in Berlin. These programs are oriented at executing the measurements agreed in regional legislations and strategies. In this context, the Multi-Level Governance structure and its impact on sustainable urban transition (SUT) becomes clear.

4.3. Hydrogen developments in Germany and Berlin

the niche before 2015.

Hydrogen is not a new technology but has been around for more than 200 years, picking up momentum as a niche technology in the 1960's (Schmidt-Achert & Pichlmaier, 2021). In the 1970s, the oil crisis in 1973/74 forced Europe to look for alternative energy technologies. The funding of hydrogen technology research and development projects increased around the world (IEA, 2019). In the 1980's and 90's hydrogen was part of demonstration projects like the German-Saudi Arabian project HYSOLAR or the Solar-Hydrogen-Project in Neunburg (ibid.). The latter being the first solar-powered hydrogen production plant worldwide (ibid.). However, despite progress in research on fuel cells and hydrogen technologies, it remained a high-cost solution with consumption restricted to niche applications, such as for fertilizer production and as rocket fuel in the space industry. Nevertheless, the international oil crisis shows how landscape changes had direct influence on progressing hydrogen as a niche through upscaled industrial and governmental funding of experimental research projects.

At the turn of the millennium, hydrogen technology again gained momentum. In 2000, major German transport and energy sector industry actors, supported by the Federal Ministry of Transport, took initiative to a new Transport Energy Strategy (VES) – included in the initiative were transport sector actors such as BMW, DaimlerChrysler, MAN and VW and the energy companies Shell, ARAL and RWE (Bundesregierung, 2000, p. 34). The aim was to develop a fuel-independent fuel to be produced from renewable energy and that would reduce the CO_2 emission along the entire production chain (ibid.). Hydrogen was evaluated as the fuel with the highest potential and became focus of further research. As a result, the *Clean Energy Partnership* (CEP) was launched in Berlin in 2004. The CEP included setting up two hydrogen fuel stations for 17 vehicles in Berlin and pilot demonstration of hydrogen buses in the public transport system. The Federal Ministry of Transport (later: Federal Ministry of Digital Affairs and Transport) was sponsor of the CEP from the start through the NIP I program.

The BVG, the main actor of Berlin's public transport system, and a new member of the CEP in 2010, included four hydrogen powered buses into their fleet. Hydrogen production was produced decentral, and supplied to the fuel stations. The CEP evolved by involving new actors, extending the network of hydrogen fueling stations in Germany and by planning introduction of new hydrogen powered vehicles (Linde Group, 2010). The CEP established a framework for testing and experimenting with hydrogen technology in and pilot projects to demonstrate the potential in the transport sector. Though only focused on hydrogen in the transport, its research contributed also with feasibility studies and to solving challenges in production of green hydrogen and its infrastructure (BMDV, 2012).

Connected to these development efforts, also more social networks started to emerge in Berlin. Such networks are an important factor in niche developments as they coordinate common causes while simultaneously creating competitiveness which drives down the price of the technology. In 2011, Berlin and Brandenburg adopted the “Joint Innovation Strategy of the States of Berlin and Brandenburg" (innoBB) aiming to lay the foundation for clusters to form across sectors and work towards innovative solutions in all fields. This cooperation amongst the states enabled the foundation of the network *Cluster Energietechnik* with the aim to expand the region Berlin Brandenburg as an “attractive and competitive location in the field of energies and energy efficiency technologies” (SenWEB, 2022). It represents the door between the sectors of science and economy through research and investment and in this context, supported by third party actors like political institutions, NGO’s, public administrations, and other networks. Energy (hydrogen) providers, small and medium enterprises (SME), universities and research institutions, infrastructure developers and urban planners, and multiple networks incorporate the cluster. As a result, projects in hydrogen distribution, production, storage, and consumption were tested, but also a digital platform ‘*localizer*’ was created for coordinating a hydrogen value chain and to facilitate a hydrogen-infrastructure into Berlin’s and Brandenburg’s urban setting.

Hydrogen projects in the energy system of Berlin the niche after 2015.

Even though hydrogen has been vastly discussed in political debates and in the industry its development and implementation remain a niche phenomenon. Hydrogen technology has reached multiple sectors in Berlin e.g., the transport sector, the heating sector and energy sector, inter alia. Apart from pilot projects and experimentation its commercialization is just a reality on paper. However, there are some significant developments in Berlin that drive a H_2 innovation towards a possible breakthrough. One finding of my interviews with representatives of the Senate Department and a representative of Sunfire GmbH is that green hydrogen as a clean resource experiences a momentum not only as fuel in the transport sector but especially in the hard-to-abate sectors e.g., energy production and industry.

While hydrogen was a resource that has been part of R&D for fuel cell technology in the transport system, it gained relevance after 2015 as a means for storing and transporting renewable energy. Storage and transport of energy is of utmost importance in Berlins energy system since it mainly relies on energy imports, as the interview with H2Berlin concluded. Because of the intermittency of renewables, the role of storing peak energy and transporting it through hydrogen becomes one of Berlins biggest challenges but also biggest opportunities in transitioning into a sustainable energy supply. Berlin's vast pipeline network supports this development, being able to store around 8 times more energy as the current electricity grid as well as being flexible in its supply. H2Berlin (further mentioned below) recognizes the pipeline network as an advantage rather than a lock-in mechanism which would bind Berlin to natural gas in the future. This advantage towards electrifying has led to plans in expanding the pipeline network around Berlin and throughout Germany.

As net-zero targets became binding with the Paris Agreement, the KSG and the EEG made clean hydrogen part of the future energy portfolios of companies like Vattenfall and GASAG, especially in hard-to-abate sectors (e.g., steel production). Such sudden interest boosted social networks like *Cluster Energietechnik* pushing cooperation across sectors. With the implementation of the NHS hydrogen has sparked the creation of hubs and networks in Berlin. In 2020 the foundation *H2Berlin* started their work in identifying projects to replace fossil fuel solutions with hydrogen. Together with inter alia Vattenfall, GASAG and Berliner Stadtwerke they work towards the implementation of hubs throughout the city targeting the production, storage and distribution of clean hydrogen across all sectors. They have also partnered with research institutions such as the Fraunhofer Society or Max-Planck Society as well as with a Berlin university TU Berlin or the Berlin Fire Department, amongst others (H2Berlin, n.d.).
In 2020 they published the study "Hydrogen Potential in Berlin 2025" which has been used as a reference for many actors in the energy and transport sectors.

Though hydrogen cars are already on the road with *Berlin City Sanitation* (*BSR)* (BSR, 2021), but so far fail to take over due to the high cost of green hydrogen production, thus only functioning as a pilot project. This high cost is also condemned by multiple interview partners both from the Senate Departments and Sunfire and are expected to continue at least until 2030. In its heating strategy from 2021 the SenMVKU has analyzed implications for a hydrogen use in a climate protection scenario (Table 4) in which 100% of Berlins heat would come from climate neutral gas. The scenario shows that hydrogen could be around 11,4% in 2040 and 36,8% of the overall gas mix by 2050. As comparison, a business-as-usual in the current heating policies of Berlin would mean a gas mix share of 3,5% and 7% in 2040 and 2050, respectively (Dunkelberg et al., 2021). Such difference in scenarios shows the importance of policies on a hydrogen breakthrough in Berlin for the following decade.

Table 4 Composition of Berlin gas mix with a Climate Protection Scenario (Dunkelberg et al., 2021, p. 114)

Zusammensetzung des Gas-mix (in Energieprozent)	**2020**	**2030**	**2040**	**2050**
Biomethan	2,5%	5,0%	19,0%	37,2%
Wasserstoff	0,0%	0,0%	11,4%	36,8%
Synthetisches Methan	0,0%	0,0%	6,3%	26,0%
Erdgas	97,5%	95,0%	63,3%	0,0%
EE-Gas in GWh	400	546	1.998	2.642

Most hydrogen projects in Berlin are looking to use green hydrogen rather than producing it emphasizing the vulnerability of a hydrogen ramp-up and its challenges. The production of green hydrogen is experimented with start-ups in the energy sector such as *greenbox* or *HH2E*. In 2023 *HH2E*, a start-up for producing green electricity, heat and hydrogen through retrofitting and building new power plants, has announced the production of green hydrogen power plant in Berlin by 2027 (Senate Chancellery, 2023a). The goal is to produce green electricity from wind and solar, using hydrogen as a stored energy resource to counteract the volatility of intermittent renewables.

In 2023 Toyota provided Berlin with 200 hydrogen cars used for the mobility service company Uber. Over a two-year trial named 'H2 Moves Berlin' these hydrogen-cars will run on 50% grey and 50% green hydrogen (H2 Moves Berlin, n.d.; Hydrogeninsight, 2023). In the center of Berlin H2 Mobility opened one of the most efficient H_2 fueling station in Europe providing the fleet of H2 Moves Berlin and the BSR with hydrogen. This company, founded by actors of the transport and energy regime (inter alia, Daimler, Shell, TotalEnergies, OMV) and funded through the NIP II, are responsible for supplying all hydrogen fueling stations across Germany.

Also, favorable sites in Berlin are identified where green hydrogen can be produced. Berlin Tempelhof, a former now decommissioned inner city airport, provides space for wind and solar energy in combination with hydrogen production, and is promoted through the digital H2 marketplace as a renewable energy site. *Greenbox* aims to produce green electricity and green hydrogen through independent solar and wind energy modules (H2 Marktplatz, n.d.). In addition to these niche developments, Berlin has pushed clean hydrogen development especially by providing subsidy programs in the fields of storage, fuel cell and heating (SenMVKU, n.d.). These programs are part of the measurement plan of the Berlin Hydrogen Roadmap and the BEK2030.

Concluding the niche developments of hydrogen, it becomes clear that it has experienced a ramp-up especially in the transportation sector, while in the heating industry it remains a planned resource to come after successful nationwide infrastructure and implementation of definition, norms and standards enabling a hydrogen market and thus commercialization across all sectors.

4.4. The hydrogen roadmap for Berlin

drivers and barriers.

A common thread that emerges from the interviews is that there is a lack of regulations and laws to bring about the hydrogen breakthrough quickly. The chicken-and-egg problem, which is that expensive hydrogen production prevents companies from making the investments now that are needed to create demand in the future, prevent a rapid hydrogen ramp-up in the coming years, also due to the lack of appropriate infrastructure. Solutions to this problem have been presented through the establishment of H2 Global, which creates a safety net in which the margin between supply and demand is initially covered by government funds to create a hydrogen ramp-up. This would be facilitated by a hydrogen marketplace, uniform standards and definitions that would lead to trade not only within the country but also across international borders. Such ambitions are manifested within the hydrogen roadmap of Berlin showing a recognition of such barriers and drivers within the city.

Hydrogen strategies have been formulated not only by governments but also by cities and individual actors within the urban environment. Next to a hydrogen development in R&D and the ongoing pilot projects in the transportation and energy industry of Berlin, a hydrogen breakthrough has developed much more on paper than it has in real life. H_2 is emerging as an inevitable resource in the strategies and goals of political agencies and industrial actors like the Berlin Senate and Vattenfall, whose visions include rapid expansion of hydrogen in urban areas from 2030. Those visions include individual measures in the fields of production, infrastructure, storage, distribution and application in the urban setting (Landesarchiv Berlin, n.d.; MWAE & SenWEB, 2021; Vattenfall, n.d.b). A break of the Chicken-and-Egg Dilemma and a breakthrough for Berlin would require developments in not only Berlins but also Germanys infrastructure, H_2 production (supply), distribution, storage and implementation (demands). Following shall give a brief overview of Berlins planned and necessary developments mentioned in their H2-Roadmap to ramp-up hydrogen across sectors. It incorporates the concerns and visions of actors of the Berlins energy system, including its industry and transport actors.

Production

The production process of H_2 should be met with high investments of both private and public actors. Therefor, financial security is necessary to start production by national and regional actors. Another concern brought up in the interviews as well as in the hydrogen strategy of Berlin is the technical improvement potential especially in industrial production processes of electrolyzers. Legislation and framework conditions may lay the groundwork for pushing hydrogen and showing a solution out of the 'Chicken-and-Egg Dilemma'. As seen with EU legislation and its impact on national strategies, policies can take an essential role in providing guidance and planning security for industrial, private as well as public actors in the energy sector. Challenging is also the supply of renewable energy which must undergo a ramp-up as well if it is to provide enough electricity for green hydrogen in the future.

Infrastructure

A common barrier to hydrogen breakthrough was found to be lacking infrastructure. With German plans to increase the transmission system for natural gas and ultimately hydrogen, Berlin is set out to be connected to the national network and directly supplied through the European Hydrogen Backbone (EHB) initiative by 2030 with further expansion until 2050 (MWAE & SenWEB, 2021).

The national hydrogen network maps for 2030 and 2050 show the evolution that would follow a breakthrough (Figure 7, Figure 8). The network connects important industrial clusters in the west and north securing import routes to the Netherlands, Denmark, North Sea and the Baltics whereas in the south and east the network expands to Belgium, France, Poland and the Czech Republic by 2050 (FNB Gas, n.d.). The solid green lines represent converted natural gas pipelines as well as parallel running H_2-pipelines whereas the dashed lines are newly built hydrogen pipelines. Both maps show a scenario in which the national H_2 requirements of the NHS (90-110 TWh) are met for both consumers and producers (ibid.).

Specifically for Berlin, that means developments are yet to be made. The city is planning to connect their hydrogen demand to the national network and prepare the industries and regional network operators for a hydrogen supply by 2030. The limit value for admixture is currently up to 10 percent by volume according to the German Technical and Scientific Association for Gas and Water (DVGW) regulations (MWAE & SenWEB, 2021). Resulting from the interviews with both the Senate Departments and industry actors it has become clear that this regulatory framework is seen as a barrier and must be changed to provide planning security for industrial actors. Furthermore, the costs of infrastructure are seen as a potential barrier that must be covered by investment security.

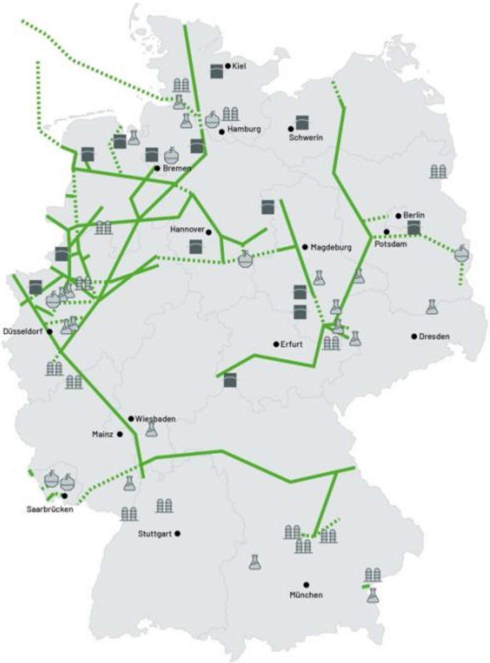

Figure 7 Hydrogen Network 2030 (FNB Gas, n.d.)

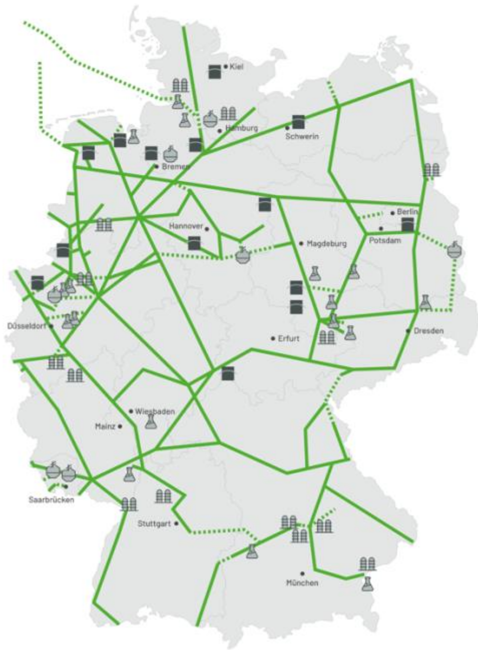

Figure 8 Hydrogen Network 2050 (FNB Gas, n.d.)

Storage

The storage of energy not only for sector coupling but also for a green energy transition of the energy sector is one of the biggest challenges but also greatest opportunities of SUT. Especially when using intermittent renewable energy, this 'breathing' of the renewable energy supply must be countered with effective and efficient energy storage of which hydrogen can solve multiple challenges for the electricity and heating sector simultaneously.

Since Berlin has limited space concerning storage it must evade to its neighboring state Brandenburg. There, a salt cavern has been tested for impermeability over the last years and has begun its preparation phase for testing hydrogen storage. In context of the IPCEI project 'Doing Hydrogen' it is supposed to be connected to a H_2 pipeline from Rostock in 2026 (H2Berlin, 2020). Stored hydrogen would enable Berlin to regenerate renewable electricity in times of low solar or wind generation. A concern though is the topic of safety which the roadmap is tackling through public education on hydrogen risks and innovation in storage technology. Public opinion can have a leading effect on a hydrogen breakthrough, in which negative experiences (explosions, range anxiety) could become a barrier towards a commercialization of the technology (MWAE & SenWEB, 2021). A negative experience such as range anxiety could be countered with a balanced distribution of fueling stations. Safe and educated storage of H_2 must be always provided for a successful breakthrough across all sectors in which not only industrial actors but private and public actors profit from renewable energy.

Distribution

Once storage is provided its distribution must occur to penetrate the consumer market. Though this means two different things for industrial and private actors. Industrial actors are to be directly connected to the EHB through a pipeline network whereas private actors and consumers need local distribution through fueling stations.

Industrial actors like energy companies and steel producers with high possible demand in the future are to be connected directly to the hydrogen network EHB. This requires a revision of the DVWG regulations enabling higher volume percentage in natural gas pipelines as well as newly constructed pipelines (ibid.). Private actors especially for the transportation sector require sufficient fueling stations with possible local production opportunities. Distribution thus means the accessibility for industrial and energy actors through a connection to the EHB and a network of fueling stations for tucks and transport vehicles in the city at which hydrogen can also partly be produced locally.

Implementation

Given the production, infrastructure, storage and distribution of H_2 in Berlin, its implementation ultimately is key to breaking H_2 technology into the energy regime. This implementation must be guided by incentives for consumers (subsidies and tax cuts on hydrogen technology e.g., H_2-cars, heating system etc.) and a legislative framework to support a smooth ramp-up also for new actors (start-ups, pilot projects) to penetrate the market. No-regret investments are necessary to signal readiness on the demand side. Green hydrogen is planned at the Berlin airport BER airport in small projects involving on ground services. Decarbonizing the transport, heating and electricity consumption of BER is currently underway with H2Berlin as the main partner (Enlit, 2022). Hydrogen production is planned in the west of Berlin through wastewater pyrolysis and a future connection to the European Backbone project by 2030 (ibid.).

A key takeaway from the interview with Sunfire is that so-called 'no-regret' investments are already done by industrial actors with the anticipation that a regulatory framework by Berlins government agencies will ultimately favor a hydrogen breakthrough from 2030. Hydrogen producers but also actors around its production, such as Sunfire, are calling for a rapid framework under which hydrogen can also be traded.
The roadmap envisages that startups and new actors will also facilitate the introduction of hydrogen through financial incentives from the senate administrations (ibid.). Such incentives come in form of funding projects as well as favorable conditions for hydrogen actors such as tax cuts and subsidies. Another measure to be taken is the consistent pricing of carbon (EU ETS). Carbon tax has continuously increased showing a the potential in financing renewable energy investments (Dushime, 2021). Furthermore, the roadmap reinforces the plan to increase investments in fuel cell and hydrogen technologies via the NIP, for example.
The implementation phase must therefore be supported by government policies and the willingness of niche actors. The implementation of hydrogen in Berlin has already begun and must follow a simultaneous phase-out of fossil fuel alternatives in the transportation and energy sectors.

The fact that one condition cannot live without the other makes up the core of the Chicken-and-Egg Dilemma acting as a barrier for a hydrogen breakthrough in Berlin. For this reason, the conditions for a successful breakthrough prompt a simultaneous review of all measures across sectors of the Hydrogen Roadmap for Berlin.

4.5. Summary of empirical analysis and main results

Since the mid-20th century, Berlin has been shaped by post-war developments in German politics as well as by landscape changes such as the oil crisis of the 1970s, the explosion of the nuclear reactor in Chernobyl, and the incisive events of the construction and fall of the Berlin Wall. These changes have impacted the energy system and incumbent regime actors in a way that new ways of energy production through locally produced city gas had to be organized, thus during its division concentrating the energy production in Berlin on coal and mineral oil in the West and imported natural gas in the East.

When looking at the MLP conceptual model (Figure 9), the period from 1990 until 2015 can be visualized with phase 1 in this framework. Throughout this period actors of the fossil fuel industry have benefitted of reproduction processes manifesting in e.g., infrastructure projects, lock-in mechanisms etc. the incumbent regimes of the energy system. Even though politically turbulent during the 1990's, consequences of the fall of the Berlin wall or Chernobyl can be seen as landscape developments putting pressure on the regime in Germany and Berlin though leading to energy alternatives that still rely on fossil fuels. Even though hydrogen has been a part of Berlin's energy mix since the 50's its production was through the burning of fossil fuels and was more a byproduct than a planned energy resource. Dynamics on the landscape level have evidently pressured the regime to adapt its energy use as the beginning of nuclear and coal phase out shows. In the 2000's first hydrogen projects have been developed with political and industry actors. Hydrogen started to evolve at the niche level with pilot projects in Berlin supported by the transport sector. This interest of the transport sector was supported with national programs such as NIP I and the CEP. Investment into R&D as well as conducting studies for the feasibility of hydrogen have pushed its technology in the urban development of Berlin. Though goals were not fully reached regarding hydrogen infrastructure and commercialization of hydrogen powered vehicles, these developments have manifested the potential as a carbon neutral fuel and included the resource in legislation such as the NIP I thus pushing further innovation.

The developments of Berlin's energy sector over the past 5 decades show reconfiguration processes and even transitions from lignite to natural gas. When looking at hydrogen technology, it has remained at the niche level where it has been experimented with and invested in by incumbent regime actors of the transport sector. During the time where hydrogen has come up as a niche development, even when incumbent regime actors has invested financial resources on its innovation, they kept the status quo regarding the energy production. Geels call this the 'reproduction' phase (phase 1).

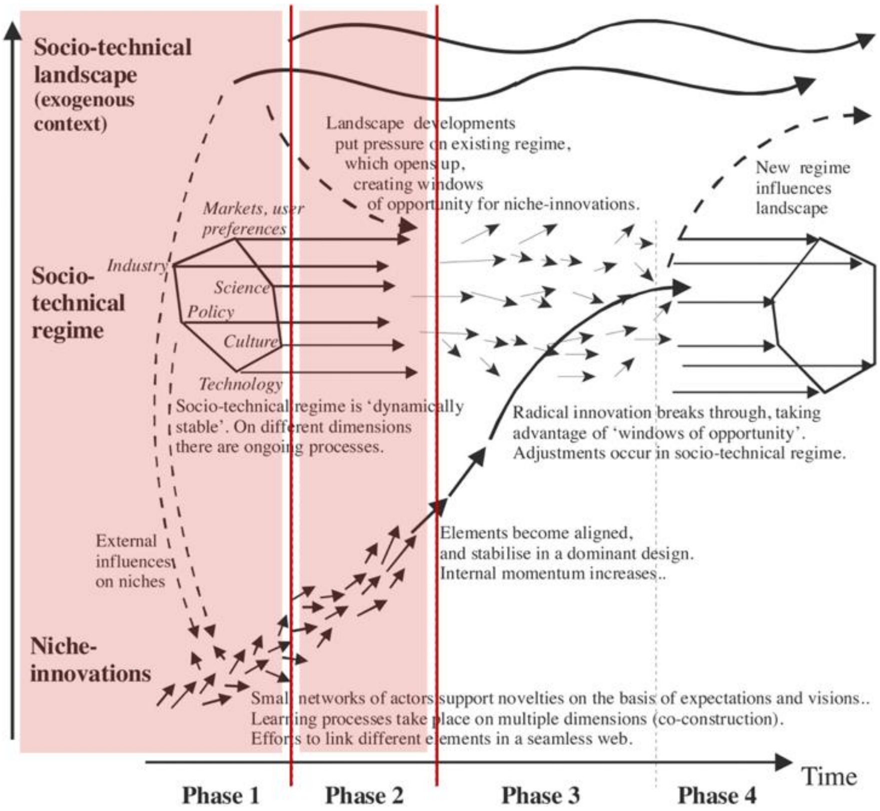

Figure 9 Socio-technical Transitions in Phases 1 and 2 of the MLP

The post-2015 period is marked by an increase in legislation supporting hydrogen deployment in the city, leading back to the effects of the Paris Agreement. The revision of existing climate policies in Berlin and the adoption of EU policies, ultimately leading to national hydrogen strategies and regional roadmaps, laid the foundation for pilot projects to gain traction in Berlin. Even though hydrogen has become an essential part of the future energy portfolio of energy system actors, its momentum is mostly felt in the transportation sector. Projects with the BSR, filling stations, and "H2 Moves Berlin" hydrogen development is clearly dominated by R&D in fuel cell technology. Concerning the energy sector hydrogen has been included in every mayor energy actor's energy portfolio aiming to use it by 2030 onwards. Vattenfall and GASAG both have included hydrogen into their energy portfolio as they aim to become climate neutral by 2040. The developments on the landscape, regime, and niche levels can be seen in Figure 10.

drivers and barriers at the different levels.

Looking at the transformation of the energy system over time reveals some drivers and barriers. On the one hand, political cooperation between West Berlin and the Allies and East Berlin and the Soviet Union drove the energy sector to adapt quickly to the changing landscape. The allocation of resources by the Allies and the Soviets was crucial for Berlin to maintain an energy flow, especially after the end of World War II. Also, the infrastructure of an extensive pipeline network that was built later made natural gas cheaper and thus more accessible. Although this transformation does not include the introduction of hydrogen, it shows the driver that inspires a transition process in the future - a potential H_2 infrastructure.

Nevertheless, the division of the city and its actors made it impossible to find a common strategy for a transition. Actors in East and West had to look for individual solutions, making cooperation almost impossible and delaying the transformation process. Lock-in mechanisms, such as the existing infrastructure of coal and lignite power plants and their local production, made the transition to more environmentally friendly alternatives more difficult. In addition, households and the commercial sector were not equipped for natural gas heating until the late 1990s.

The Fall of the Berlin Wall certainly is the key driver in bringing together main actors in the energy and political regime. Germanys reunification after 1990 sparked a complete reboot of Berlins political, cultural, social but also industrial and energy sectors by creating a synthesis of both east and west structures into a newly itself reinventing city. With a series of national policies acting as external institutional landscape factors, Berlin also followed with laws such as the EWGBln or the BEnSpG creating environmental awareness amongst political and industrial actors. These developments immediately after the Fall of the Berlin Wall make it a key driver in the energy system transition.

In the 1990s, the effects of the oil crisis and Chernobyl were still being felt in social movements thus crystalizing environmental awareness among citizens, and the call for a nuclear phase-out, leading to the founding of today's Green Party (Bündnis 90/Die Grünen). The role of renewables gained an increasing importance leading to and interests in a climate-friendly energy supply. This has created a dynamic in the political regime that has led to more renewable energy in the energy sector.

Infrastructure projects such as the Soyuz pipeline or Nord Stream 1 can be seen as both a driver and a barrier. Such infrastrucuture is usually considered as a barrier as it represents a lock-in mechanism, preventing rapid changes in the energy system of Berlin. In the case of transitioning away from the more emission heavy coal, they can be seen as a driver towards more sustainable urban development. But also, they represent a lock-in mechanism that increases dependency and reduces the chances of novel hydrogen technologies to replace the incumbent regimes. The same is true of the oil crisis in the 1970's, which affected Germany's natural gas imports and led to an increase in the supply of nuclear power, albeit accompanied by a surge in anti-nuclear movements and opposition. But in Berlin's case, the pipeline network is seen as the driving force, as the interviews show. Due to the similar properties of hydrogen and natural gas, Berlin is working on increasing the share of hydrogen in the natural gas mix and hopes for a full conversion in the future.

Policy as an instrument for driving innovation was an important driver for the promotion of hydrogen technology in Berlin, as can be observed through the Clean Energy Partnership (CEP) in the early 2000's. Niche development of hydrogen was pushed by goal setting of governmental institutions together with lobbying by incumbent regime actors of the transport sector. These actors eventually formed a cluster with the goal of developing hydrogen in Berlin. However these efforts, efficiency of combustion engines was much higher than other fuel cell technology and electric motors at the time leading to the manifestation of the incumbent regime actors.Furthermore, the financial crisis of 2008 has also put environmental policies on hold and may have hindered investment in hydrogen projects. The nuclear disaster in Fukushima raised nationwide concerns about German nuclear power plants and the issue of nuclear waste, leading to a radical turn in the *Energiewende* and a greater focus on renewables in Germanys energy supply.

The Paris Agreement can be seen as having the greatest impact on national and regional policies. Since its adoption, the binding agreement has been the source of inspiration for climate-friendly transition processes across sectors and continues to do so. It has sparked investment in renewable energy, including hydrogen thus indluencing it directly at the niche level. The Agreement is also the initial driver for revising old laws and climate legislations and continues to spark stricter regulations on national and regional levels until today with e.g., the National Hydrogen Strategy, the NIP II, the Berlin Energy Transition Act or the Berlin Energy and Climate Protection Program 2030.

The energy crisis caused by the Russian invastion into Ukraine can be seen both as a driver and barrier for H_2 in Berlin. With rising natural gas prices, the price of blue hydrogen has gone up as well compromising a H_2 momentum and leaving space for more reliable energy sources found in fossil solutions. While legislative frameworks caused by the corona pandemic and the war have improved hydrogen development in Germany (LNG Acceleration Act with hydrogen ready terminals), the consequences of both pressures might have long lasting effects on the hydrogen market.
However, the war has also sparked new discussions about energy resilience and the use of hydrogen for energy storage. It shows that hydrogen can play a key role in the energy crisis, as its storage and transportation offer opportunities for energy independence. Global hydrogen competition between the USA and Europe leads to EU legislation like REPowerEU and its strategies with the European Hydrogen Backbone. In face with the Inflation Reduction Act more ambitious legislation has been agreed upon in the REPowerEU leading to stricter revisions in Germany (KSG) and Berlin (EWGBln). In this sense, competition is a driver causing legislations in setting up a framework under which a hydrogen rollout can successfully be managed.

In conclusion, based on the pressure of the landscape, the energy system in Berlin has adapted by phasing out coal and formulating strategies and roadmaps that include hydrogen for decarbonization as national and regional legislation dictates a drastic reduction of GHG. Although hydrogen is a highly discussed topic in Berlin, its implementation is far from reality as the production, infrastructure and implementation conditions are not yet ideal to support a breakthrough in the energy sector. However, H_2 has developed in niche markets and continues to gain momentum in the transportation sector as incumbents quickly jump on the bandwagon. Looking at the overall evolving developments of Berlins energy sector and the dynamics between the actross across levels, I have identified the fall of the Berlin wall to be the beginning of phase 1, after which hydrogen has slowly started to develop in the niche. The Paris Agreement marks another incisive event that caused a rapid increase in policy supporting a hydrogen momentum in Berlin. Here I see the end of phase 1 and the beginning of phase 2 of the MLP framework. For this reason, I conclude that Berlin currently is in the second phase of the MLP with respect to a hydrogen breakthrough (Fig. 10), where the momentum eventually leads to a window of opportunity.

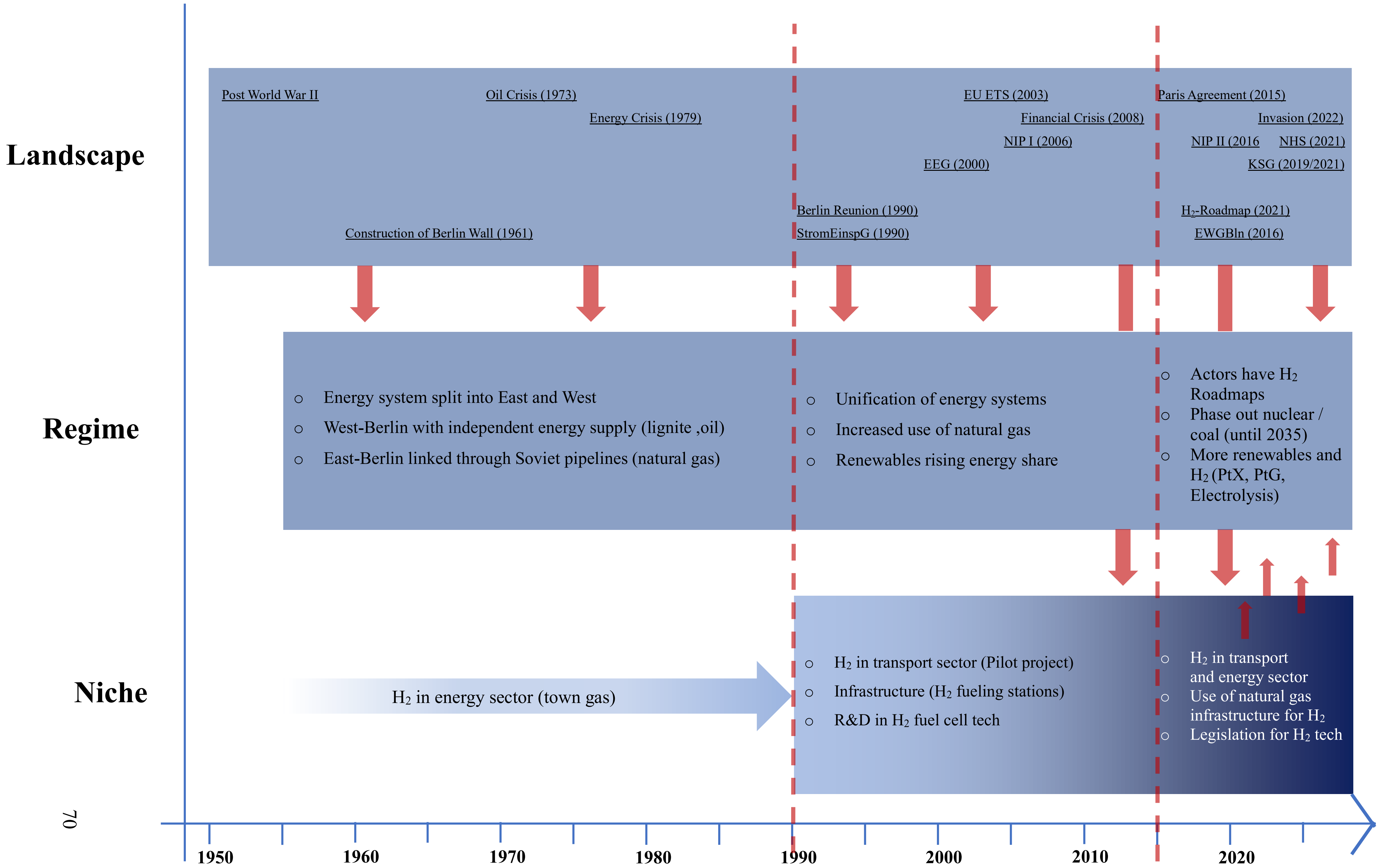

Figure 10 Overview of Landscape, Regime and Niche developments 1950 - 2023 (own work)

V. Current Conditions and Future Development for H_2

On the road to 2045

The emergence of hydrogen into Berlin's energy system (the regime) is no accident, as the interactions and processes since 1990 show. The landscape around Berlin's energy system has changed several times over the past 30 years, with major events being the financial crisis in 2008, the signing of the Paris Agreement in 2015, and the Russian invasion of Ukraine in 2022 - all of which put pressure on and influenced the regime in Berlin, directly and indirectly. Niche developments have begun to emerge around hydrogen technology as a solution to enable further transition of the city energy system towards renewable energy. Networks have formed around a hydrogen coalition, and small-scale pilot projects are already demonstrating that widespread implementation of hydrogen is a possibility. Plans for a hydrogen infrastructure are underway or already under construction, and policies are continually being adjusted to support more sustainable and resilient energy production.

Berlin can be seen as a center of developments in Germany, hosting hydrogen pilot projects in the transportation sector and providing R&D in hydrogen technology as well as feasibility studies by research institutes for future hydrogen pathways to support a sustainable urban transition.

However, while there is currently build-up of momentum to elevate hydrogen to the "fuel of the future," there are still many unanswered questions and barriers that may hinder the momentum to sustain toward a wider breakthrough. Looking at past transitions observed by MLP-inspired scholars such as Geels (2002, 2005, 2006, 2011); Geels & Kemp (2007); Hodson & Marvin (2010); Markard et al. (2012), certain conditions and drivers are necessary for hydrogen to break out of the niche market and contribute to replace the incumbent regime (energy system heavily dependent on fossil fuels). What are the critical factors needed for such development to take place, and how do they relate to the MLP levels?

I will begin by discussing the feasibility of the MLP framework for understanding future transitions and the evolving role of hydrogen in Berlin's energy transition. I will then, based on the MLP model, discuss main conditions that brought hydrogen into its current phase 2 of the transition, according to the MLP framework, and ultimately, the necessary conditions for hydrogen to take a wider role (enter phase 3 and 4 according to the MLP framework in Figure 11) as have been expressed in many trajectories, roadmaps, and measurement plans of Berlin.

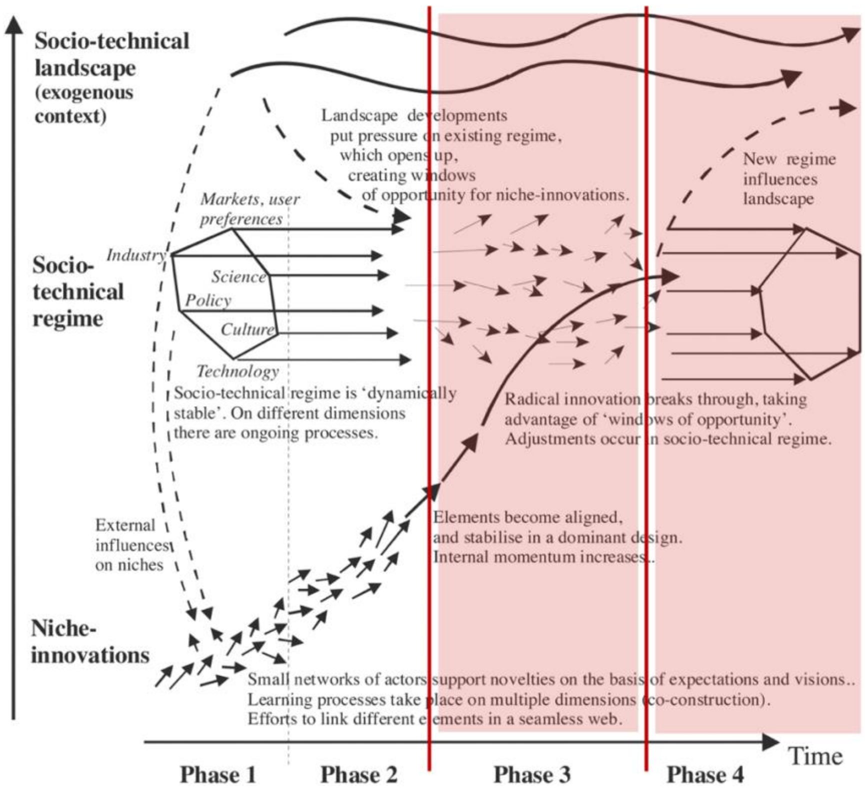

Figure 11 Socio-technical Transition in Phases 3 and 4 of the MLP

5.1. The Feasibility of the MLP for analyzing the evolving role of H_2 in Berlin's energy transition.

To what extend can the MLP framework be used to understand future transition processes?

As the MLP is a framework for analyzing historical socio-technical transitions, it has established itself to understand how the interaction of the different levels of regime, niche and landscape leads to multiple transition pathways. The different pathways through which a transition can occur are explained by Geels et al. (2016) and show the possible developments of actors at the niche and regime level, influenced by landscape pressures. As already concluded, Berlin has gone through several transition pathways in the past, caused by both landscape factors and learning processes of actors at the regime level.

Large and sudden landscape changes, also referred to as avalanche changes, such as the construction of the Berlin Wall, led to the de-alignment of existing energy regime pathway (Geels et al., 2016; Geels & Schot, 2007). Actors within the energy regime had to face the new reality of energy supply separated from the main German energy system, so they had to look for alternative energy resources, which they eventually found in city gas, thus re-aligning through the emergence of new actors.
Later, from the early 2000s, regime actors actively pushed for innovation and development in hydrogen technology to reconfigure the incumbent regimes towards a sustainable application of H_2 within the mobility sector. This development is marked by 'symbiotic innovations' that are developed at the niche level and adopted by incumbents at the regime level thus adjusting regime structures and ultimately causing a reconfiguration of the regime pathway (ibid.).

In the case of Berlin, the framework has worked well to analyze and explore past transition processes in the energy and transport system that led to identification of different transition pathways for each sector. After 2015, some initial reconfiguration processes in the regime are observed, linked to the development and incorporation of hydrogen by the incumbents of the city energy system. This reconfiguration is enforced by policy-making processes of government agencies at regional (Berlin), national (Germany) and supranational (EU) levels. However, the dynamics was spurred also by the pressure of niche developments in hydrogen technology.

Although the MLP, through its flexible and open nature, offers different explorative developments of a transition, "it cannot provide answers on how a certain trend, innovation or phenomenon develops further" (Vähäkari et al., 2020, p. 8). Therefore, its framework is not suitable for predicting future transition processes. However, it provides a template for assessing various dynamic processes of a transition between and across niche, regime and landscape levels, thus providing a tool for discussing possible pathways for an evolving transition.

The MLP framework is not designed to determine if and when a breakthrough will ultimately occur. But, as Vähäkari et al. (2020) discuss, it can generate archetypes of development paths that explore transition mechanisms. The empirical analysis of the current status for the niche (hydrogen) within the regime (the energy system) and perceptions of their actors about future prospects enhances understanding the different paths that these actors may take. The actors have presented future studies including roadmaps and visions, based on landscape and niche pressures, as well as investment trajectories, indicating commitment to a transition pathway with wider deployment of hydrogen. The purpose of these studies is mainly to determine what conditions, whether political or technological, are necessary to sustain either a business-as-usual or a future transition pathway. It is basically a "what could be" and a "what will be" scenario. The analysis of the dynamics at different levels and the key drivers and barriers of further reconfiguration processes within the levels can ultimately provide a checklist of what potential scenarios will most likely become realized and hence, whether far wider deployment of hydrogen (breakthrough) may be expected in Berlin. For example, Vattenfall and GASAG, as main incumbent actors, both aim to become carbon neutral by 2040 by following coal phase-out plans and reconfiguring their system towards a hydrogen inclusive energy supply for Berlin.

An interesting question is raised by Vähäkari et al. (2020) regarding the evolution of sustainable and unsustainable transitions analyzed in the MLP framework. Do sustainable and unsustainable transitions evolve in the same way? Historically, landscape pressures have dominated as driver for emerging transitions in Berlin. Whether it was environmental disasters that sparked public and political discussion about alternative energy production (nuclear power), the division of Germany and Berlin, the oil crisis (1973/74), or the financial crisis (2008), they all triggered change within the incumbents and innovation at the niche. In this thesis, I argue that landscape factors have continued to be the main drivers of the energy system transition in Berlin, in the form of political governance and policy - especially for a wider hydrogen deployment. As relevant policies are defined at different levels of governance, this calls for combining the MLP with a multi-level governance (MLG) perspective when analysing prospects for wider deployment of hydrogen in in the future energy transition pathway for Berlin. The MLG perspective has similarly informed this study, enhancing my understanding of how policy-making processes in the past acted to influence regime reconfiguration and developments up till now.

On the other hand, the policies that has steered the transition in Berlin, through climate laws and subsidy programs, have in turn been influenced by incumbent regime actor lobbying, as exemplified by the establishment of the Clean Energy Partnership in the early 2000s by incumbents. Here, actors in the auto industry created a network funded by the national government program NIP I. This bottom-up institutionalization dynamic, in which regime actors create a landscape factor that is important in shaping their trajectories, reveals a reciprocity between landscape and regime that has received little attention in many MLP studies, which tend to understand landscape as a slowly changing exogenous factor. According to my exploratory study of hydrogen developments in Berlin, the regime co-creates its own external pressure through a legal framework, once again revealing the multi-layered governance structure that coordinates and controls niche and regime development in favor of wide deployment of hydrogen in the energy and transportation sectors.

5.2. Conditions of Past Transition Processes and Pathways in Berlin

Under what conditions did Berlin's energy sector change in the past?

Having concluded that the MLP provides a good conceptual framework for my analysis of Berlin's long-standing energy system transition, I proceed in this section to discuss RQ1 in more detail, the conditions under which Berlin's energy system has changed in the past. Here, the development of the regime, the landscape, and the niche must be seen in relation to each other. The regime in Berlin, constituted by the different actors involved in energy supply, was exposed to landscape pressures that forced them to change their business as usual (BAU) mode of supply. Looking at the dynamics between the regime and landscape levels, it becomes clear that external pressures (landscape changes) initiate change processes within the regime. To understand where the MLP phases 1 and 2 start and end, Berlins historical context needed to be explored. This has led to the conclusion of phase 1 starting in 1990 with the fall of the Berlin Wall and ending with the Paris Agreement in 2015, thus initiating the second phase, in which Berlin continues to be.

External factors such as the Berlin Wall, Chernobyl, and the oil crisis in the mid-1970s forced West Berlin's energy production to shift to locally produced electricity and heat, relying primarily on coal and lignite power plants. Meanwhile, East Berlin shifted to supplying natural gas to the Soviet Union, expanding the regional pipeline network and creating a lock-in mechanism for decades to come. With the environmental crisis and the Chernobyl nuclear disaster, the dangers of nuclear power became a matter of public concern, forcing the government to include energy alternatives in the policy discussion, such as renewable energy (wind, solar) and natural gas, for which Berlin was supplied through infrastructure projects such as the Soyuz pipeline and Nord Stream 1. These developments came after the implementation of national legislation to manage the transition, in favor of incumbent energy players such as GASAG and Vattenfall. The legislation in Berlin was primarily in favor of energy resilience and independence shown with an initial implementation of the Energy Savings Act from 1990 and then a further distancing from coal and lignite imports from the Soviet Union. The rise of renewable energy in the 1990s was also supported by legislation such as the federal Feed-in Tariff and the Berlin Energy Saving Act (BEnSpG), which led to competition among not only regional but global players and drove down the price of solar PV technology. All in all, these changes in the landscape put a variety of pressures on Berlin to begin transitioning its energy system, forcing both federal and regional government agencies to adapt with new laws and regulations that primarily supported a transition to greater use of natural gas. This political pressure through policymaking remained a key driver for the transition of Berlin's energy system from the fall of the Berlin Wall to the Russian invasion of Ukraine.

Hydrogen did not play a major role in this early energy transition, although it had been part of Berlin's energy supply since the 1950s, mostly as a by-product of city gas and not produced for its environmental benefits. Hydrogen remained a niche technology, showing its unique potential only in pilot projects initiated in Berlin and elsewhere in Germany and developed in protected "safe spaces" managed by regime actors in the transportation sector. It was these regime actors who first introduced hydrogen as an environmentally friendly resource capable of replacing fossil fuels. Table 5 visualizes and summarizes the main points of the dynamics at the different levels and identifies the main transition paths of the energy and transport sectors. The transport sector is included here because hydrogen first emerged in this sector in Berlin before being considered in the energy sector.

Table 5 Landscape, Regime, and Niche Dynamics in Phase 1 of the MLP (Own work, inspired by Larbi et al., 2021)

Sector *(Regime)*	**Landscape impact**	**Niche impact**	**Transition path**
Energy *(Heating and Electricity)*	Landscape changes e.g., oil crisis, Chernobyl, Berlin Wall etc. led to the implementation of nationwide legislation for clean technology application in favor of energy resilience and independence. These legislations acted as landscape factors for Berlins engagement in sustainable urban development prompting dynamics at the niche level (financial, resource, science).	Hydrogen in the energy sector has only been a byproduct of city gas and not actively sought after in the period 1950-1990. After, natural gas has taken over as the dominant niche technology used in heat and electricity generation in Berlin.	Changes in the energy sector follow the *de-alignment and re-alignment path* (Geels & Schot, 2007). The Berlin Wall has forced regime actors to reorient towards new forms of energy. Regime problems, being the division of infrastructure and their entire chain, caused by the cold war/ division of the city, led to the rise of natural gas and nuclear power.
Transport	The landscape changes (cold war, division of Berlin, environmental disaster) led to more awareness of environmental impact on air, water and land thus looking to improvements through legislative action (e.g., Immission Control Act, Feed-in tariff).	Hydrogen technology started to develop in the early 2000's on a national and regional level. Berlin was part of the CEP leading to experimentation and pilot projects in the transport sector. Technological development was seen as crucial for a hydrogen breakthrough leading to the formation of a cluster. This cluster ultimately impacting hydrogen plans in the energy sector.	Changes in the transport sector follow the *transformation path* (Geels & Schot, 2007). Regime actors actively pushed for innovation and development in hydrogen technology to reconfigure incumbent regimes towards a sustainable application of H_2 within the mobility sector.

Since the Paris Agreement of 2015, hydrogen technology has received more and more attention not only in the transport sector, but also in the energy system in Berlin. As Berlin defined roadmaps with the EWG Bln in 2016 and 2021 as well as with the BEK2030 in 2018 on how to become carbon neutral using renewable energy, energy actors like Vattenfall and GASAG were forced to find ways to reduce their emissions in Berlin. Hydrogen quickly became a solution with the potential to support the decarbonization of multiple sectors, and was embraced not only by the city's roadmaps, but also by its stakeholders in the transportation and energy (heat and power) sectors. Hydrogen is already present in Berlin through mobility concepts in the public and private sectors and has sparked clusters and social networks working towards the widespread implementation of H_2 in industry, heat and power generation, and the transport sector.

5.3. A Future Breakthrough for Hydrogen in Berlin?

What are the conditions under which a successful breakthrough for hydrogen could take place in Berlin?

If the Berlin Roadmap is to be believed, a hydrogen breakthrough could be expected by 2030. However, certain conditions would have to be met that would drive the hydrogen momentum through economic, political, logistical and technical conditions, ultimately opening a window of opportunity. For reasons of space and importance, I will discuss only two of the above conditions - technical and political.

Discussing conditions at the regional level, in this case Berlin, also means discussing national conditions, as Berlin is directly embedded in German policy-making and (also) acts as an executive force for policies such as the National Hydrogen Strategy in 2020.

Technical Conditions

MLP scholars such as Frank W. Geels suggest to look for "interesting combinations of multiple technologies" that provide a solution, i.e., multiple technological paths that are linked and reinforce each other as a strategy to sustain a transition (Geels, 2006, p. 181). Such a strategy is already observed not only in Berlin, but in Germany at large. Multiple technological paths for hydrogen can be observed in different sectors such as the energy sector, the transport sector and the heating sector.

In the energy sector, this has led to innovation and efficiency improvements in hydrogen production and use technologies, such as for electrolyzer technology for green hydrogen production, informed by my interview with Sunfire GmbH. Moreover, Berlin has invested a significant amount in R&D on how hydrogen can be stored to meet peak demand of electricity then mitigate peak emissions and ensure safety in the transportation sector. There are currently several solutions for liquefying hydrogen, compressing it at low temperatures, or binding it to a liquid to reduce safety issues and/or economic concerns related to its storage and transportation. In addition, there is increased research into hydrogen fuel cells, including work by the Fraunhofer Institute. Although only a couple houndred hydrogen cars are on the road in

Berlin, research into the efficiency of fuel cells is continuing to give them an advantage over fossil fuel alternatives in the future. In the heating sector, hydrogen is being discussed as a replacement for natural gas in district heating and decentralized heating systems. As the new Building Energy Act in Germany is under way, its aim is to limit fossil fuel use in heat generation by dictating that decentralized heating systems must run on at least 65% renewable energy by 2024, including 'hydrogen-ready' heating systems. It is unclear whether hydrogen-ready heating systems are exempt from this law if they run on blue hydrogen and may fall under the 65% mark. Nevertheless, a "hydrogen ready" heating system for buildings not connected to district heating would further support the current hydrogen momentum and its uptake across sectors.

It should be noted, however, that these multiple technological developments are strongly supported by national and regional funding aimed at catalyzing a hydrogen breakthrough. Without these government investments, the hydrogen momentum would be expected to be much slower than the current rate of almost annual revisions of regional and national hydrogen policies. It can be argued that without government funding in all sectors (including R&D, refueling station construction, pilot project subsidies, etc.), such technological developments would not be seen at the niche and regime level.

The "technical add-on and hybridisation" of hydrogen can also be an indicator of a window of opportunity (Geels, 2006, p. 181). This means integrating hydrogen technology into existing transition pathways. Such a hybridization can be observed in the energy sectors through the upcoming Energy Building Act.

With plans to include hydrogen in the heating sector by gradually replacing natural gas in the district heating supply, a hybridization or "gas mix" is being discussed among political and industrial actors, as the interviews conclude. Currently, the DVWG regulates the blending of 10% hydrogen into the existing gas pipeline network. This regulation is criticized, as both representatives of SenWEB and H2Berlin see a higher hybridization of H2 and natural gas in the heating network. The study "Hydrogen Potential in Berlin 2025" confirms that most actors are pushing for a 20% volume mix, as this would not require any major changes in current infrastructure or specific end uses. Vattenfall is already using hydrogen in one of its CHP plants in Berlin to power a gas turbine for electricity generation. Hydrogen is also being added to the transportation sector through the H2 Moves Berlin project. The fleet of over 100 hydrogen-electric hybrid cars supports a sustainable mobility concept. Further hybridization in the transportation sector is being supported by the German government by funding car companies to develop hydrogen-electric hybrid cars. (Carey, 2021).

The hybridization of hydrogen and other technologies is already available but is still in its early stages as actors in all sectors try to maintain their economic viability. Although hydrogen is seen as a promising resource in several sectors, its implementation is still too expensive to achieve market penetration without additional external investment. For this reason, H2 is increasingly being included first in the sustainability plans of regime actors, where hybridization of hydrogen with other technologies is seen as having great potential. Its implementation is now to be realized with the help of government funding and implementation-friendly legislation.

Lock-in mechanism as a transition driver

A brief excursion.

The MLP uses the term "lock-in mechanisms" to elaborate on the challenges of transition. They include, for example, that sunk investments or existing infrastructure support the incumbent regime to maintain the status quo and incentivize business as usual (BAU). Looking at the example of Berlin, the apparent "barrier" of a fixed infrastructure turns out to be one of the main reasons why hydrogen technology and its use in the urban environment has been pushed to become a main driver for sustainable change. Considering that Berlin has the largest district heating network in Europe, currently fueled by natural gas, a switch to fossil-free energy sources would require an immense transition to renewable alternatives. The ability to use this network, rather than seeing it as a 'locked-in' system that allows only small incremental changes over long periods of time, presents an attractive long-term solution for district heating in Berlin. The ambition to produce and use green hydrogen for the purpose of slowly taking over and forming a symbiosis with the existing system will only drive innovation in the market as well as an increased production of green hydrogen not only in Germany but also in the European and international context, according to the National Hydrogen Strategy of Germany. The Hydrogen Roadmap for Brandenburg and the capital region even defines the existing infrastructure and the integration of buildings and technical machinery as an advantage for the use of H_2 for its thermal and energetic attributes. (MWAE & SenWEB, 2021). The Roadmap also plans to retrofit current production and storage projects of the existing gas and electricity infrastructure to adapt to hydrogen in its measurement plan (ibid., p.39).

Taking advantage of market dynamics where "novelties may break out of niches by piggy backing on the growth of particular market niches" is another feature of identifying a window of opportunity (Geels, 2006, p. 181). This means that hydrogen can be further diffused into an existing market, which then acts as a stepping-stone for a radical technology - in this case hydrogen.

Such a development can also be observed in Berlin's energy sector, albeit only minimally in practice and mainly in actor-specific roadmaps such as those of Vattenfall and GASAG. Although Vattenfall already operates a hydrogen-hybrid cogeneration plant in Berlin, full H_2 operation is still to come. The transportation sector is already enjoying the breakthrough of electric vehicles (EV), with all car manufacturers offering electric mobility in Berlin (also through car sharing mobility), thus riding a wave of sustainable mobility. This momentum in the transportation sector is supported by hydrogen fuel cell research and its implementation in H_2 cars. Although H_2 cars for private use are still comparatively more expensive than their alternatives, H_2 solutions are gaining ground in the transportation sector through projects such as H2 Moves Berlin or hydrogen trucks in the city cleaning or fire services.

This piggybacking on the energy and transportation markets is still in its early stages, as policies and regulations are lacking to further support a breakthrough. Riding the sustainable wave in several sectors is only visible in pilot projects, although they are getting a lot of attention. It cannot be fully argued that these markets are piggybacking, but rather that they are taking hydrogen by the hand and guiding it towards a possible breakthrough.

Another way to find out whether a technology is on its way to breaking through a window of opportunity is to look at whether outsiders are contributing to or establishing themselves in the niche market (ibid.). Even if incumbents try to protect their own interests by investing in niche technologies through R&D and pilot projects, this does not prevent new actors from entering the niche. Regime actors in the transport and energy sectors are investing heavily in hydrogen technology, although they act as actors in the demand chain and focus on consumption rather than production.

The question "Where will all this hydrogen come from?" is ubiquitous when discussing hydrogen production and transportation. As envisaged in the Berlin Hydrogen Roadmap, this requires not only domestic production, but above all international trade and imports. Particularly because of the preferential conditions in southern countries (green hydrogen from solar energy), international cooperation is inevitable for a breakthrough in Berlin. Although

Berlin has a good national position in renewable energies through Brandenburg, hydrogen has to be imported. This is where H2Global comes in, for example, which strives for the unconditional procurement of H_2 to counteract the chicken-and-egg problem. In addition, there are start-ups such as HH2E or the formation of clusters and networks such as the Cluster Energietechnik in the Berlin area, which take care of the electricity and heat supply with hydrogen production and organize and promote the cooperation of various actors from different sectors. Again, such international cooperation requires government support to create favorable conditions for hydrogen trade among global partners.

Some barriers to an evolving hydrogen breakthrough in Berlin are manifested, among other things, in the lack of regulations that would support a hydrogen technology in established energy systems. From the interviews, it was concluded that unbundling, although currently supported by the 2009 EU Gas Directive, would benefit the speed of the transition to hydrogen transport and its use in district heating in Berlin, if revised. This revision would specifically pick up the demand by grid operators to allow the production of hydrogen next to operating the grid network. Currently, unbundling means the separation of energy supply and generation from transmission operations (European Commission, n.d.). Its revision is being discussed with exceptions for hydrogen giving it regulatory freedom from the Gas Directive until 2031, including unbundling (ibid.).

In addition, sudden changes in the landscape, such as the Russian-Ukrainian war, can act as both a driver and a barrier. It has caused an energy crisis in Berlin, driving up the price of natural gas and therefore the price of blue hydrogen. But it also caused Germany to turn to renewables for greater energy independence and resilience. As Germany implements blue hydrogen into its NHS, an affordable production process is needed to complement a simultaneous ramp-up of renewable technology. Such avalanche changes must therefore be met with rapid policy processes such as the LNG Acceleration Act.

Both the advancement of hydrogen technology, made possible by investments in R&D, and policy drivers, such as the Berlin H2 Roadmap with its policies, are key drivers for a hydrogen momentum in the city that could ultimately lead to the opening of a window of opportunity. However, changes in the landscape may affect the pace of hydrogen development. This needs to be addressed by timely policies that counteract the negative impacts of landscape change. Having discussed the drivers and barriers of Berlin's past transition conditions, the following section attempts to discuss the conditions for a future hydrogen breakthrough in Berlin.

Policies and revision of policies to trigger hydrogen entering 3rd and 4th phase of the MLP

Political Conditions

Geels mentions policy as an instrument that cannot coerce, but can encourage diversity at the niche level and modulate ongoing practices at the regime level in order to link the two (Geels, 2006). In the first two phases, the niche technology is supported by policies that allow the niche to develop networks and clusters, to experiment and to build visions (ibid.). This development can be observed in the context of hydrogen in Berlin following a mixture of the governance paradigms explained by Geels (ibid.). The classic steering paradigm (top-down) implements formal rules and regulations as an instrument to guide a transition, while "subsidies, taxes and (financial) incentives are common in the market model" (ibid., p.179). The policy network paradigm encourages network building, learning, shared visions and experimentation (ibid.). Berlin incorporates a little bit of everything, depending on the timeline. Supporting a breakthrough (ergo phase 3 and 4) requires policies that push the new technology, such as adoption subsidies and regulations, as well as adjustments in the socio-technical regime, such as new infrastructure and maintenance networks (ibid., p.180). In this case, policies are needed for structural change, which in turn leads to the adjustment of policies further down the line, resulting in a circular adjustment of policies and change towards system innovation. The BEK2030 and its revisions since 2018 are a good example of this dynamic.

According to Geels (2006), in the third phase, technology gains momentum through the definition of clearer targets. Over the years, Berlin has defined climate targets that follow a reduction of greenhouse gas emissions as required by the Paris Agreement. With the revision of the BEK2030 and the creation of a H2 Roadmap for Berlin, the formulation of hydrogen targets in the energy and transport sectors becomes clearer. To push Berlin further towards a window of opportunity, adjustments in the policy-making process need to be made.
However, Geels calls this policy placement "ideal-typical and theory-based", leaving each case to its own search for the best mix of policy instruments at its own pace (ibid.). In the case of Berlin, the following discussion provides a brief overview of the policies already in place and the adjustments that need to be made to support a hydrogen breakthrough momentum in Berlin's pursuit of a sustainable energy transition. The conditions for a successful hydrogen

breakthrough, i.e., a point at which hydrogen becomes an irreplaceable energy resource for Berlin's energy sectors, are political.

The policies already in place to guide a hydrogen momentum in Berlin are at the landscape level and include national policies such as the NHS. The NHS already clarifies goals for a hydrogen market in Germany and provides an overview of specific measures to achieve these goals. It is currently being revised and is expected to be published in mid-2023 with more ambitious goals, such as doubling electrolysis capacity from 5 GW to 10 GW by 2030 and including blue hydrogen as a sustainable resource in the strategy. Such ambitions give a signal to actors at the regime and niche level and provide them with the planning certainty needed for initial investments, including no-regret investments. These no-regret investments are particularly important in industry, as they signal to policymakers a willingness to embrace hydrogen. Anna Borg, CEO of Vattenfall, supports this, claiming that regulatory frameworks drive the expansion of renewables and provide guidance on geopolitical independence and affordable energy. (Cwiertnia & Heuser, 2023). This reciprocity in the relationship between policy makers and hydrogen actors is represented in the policy network paradigm. The formation of the Cluster Energietechnik also represents strategic networking, experimentation and vision building among regime and niche actors in Berlin.

The market model paradigm can also be observed through the implementation of a carbon tax and trading system at the EU level. Carbon pricing in the EU can lead to higher investments in renewable technologies, while the EU ETS can further support this development. This policy paradigm is preferred by the business community, as confirmed by the interview with Sunfire GmbH. Rather than controlling the market development of hydrogen, policymakers should guide it through regulatory revisions and create a favorable framework for hydrogen to thrive across multiple sectors. Even if business as usual is threatened by high energy prices, it can incentivize companies to invest in renewable solutions that are also subsidized by government funds. To further support this development at the regime and niche level, regulations must provide clear definitions and standards for hydrogen production, infrastructure, and transportation. For Berlin, this means waiting for the EU to adopt such regulations. To conclude an interview with a representative of SenWEB, this means that the standards for hydrogen production, distribution, and storage need to be adopted at the EU level so that countries can incorporate them into their national policies, thus stimulating a hydrogen market from which Berlin would benefit. Knowing, for example, which hydrogen color can be classified as sustainable and which is not, gives energy actors more planning security.

However, this does not protect against landscape dynamics that may negatively impact this development. The current energy crisis is affecting the production process by increasing energy prices, thus threatening a hydrogen breakthrough. For this reason, a shift to green hydrogen is advantageous by simultaneously increasing renewable energy and green hydrogen production, thus supporting energy resilience and independence in the future.

Finally, for Berlin, the issue of unbundling could become a key driver for a hydrogen breakthrough. Initially, there was a very strict requirement from the EU Commission that gas network operators were not allowed to operate hydrogen networks. This was regulated by the EU Gas Directive of 2009, which is also seen by the interviewees as very difficult for the transformation. Since March 2023, the EU Council has adopted a revision that would allow incumbent network operators to set up a hydrogen network and thus unbundle their business. However, this is still only a formulation and has to be approved by the EU Parliament. As also confirmed by the interviewees, this revision of the Gas Directive would be a pragmatic option to allow gas operators to transform and restructure towards a more hydrogen-inclusive market.

All technical and political conditions cannot be seen in isolation but must work together. They correlate, support, presuppose each other, and together can create a favourable framework for a successful breakthrough in Berlin as a basis for an effective sustainable urban transition with hydrogen.

VI. Conclusion

To better understand Berlin's hydrogen energy transition, I have used the theoretical framework of the MLP. As a transition theory, it examines historical transitions of entire systems through the explorative description of socio-technical processes on three levels - the landscape, regime, and niche levels. Transition processes in Berlin within and between these levels were described and analyzed corresponding with the first and second phases of the MLP. The historical background was reviewed, which provides for the understanding why and how hydrogen emerged as a niche in Berlin's energy system.
Moreover, key political and technical conditions that enabled and drove the hydrogen momentum in the transportation and energy sectors have been discussed. On the regime level, I have identified key actors of the energy system, as evolving and changing through history, and analyzed their visions for transition of the energy system, to achieve GHG reduction in Berlin. Emergence and developments of the niche related to development and deployment of hydrogen technologies in the urban space were identified and explained in the context of landscape and regime pressures.

The research questions focused on three central themes: exploring the conditions for past hydrogen-related transformation processes in Berlin, discussing the conditions for an upcoming breakthrough (wide deployment) for hydrogen in Berlin, and analyzing the suitability of the MLP framework for exploring the current status for hydrogen in the transition of Berlin's energy system and its future prospects. The exact formulation of the questions is repeated here:

Q1: To what extent can the MLP framework be used to understand past and future transition processes?

Q2: Under what conditions did Berlin's energy sector change in the past?

Q3: Under what conditions could a successful breakthrough for hydrogen take place in Berlin?

To conclude the first question, the MLP has been analyzed as a suitable theory for exploring past and future trajectories of hydrogen. The past transition of Berlin's energy system (regime) can be understood and explored through the theoretical framework by following the impacts of evolving developments at the landscape and niche levels. These impacts are pressuring the regime to adapt accordingly by supporting hydrogen innovation through pilot projects, and considering hydrogen policy in its roadmaps towards climate neutrality of Berlin. Although future transitions cannot be predicted or foreseen with the MLP framework, its methodology allows for the recontextualization of past transition developments studied and thus opens space for possible interpretations of current and future trajectories and their assessment for plausibility and effectiveness.

The conclusion on the second question is that policy, as a driver, has been instrumental for the development of hydrogen technologies in Berlin's energy system. Government funding programmes supported social networks and encouraged the willingness of industry to participate in pilot projects, but also brought the public (e.g. through citizens' initiatives and referendums) closer to a new technology that can serve as an inescapable resource in the fight to reduce greenhouse gases. First introduced and experimented with in the transport sector, hydrogen, as a renewable fuel, has then been included in the energy industry's roadmaps as a substitute for natural gas, with ambitious targets for 2045. Such ambition can be traced back to stricter revision of policy on national and regional level and concludes policy to act as an instrument for sparking and supporting transition processes in the regime and niche level of Berlin. Geopolitical events such as the fall of the Berlin Wall and the Russian invasion of Ukraine, but especially the Paris Agreement as an external institutional factor, have acted as key drivers on the landscape, directly shaping national environmental policies and thus indirectly influencing regional hydrogen transition developments in the Berlin energy system. These crucial developments in Berlin's history forced the energy regime to reorient its energy strategy towards alternative energy resources, including investing in hydrogen as a niche technology, thus further supporting its momentum.

To conclude the third research question, in addition to political conditions, technical requirements are indispensable for a future breakthrough for hydrogen in Berlin's energy system. As in the past, legislation is leading the way for guiding the momentum of hydrogen in Berlin's energy system. However, technical conditions at the national and regional level are needed to open a window of opportunity. This requires support from regime actors and more concrete regulations for a hydrogen market, but also clearer sustainability definitions for its production and infrastructure as well as investments in storage and distribution of hydrogen. In addition, new infrastructure projects must go through fast approval procedures, and at the same time, the hydrogen dynamic in Berlin must be promoted through international cooperation to signal a readiness for hydrogen and thus bring about a breakthrough across sectors.

In summary, the main conclusion is that a breakthrough for hydrogen in Berlin will require political legislation (landscape changes) to spur further technical developments in production, storage and infrastructure (regime adjustments). These conclusions also support the dynamism of the MLP theoretical framework and show that its application in an urban setting is feasible and that the possibilities of a niche technology can be explored for the future.

For future research, a fruitful strategy might be to combine the MLP with future studies and the MLG to examine in more detail the conditions at different levels that are likely to promote a breakthrough for hydrogen. Another topic of interest to explore further would be the two-way dynamics between a regime and policies (as a landscape factor), beyond the simple one-way, top-down dynamics seen in various MLP studies. It could be argued that the importance of landscape pressures or external factors will become increasingly relevant for future sustainability transitions. The direct influence of the regime on its own transition framework is therefore an interesting dynamic that requires further analysis.

Personally, following the trend of hydrogen implementation over the last decade, I expect that it will only find more industries and sectors to be used in. From answering the research questions, I personally conclude that hydrogen has great potential as a long-term sustainable energy source - especially when used as energy storage to support the intermittency of renewables. Considering the overall success of an energy transition in Berlin, hydrogen technology will be an outcome that the city is working towards rather than with. As the net-zero targets are quite ambitious and hydrogen technology is still in its infancy, other renewable technologies will play an overriding role in achieving these targets. Technologies, such as solar and wind, will continue to drive the energy transition and enable hydrogen to become a more viable, affordable, and feasible energy source in the future.

VII. References

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