The influence of endogenous and exogenous factors on the diffusion dynamics of renewable energy innovations in Argentina

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Abstract

Zusammenfassung

Im Rahmen dieser kumulativen Dissertation werden die maßgeblichen Dynamiken für die Diffusion der erneuerbaren Energien im argentinischen Kontext untersucht. Dies geschieht vor dem Hintergrund, dass das argentinische Stromsystem mit zahlreichen Herausforderungen konfrontiert ist: Eine starke Abhängigkeit von der thermischen Stromerzeugung, eine unzureichende nationale Erdgasförderung, negative Energiehandelsbilanzen und hohe Energiesubventionen. Gleichzeitig hat sich Argentinien dem Pariser Klimaschutzabkommen verpflichtet und sich ehrgeizige CO_2-Reduktionsziele für den Stromsektor gesetzt. Weitere relevante Rahmenbedingungen, die dezidiert in dieser Arbeit betrachtet werden, sind die Einflüsse der Instabilitäten auf makroökonomischer und politischer Ebene.

Durch ein hohes und hinsichtlich der unterschiedlichen Erzeugungstechnologien geographisch breit verteiltes Potential für erneuerbare Energie verfügt das Land über sehr gute Ausgangsbedingungen. Diese bieten die Möglichkeit, Strom auf kosteneffiziente und ökologisch nachhaltige Weise zu erzeugen, die Energieautonomie des Landes zu stärken und durch die resultierende Reduzierung fossiler Energieerzeugung dazu beizutragen, strukturelle nationale Herausforderungen – wie die knappen nationalen ausländischen Devisenreserven – zu bewältigen.

Um die Diffusion erneuerbarer Energien in Argentinien umfassend zu analysieren, werden in dieser Dissertation sowohl endogene Faktoren, wie die Verbreitung von Wissen und Nischenanwendungen, als auch exogene Faktoren, einschließlich makroökonomischer und energiewirtschaftlicher Zusammenhänge, untersucht. Um die komplexe Dynamik sozio-technischer Systeme zu erforschen und die verschiedenen angewandten Forschungsrahmen zu operationalisieren, wurden spezifische methodische Ansätze gewählt. Die Dissertation ist in vier einzelne Fachpublikationen gegliedert, die sich jeweils auf unterschiedliche Aspekte dieses Themas konzentrieren und zusammen die Grundlage dieser kumulativen Dissertation bilden.

Diese Forschungsarbeit leistet einen Beitrag zum Forschungsfeld des Sustainability Transition Research, indem sie theoretische Rahmenwerke wie die Multi-Level-Perspective (MLP), das Strategic Niche Management (SNM) und Technical Innovation Systems (TIS) anwendet und weiterentwickelt. Sie liefern wertvolle Erkenntnisse darüber, wie diese Rahmenwerke weiterentwickelt werden können, um die Energiewende in Ländern des globalen Südens, insbesondere in Argentinien, besser zu verstehen. Die Ergebnisse bieten auch praktische Anleitungen für politische Entscheidungsträger und Interessenvertreter, die an der Energiewende Argentiniens beteiligt sind.

Abstract

This cumulative dissertation examines the relevant dynamics for the diffusion of renewable energies in the Argentinian context. This is conducted against the background that the Argentinian power system is facing numerous challenges: a heavy dependence on thermal power generation, insufficient national natural gas production, negative energy trade balances and high energy subsidies. At the same time, Argentina has committed itself to the Paris Agreement and has set itself ambitious CO_2 reduction targets for the electricity sector. Other relevant framework conditions that are considered in detail in this dissertation are the influences of macroeconomic and political instability.

With its high and geographically broadly distributed potential for renewable energy in terms of different generation technologies, the country possesses excellent preconditions. These offer the opportunity to generate electricity in a cost-efficient and ecologically sustainable manner, strengthen the country's energy autonomy and help overcome structural challenges at the national level, for example low national foreign exchange reserves, through the subsequent reduction in conventional power generation.

In order to comprehensively investigate the diffusion of renewable energy in Argentina, this dissertation examines both endogenous factors, such as the diffusion of knowledge and niche applications, and exogenous factors, including macroeconomic and energy-economic contexts. Specific methodological approaches were chosen to explore the complex dynamics of socio-technical systems and operationalise the different research frameworks applied. The dissertation is organised into four individual publications, each of which focuses on distinct aspects of this topic and together form the foundation for this cumulative dissertation.

This research contributes to Sustainability Transition Research by applying and advancing theoretical frameworks such as the Multi-Level Perspective (MLP), Strategic Niche Management (SNM) and Technical Innovation Systems (TIS). The findings provide valuable insights into how these frameworks can be further developed to better understand the energy transition in countries of the Global South, particularly Argentina. The results also offer practical insights for policy makers and stakeholders involved in Argentina's energy transition.

Acknowledgements

The starting point for this journey was my interest in the paradox of how Argentina, a country with abundant renewable energy resources, has failed to effectively utilise these resources in light of its ongoing structural energy crisis. Another compelling reason that inspired me to embark on this journey was recognising that a successful energy transition in the Global South will play a critical role in achieving global climate goals. Since then, the country, and in particular the energy sector, has changed considerably. During the course of my research, Argentina has undergone developments that gives hope for the country's renewable energy future. However, in light of recent changes at the political level, it is also still evident that in the 2020s the country will continue to fall victim to its cyclical upheavals.

I would like to thank all the people who have accompanied me on this journey. First and foremost, I would like to thank my first supervisor, Prof. Dr Manfred Fischedick, who consistently gave me valuable advice and made sure that even when the ship veered off course, it always came back on course for the destination harbour. Special thanks go to Dr Willington Ortiz, with whom I was able to discuss my ideas. He critically examined my approaches and gave me valuable feedback that significantly enriched my research. I would also like to express my gratitude to the Wuppertal Institute, whose doctoral programme provided the institutional framework for this dissertation and enabled an interdisciplinary and enriching exchange with my fellow researchers. I would also like to thank the Wisions programme associated with the Wuppertal Institute and Friends of the Wuppertal Institute e.V. for sponsoring the proofreading of my articles.

I would like to thank the numerous interviewees who gave up their time to provide me with deep insights into the Argentinian context. Their valuable knowledge has significantly enriched my research. I would also like to thank my co-authors for their inspiring collaboration and commitment, whose valuable contributions and ideas have contributed significantly to the quality and depth of the articles. I would further like to thank the numerous reviewers whose suggestions have helped to improve the articles in this thesis.

Last but not least, I would like to thank my family, with the greatest thanks going to my wife. She has had my back so that I could find the time for this research alongside my professional activities and our children. Her support and understanding have been invaluable to me.

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List of Abbreviations

BCRA	Banco Central de la República Argentina (Central Bank of the Argentinian Republic)
BICE	Banco de Inversión y Comercio Exterior (Argentinian Bank for Investment and Foreign Trade)
CA	Constellation Analysis
CADER	Cámara Argentina de Energías Renovables (Argentinian Association for Renovable Energies)
CAMMESA	Compañía Administradora del Mercado Eléctrico Mayorista S.A. (Argentinian Wholesale Electricity Market Clearing Company S.A.)
Covid-19	Coronavirus disease 2019
CREE	El Centro Regional de Energía Eólica (Regional Centre for Wind Energy)
DNC	Declared National Component
El	Electricity
EMBI	Emerging Markets Bond Index
ENARSA	Energía Argentina S.A. (Energy Argentina S.A.)
ENRE	Ente Nacional Regulador de la Electricidad (National Electricity Regulatory Authority)
EU	European Union
FIP	Feed-in premium
FODER	Fondo para el Desarrollo de Energías Renovables (Trust fund for the development of renewable energies)
GDP	Gross domestic product
GENREN	Programa Generación Renovable (Programme for renewable generation)
GIS	Global Innovation System
HWS	Household wind system
IMPSA	Industrias Metalúrgicas Pescarmona Sociedad Anónima (Pescarmona Metallurgical Industries Public Limited Company)
INET	Instituto Nacional de Educación Tecnológica (National Institute of Technical Education)
Intern	International
INTI	Instituto Nacional de Tecnología Industrial (National Institute of Industrial Technology)
IRESUD	Proyecto De Interconexión De Sistemas Fotovoltaicos A La Red Eléctrica En Ambientes Urbanos (Project for the Interconnection of Photovoltaic Systems to the Electricity Grid in Urban Environments).
MATER	Mercado a Término de Energía Eléctrica de Fuente Renovable (Electricity Term Market for Renewable Energy Sources)
MLP	Multi-Level Perspective
NIS	National Innovation System

SNM	Strategic Niche Management
OWE	Onshore Wind Energy
PERMER	Proyecto Energías Renovables para Mercados Rurales (Renewable Energies for Rural Markets Programme)
PPA	Power Purchase Agreement
Pre	Presidency
PROINFA	Programa de Incentivo a Fontes Alternativas de Energía Elétrica (Programme of Incentives for Alternative Electricity Sources)
PV	Photovoltaic
R&D	Research and development
RenovAr	Programa de abastecimiento de energía eléctrica a partir de fuentes renovables (Programme for the supply of electricity from renewable energy sources)
RNI	Red Nacional de Interconexión (National Interconnected Grid)
SADI	Sistema Argentino de Interconexión (The Argentinian Interconnection System)
SIP	Sistema Interconectado Patagónico (The Patagonian Interconnection System)
STR	Sustainability Transitions Research
TIS	Technical Innovation System
US	United States
WI	Wuppertal Institut für Klima, Umwelt, Energie gGmbH
YPF	Yacimientos Petrolíferos Fiscales S.A. (Fiscal Oilfields S.A.)

Preface and list of publications

This cumulative thesis is based on the four articles listed in the appendix:

- Schaube, P., Ortiz, W., & Recalde, M. (2018). Status and future dynamics of decentralised renewable energy niche building processes in Argentina. Energy Research and Social Science.
- Leary, J., Schaube, P., & Clementi, L. (2019). Rural electrification with household wind systems in remote high wind regions. Energy for Sustainable Development.
- Schaube, P., Ise, A., & Clementi, L. (2022). Distributed photovoltaic generation in Argentina: An analysis based on the technical innovation system framework. Technology in Society, 68, 101839.
- Schaube, P. (2024). The influence of context-specific factors on the diffusion dynamics of onshore wind energy in Argentina. Wuppertal Paper (Vol. 203). Wuppertal Institut für Klima, Umwelt, Energie.

The following framework paper places the four articles within a common context. In this regard, the overarching research question, as well as the theoretical and methodological approach of this dissertation, are outlined. Furthermore, the main findings of the articles are summarized, interconnected, and discussed in relation to the overarching research question and research gaps.

This framework paper partially contains excerpts from texts previously written and published by the author as part of this research. In the respective chapters (3.2 and 5.1), this is indicated with a brief note, and the relevant passages are highlighted in *italics*. This has been approved by the supervisor of this thesis.

1 Introduction

The dissertation represents an important contribution to the field of Sustainability Transition Research by applying and further developing concepts of socio-technical change in the Latin American context, in particular Argentina. The aim of the research is to explore the decisive dynamics for the diffusion of renewable energies in the Argentinian context. There, renewable energy is being deployed within an electricity system that faces a number of challenges: Thermal power plants form the backbone of electricity supply, but since the mid-2000s national natural gas production has been insufficient to meet national demand. Negative energy trade balances are putting pressure on Argentina's scarce foreign exchange reserves, and high energy subsidies are an increasing burden on the national budget. At the same time, the country has committed itself to the Paris climate change goals and has set ambitious CO_2 reduction paths in the electricity sector.

However, the country possesses exceptionally high potential for renewable energies, which, depending on the technology, are distributed across different geographical regions (M. Recalde, 2015). In the Argentinian context, renewable energies offer the opportunity to generate electricity in an environmentally friendly and cost-effective manner, thereby increasing the country's energy autonomy, counteracting the main national structural problems and supplying remote regions with electricity. By analysing the influence of endogenous factors, such as the diffusion of knowledge and the emergence of application niches, as well as exogenous factors, such as the macroeconomic and energy-economic context, this dissertation contributes to a deeper understanding of the factors influencing the diffusion of renewable energies in Argentina.

This paper pursues two interrelated objectives within a cumulative dissertation: a) On the one hand, it aims to provide the scientific basis for contextualising the results of the four articles that have been published as part of this cumulative dissertation. A comprehensive overview of the development of the Argentinian power system as well as renewable energies is provided. The relevant and overarching research question for this dissertation is derived from this. Furthermore, this paper outlines the overarching research approach and its theoretical anchoring in depth. b) Secondly, with regard to the guiding research question, the results of the individual articles are placed in the context of the overarching research approach. The main findings are summarised and discussed in both empirical and theoretical terms. Against this background, this framework paper is organised as follows:

The second chapter begins by presenting the evolution of Argentina's power system over time, describing the main trends and challenges. This is complemented by an overview of the main actors in the power sector. Then, the geographical distribution of Argentina's renewable energy potential is outlined. Finally, the central research question of this thesis is derived by examining the development of renewable energy in Argentina in the context of the challenges faced by the power system.

The third chapter situates this dissertation in the research field of Sustainability Transition Research. The role of innovations in socio-technical transitions is addressed and the theoretical approaches of the Multi-Level Perspective (MLP), Strategic Niche Management (SNM) and Technological Innovation Systems (TIS) are outlined. The chapter concludes with an analysis of the appropriateness of the theoretical frameworks in the context of the research topic and highlights research gaps that are addressed on a theoretical level by this dissertation.

Drawing on the empirical and theoretical preliminary deliberations, the fourth chapter introduces the research approach on which this dissertation is centred. The interplay between the various theoretical frameworks is described, as are the methodological approaches taken in this thesis. The chapter concludes by outlining how the four articles, with their respective empirical foci, are embedded in the overarching research approach.

The fifth chapter contains a brief summary of the four articles that form the basis for this cumulative thesis. The full original texts can be found in the appendix to this thesis (see Appendix A -D). At the end of the chapter, the individual articles are summarised in tabular form with regard to their research questions and specific characteristics.

Chapter six provides a comprehensive summary and systematic linking of the results and findings of the dissertation. The scope of this chapter is also to point out future research approaches and to critically examine which aspects of the underlying research project could have been conducted differently from today's perspective. In relation to the research question, the most relevant endogenous and exogenous influencing factors that shape the diffusion dynamics of the respective renewable energy innovations in the context of the socio-technical transition of the Argentinian electricity power system are examined. Finally, the significance of the results for the research field of Sustainability Transition Research is discussed, illustrating how this dissertation contributes to closing the existing research gaps.

2 Background of the Argentinian power system and elaboration of the research question

2.1 Evolution of the Argentinian power system

As in other countries around the world, small coal-fired power stations were built in Argentina in the early 19th century. The main purpose of these plants was to meet local demand for electricity. As Argentinian coal had a low calorific value, it had to be enriched using coal imports for electricity generation (Furlán, 2017). However, in the aftermath of the Second World War, the use of coal was increasingly replaced by Argentinian crude oil. Argentinian crude oil production began in 1907 and dominated Argentinian electricity generation until the 1970s (Furlán, 2017). In the 1950s and 1960s, numerous efforts were made to diversify Argentina's electricity matrix through the use of natural gas, hydropower and nuclear energy. In the early 1950s, approximately 70% of the electricity was consumed in Greater Buenos Aires, which became the centre of the import-substituting industrialisation under the Peronist government (Furlán, 2017). In the absence of a supra-regional high voltage supply, individual electricity supply regions initially developed separate from each other. During the same period, cooperatives were instrumental in establishing the electricity supply in smaller towns far from the major centres of electricity consumption (Kazimierski, 2020). These developments formed the basis for the pioneering role played by energy cooperatives in the early stages of wind energy development.

During the 1960s, Argentina's power system transitioned to a diversified generation structure which characterised the second development phase (see Table 2-2). A key development was the growing exploitation of Argentina's natural gas reserves. As a result, the share of natural gas in the generation of electricity increased from 1.6% in 1961 to more than 20% in 1972 (Furlán, 2017). Furthermore, the Perón and Frondizi governments fostered investments in the construction of 46 hydroelectric plants, which mostly supplied electricity to regional power systems (Furlán, 2017). In the years that followed, the share of hydropower increased from 3% in 1950 to 12% in the early 1970s (Furlán, 2017). In addition to this, the first preliminary studies on the use of nuclear energy began in 1957, leading to the construction of the Atucha I nuclear power plant in 1968, which became operational in 1974 with a capacity of 370 MW (Furlán, 2017). During the third development phase, the expansion of geographically distributed, efficient power plant capacity triggered the construction of a national transmission grid to transport energy from surplus regions, such as Comahue and Litoral, to centres of consumption (Kazimierski, 2020). This gave rise to the National Interconnected Grid (RNI)[1], which was later renamed the Argentinian Interconnected Grid (SADI)[2] (Kazimierski, 2020).

The fourth development phase of the Argentinian power system was significantly shaped by structural reforms of the Argentinian state. Until 1989, the Argentinian energy sector was regulated by Law 14.772, which classified energy supply as a public

1 Red Nacional de Interconexión

2 Sistema Argentino de Interconexión

service supplied by state-owned utilities (Vagliasindi & Besant-Jones, 2013). Until this point, power generation, transmission, and distribution were primarily dominated by three state-owned, vertically integrated utility companies. In the 1980s, the security of supply of the Argentinian electricity system deteriorated (blackouts during water shortages) due to insufficient expansion of generation capacity. Furthermore, the electricity utilities experienced economic difficulties that were exacerbated during the hyperinflation of 1989/90 (Vagliasindi & Besant-Jones, 2013). In addition, the Argentinian state faced the challenge of massive over-indebtedness, which led to far-reaching policy reforms in the early 1990s under the Menem government. In addition to pegging the Argentinian currency to the US Dollar, another key reform was the privatisation of state-owned enterprises to reduce public debt (Haselip & Potter, 2010). This had a major impact on the Argentinian energy sector, which was unbundled into the generation, transmission and distribution of electricity as part of the liberalisation processes (Guzowski & Recalde, 2010). With the intention of creating a competitive environment, privatisation of the state-owned energy companies and liberalisation of the energy market led to the creation of the National Electricity Regulatory Authority (ENRE) and CAMMESA, the wholesale electricity market organisation (see Table 2-1) (Vagliasindi, 2012). A central development for the present electricity generation system was the extensive installation of new hydropower (3.7 GW) and thermal power plants (4.5 GW) up until 2000 in order to meet growing energy demand (CAMMESA, 2023b).The massive expansion of thermal power plant capacity in the following years led to high path dependency, which, against the background of declining domestic gas production, imposed a heavy economic burden on the country in the 2010s. In the 1990s, however, this development was favoured due to low specific power plant costs, efficiency improvements, e.g., through combined cycle power plants, increasing national natural gas extraction and low natural gas prices (M. Recalde, 2011). Building new thermal capacity was particularly attractive to private actors, as it represented an investment with a relatively short amortisation period and high returns (Serrani & Barrera, 2023).

In the mid-1990s, the electrification rate in Argentina reached 93.8% (World Bank, 2024). In order to also supply electricity to remote households not connected to the electricity grid, the Renewable Energies for Rural Markets Programme (PERMER) was initiated by the Argentinian government in 1999. As part of the programme, 29,980 systems with a total capacity of 8.15 MW were installed, which constitutes as one of the first significant deployments of renewable energies in Argentina (World Bank Group, 2013).

A decisive event with far-reaching effects on the Argentinian energy sector was the Argentinian economic crisis, which culminated in the Argentinian state being declared insolvent at the beginning of 2002. Driven by an overvalued Peso, this was preceded by a severe economic recession in 1998/99 and, as a result of capital outflows, the collapse of the Argentinian financial system in 2001. In this context, the Argentinian energy sector was severely affected by a series of crisis management measures: (a) public electricity tariffs were frozen and inflation indexation mechanisms were banned; (b) under the Emergency Law, the executive branch was given the right to renegotiate existing contracts with energy utilities; (c) existing contracts with energy utilities were converted from the US Dollar to the Argentinian Peso; and (d) the Peso exchange rate peg was abandoned, resulting in a 70% devaluation of the Peso against the US Dollar (Di Bella et al., 2015; Haselip & Potter, 2010). These circumstances also had a negative impact on the effects of the first wind energy law passed at the end of 1999. The law offered tax relief and a subsidy of 0.01 Argentinian Peso/kWh (Helmke, 2009; LaMarca, 2011). Due to economic uncertainties and the heavy devaluation of the Peso, the projects were halted at the planning stage and the law failed to materialise (Jones, 2021).

Table 2-1: Overview of key actors in the Argentinian electricity sector
Source: based on Coviello et al. (2012) and Nascimento et al. (2020)

Entity	Main functions and responsibilities
Argentinian Secretariat of Energy (Secretaría de Energía de la República Argentina)	▪ Analysing the Argentinian energy market and defining strategic planning across all segments of the energy sector ▪ Development and implementation of legislation relating to the national energy policy ▪ Promoting and monitoring projects for the extraction of conventional energy sources (gas and oil) ▪ Participation in the elaboration of tariff structures in the energy sector
CAMMESA Wholesale electricity market administrator (Compañía Administradora del Mercado Mayorista Eléctrico)	▪ Management of the wholesale electricity market ▪ Coordination of payment flows regarding the transmission system operator's fees ▪ Planning optimal operation of the Argentinian interconnected system and coordination of dispatch measures ▪ Evaluation of access and expansion requests ▪ Monitoring & development of measures to optimise the interconnected system ▪ Acquirer of PPAs of renewable energy projects
ENRE National Electricity Regulatory Agency (Ente Nacional Regulador de la Electricidad)	▪ Monitors the service quality of network operators and investigates customer complaints ▪ Determines the subsidised end customer prices ▪ Monitors compliance with safety and environmental standards ▪ Supervises compliance with competition regulations to avoid monopolistic structures ▪ Issues certificates for the expansion of the transmission grid
ENARSA Argentinian Energy Company (Energía Argentina Sociedad Anónima)	▪ ENARSA was founded in 2004 in the wake of the energy crisis under President Néstor Kirchner in order to establish a state-owned company in the fully privatised energy market ▪ Exploration and commercialisation of oil and gas reserves ▪ Supervision of tendering processes for renewable energies

After years of recession, the Argentinian economy began to recover in 2003 under the Néstor Kirchner government. This led to economic growth rates of over 8% p.a. between 2003 and 2007, accompanied by an increase in energy demand. This strong economic growth was the result of four main effects: a) maintenance of a stable and competitive real exchange rate, which promoted the export sector in particular, b) rising international commodity prices in export sectors relevant to Argentina, c) protective tariffs combined with an industrial policy to promote domestic production, and d) measures to contain domestic price development (M. Y. Recalde et al., 2015; Wylde, 2011). Two aspects were of central importance. On the one hand, energy as an essential necessity was to remain affordable against the background of social tensions that arose due to social deprivation during the economic crisis (M. Y. Recalde et al., 2015). On the other hand, affordable energy as a factor of production was supposed to counteract inflationary effects and thus contribute to currency stability (M. Y. Recalde et al., 2015). However, subsidies remained in place during the following years of government and became a major burden on the state budget. Driven by rising energy prices and growing demand, they became one of the largest items of government expenditure (Lakner et al., 2016). In terms of their share of GDP, the expenditure multiplied between 2005 and 2014, from 0.3% in 2005 to 3.5% in 2014 (Giuliano et al., 2020). While the evolution of electricity prices for large consumers continues to depend on the dynamics of the electricity exchange managed by CAMMESA, small commercial consumers and households benefit from a "seasonal price" that is set every six months and corresponds to less than 10% of actual costs (Lakner et al., 2016).[3] The remaining discrepancy is compensated by government payments to CAMMESA (Lakner et al., 2016). In addition to the negative impact on the country's fiscal capacity, there is incentive to use energy inefficiently, which in turn negatively affects long-term investment in energy efficiency and self-generation.

Between 2002 and 2022, electricity consumption in Argentina almost doubled and was mostly covered until 2015 by the expansion of thermal generation capacity (CAMMESA, 2024). For many years, additional gas demand was covered by national exploration. Since 2010, however, Argentina has become dependent on gas imports due to a lack of investment in the development of new gas reserves. This was reinforced by export taxes on conventional energy sources that, while supplying the domestic market, decoupled Argentina's market prices from rising global prices (Piragine et al., 2018). The resulting importation of natural gas had a negative impact on the energy trade balance, adversely affecting the Central Bank's limited foreign currency reserves. These reserves are crucial for monetary policy as well as trade management and are essential for the Argentinian state to meet its debt payments to international lenders. Between 2006 and 2014, 81% of the current account deficit was attributable to the energy sector (Serrani & Barrera, 2018). This is also significant in light of the fact that, particularly during the Cristiana Kirchner administration, the importation of capital goods was subject to restrictions due to a lack of foreign currency, which had a negative impact on the country's economic development (Serrani & Barrera, 2018). Between 2009 and 2021, natural gas production from conventional sources decreased by 5.6% (Serrani & Barrera, 2023). However, this negative development was compensated by an increase in natural gas production from unconventional sources until 2019, saving a total of $6,629m in foreign reserves in 2021 (Serrani & Barrera, 2023). The Vaca Muerta formation is one of the world's second largest shale gas reserves, only 10% of which has been developed (Lanardonne & Mazzochi, 2022). In addition to the strategic goal of developing non-conventional energy resources, the Kirchner government in Argentina

[3] The following example from 2014 underlines the significant financial burden on the national budget: while the average annual price on the electricity exchange was 663 Argentinian Peso/MWh, on average private individuals were only charged 31 Argentinian Peso/MWh (Lakner et al., 2016).

made numerous efforts to diversify the electricity mix. These included the resumption of the National Nuclear Plan in 2006, which led to the commissioning of the Attucha II nuclear power plant (725 MW) in 2014, and the construction of new hydroelectric plants with a total capacity of 1.1 GW. A third pillar consisted of measures to promote renewable energy[4], although these only resulted in an additional 270 MW by 2015 (Serrani & Barrera, 2023). Especially noteworthy is Law Nº26.190, passed in 2006, which sets a national target for the share of renewable energy of 8% by 2016 (M. Y. Recalde et al., 2015). As the incentive instruments included in Law No. 26.190 did not have the desired effect, 1 GW of renewable energy was tendered in 2009 under the GENREN programme (Garrido et al., 2016). However, although each project was based on a 15-year feed-in tariff denominated in US Dollars, less than 20% of the subsidised projects were implemented due to financing problems closely linked to the country's structural problems (Ruggeri & Garrido, 2021). With a share of 2% (including small hydropower plants under 50 MW), or only 0.6% (excluding this generation source), the target of 8% was not achieved by 2016 (CAMMESA, 2023a).

The change of government in 2015 triggered significant shifts in Argentina's energy system. Argentina's new president, Maricio Macri, declared a state of energy emergency in the face of growing energy security problems and rising government spending. One of the measures was to reduce energy subsidies, which led to a 150% increase in retail prices for residential customers in the Buenos Aires region (Gomel & Rogge, 2020). Another important component of the new energy strategy formulated around 'Plan 2025' was the expansion and diversification of the electricity generation infrastructure (Gomel & Rogge, 2020). In the context of the ratification of the Paris Climate Agreement in 2016 and the setting of ambitious targets, the expansion of renewable energy constituted a key element in reducing emissions from the energy sector by 103 MtCO2e by 2030 (Nascimento et al., 2020). To achieve this goal, Law Nº27.191 set the target of meeting 20% of electricity demand from renewable sources by 2025 (Ruggeri & Garrido, 2021). The following years were marked by a rapid expansion of renewable energy, reaching 6.1% by 2019 (when Maurico Macri's term ended) and 14.3% by 2022.

The election of Javier Milei as President of Argentina at the end of 2023 might have a significant impact on the development of renewable energy in Argentina. Milei's election has resulted in breaking with the previous direction taken with regard to many policies. For example, since he took office, the Ministry of the Environment has been dissolved and its responsibilities redistributed to other ministries (Leonardelli, 2024). In addition, the government is advocating a sceptical climate change narrative and promoting the expansion of fossil fuels through massive tax incentives (Messari, 2024). The ambiguities, for example regarding compliance with the Paris Agreement's climate targets and related energy policies, are increasing uncertainty for renewable energy investments in Argentina. However, as the empirical data collection was completed in 2023, current developments in 2024/25 are not reflected in this

[4] In Argentina, large hydropower is not counted as a renewable energy source in official statistics and public renewable energy targets. However, Law 27.191 contains an exception for small hydropower (<30 MW). To ensure data conformity, this research adopts this definition.

research. However, they underscore the relevance of contextual changes for the development trajectory of renewable energy in Argentina.

Table 2-2: Phases of the evolution of the Argentinian system regarding the generation mix
Source: based on Kazimierski (2020)

Phase	Main characteristics
Phase 1: 1900 – 1949	▪ Installation of small, decentralised coal-fired power generation plants close to the point of consumption and development of local grid structures
Phase 2: 1950 – 1972	▪ Early 1950s: Transition from coal-fired power generation to oil-fuelled power plants in the context of the development of national oil reserves ▪ Endeavours by the Argentinian governments to diversify the energy matrix through the use of hydropower, gas-fired power plants and nuclear power ▪ Construction of individual transmission lines to connect neighbouring regions with each other
Phase 3: 1973- 1989	▪ Realisation of the diversification strategy: - Dawn of Argentinian nuclear energy with the Attucha I power plant (370 MW) and subsequent Embalse Río Tercero reactor (648 MW). - Significant increase in hydropower generation and gas-fired power plants ▪ Continuous expansion of the national transmission grid to transport the electricity of the new power plants to the centres of consumption. The Patagonia region remains an independent grid
Phase 4: 1989 - 2000	▪ Structural reforms of the Argentinian state - Unbundling of the electricity sector and liberalisation of the energy market - Privatisation of the state-owned energy companies ▪ Massive expansion of gas-powered thermal power plant capacity ▪ Argentina is a pioneer of wind energy in South America. The main players are energy cooperatives ▪ Start of the PERMER programme: Electrification of remote rural areas using decentralised renewable energy generation
Phase 4: 2001- 2002	▪ 2001/2002: Argentinian Economic Crisis and default of the Argentinian state ▪ Sharp devaluation of the Argentinian Peso & government attempts to freeze energy tariffs in Argentinian Pesos through emergency legislation ▪ First national law to promote renewable energy, though this was ineffective due to economic conditions
Phase 5: 2003 - 2015	▪ From 2003, economic recovery with strong growth in electricity demand to be met by the construction of new gas-fired power plants ▪ Heavy subsidisation of energy prices with negative effects on the national budget ▪ Decline in Argentina's natural gas production and incipient dependence on imports, with a massive negative impact on the Central Bank's scarce foreign exchange reserves ▪ Inability to meet national renewable energy targets in a challenging economic and political context
Phase 6: 2016 - 2019	▪ Maricio Macri's government declares a state of energy emergency and cuts energy subsidies ▪ Argentina returns to the international financial market ▪ Commitment to the Paris Climate Agreement and massive expansion of renewable energy ▪ Economic crisis in 2018/19

2.2 Potential of renewable energy in Argentina

As can be seen from the overview in Figure 2-1, Argentina's diverse geographical conditions offer the country excellent opportunities to use various forms of renewable energy sources. In this respect, Argentina holds an advantageous position in the Latin American region and has the second largest potential for renewable energy sources after Brazil (M. Recalde, 2015).

Argentina's vast plains and long coastal areas offer optimal conditions for the development of wind energy. In a global comparison, Argentina is one of the countries with the greatest wind energy potential (Fenés, 2015; Zazzini & Wirszke, 2013). One of Argentina's distinguishing features is that 70% of its territory has average wind speeds of over 6 m/s at a height of 80m, which allows wind energy to be developed economically (CADER, 2013). Of particular significance is the Patagonia region, which is one of the windiest regions in the world with average wind speeds of between 9 and 12 m/s at 80m above sea level (CADER, 2013). However, the provinces of Córdoba, La Pampa, San Juan, La Rioja and parts of the Buenos Aires region, which has the largest share of national electricity consumption, also offer very good capacity factors of between 35 and 40% (CADER, 2013)

Owing to its more than 3,500 km long north-south extension and an east-west extension of more than 1,000 km in many areas, Argentina offers ideal geographical conditions for the generation of photovoltaic electricity (AHK Argentinien, 2017). Although the country's southernmost provinces have the lowest average annual irradiation values, at 1.2 MWh/m^2/year they are comparable to the highest global solar irradiation in Germany (AHK Argentinien, 2017). The overview in Figure 2-1 shows that the north-western regions of Argentina have extraordinary potential for the use of photovoltaic energy. With irradiation values of 1.8 to 2.2 MWh/m^2/year, these are comparable to the irradiation values in North Africa and Spain (Secretaría de Energía, 2009). Considering that 20 of Argentina's 23 provinces have irradiation values of over 1.5 MWh/m^2/year, in general it can be stated that economic photovoltaic generation is feasible almost nationwide (AHK Argentinien, 2017).

Biomass and hydropower represent further complementary renewable energy sources in Argentina which are, however, beyond the scope of a technology-specific analysis in the context of this dissertation. The country has considerable biogas potential, which is derived from its extensive agricultural resources. The agricultural sector is of outstanding economic importance for the country, particularly due to the export of agricultural products. The targeted utilisation of organic waste, primarily from agriculture and livestock farming, represents a promising option for tapping into biogas as a renewable energy source. Agricultural crops are grown on an area of around 35 million hectares, while around 54 million cattle are kept on an area comparable to the size of Germany (Budzinski & Barlatey, 2014; Bundesministerium für Ernährung und Landwirtschaft, 2021). With an installed capacity of 11 GW, hydropower is one of the central pillars of Argentina's electricity supply. In 2022, it accounted for around 22% of Argentina's electricity mix, generating around 31.25 GWh (CAMMESA, 2023c). However, it is important to note that large-scale hydroelectric power plants are explicitly not part of the official definition of renewable energy and therefore are excluded from the Argentinian national target and renewable energy statistics.

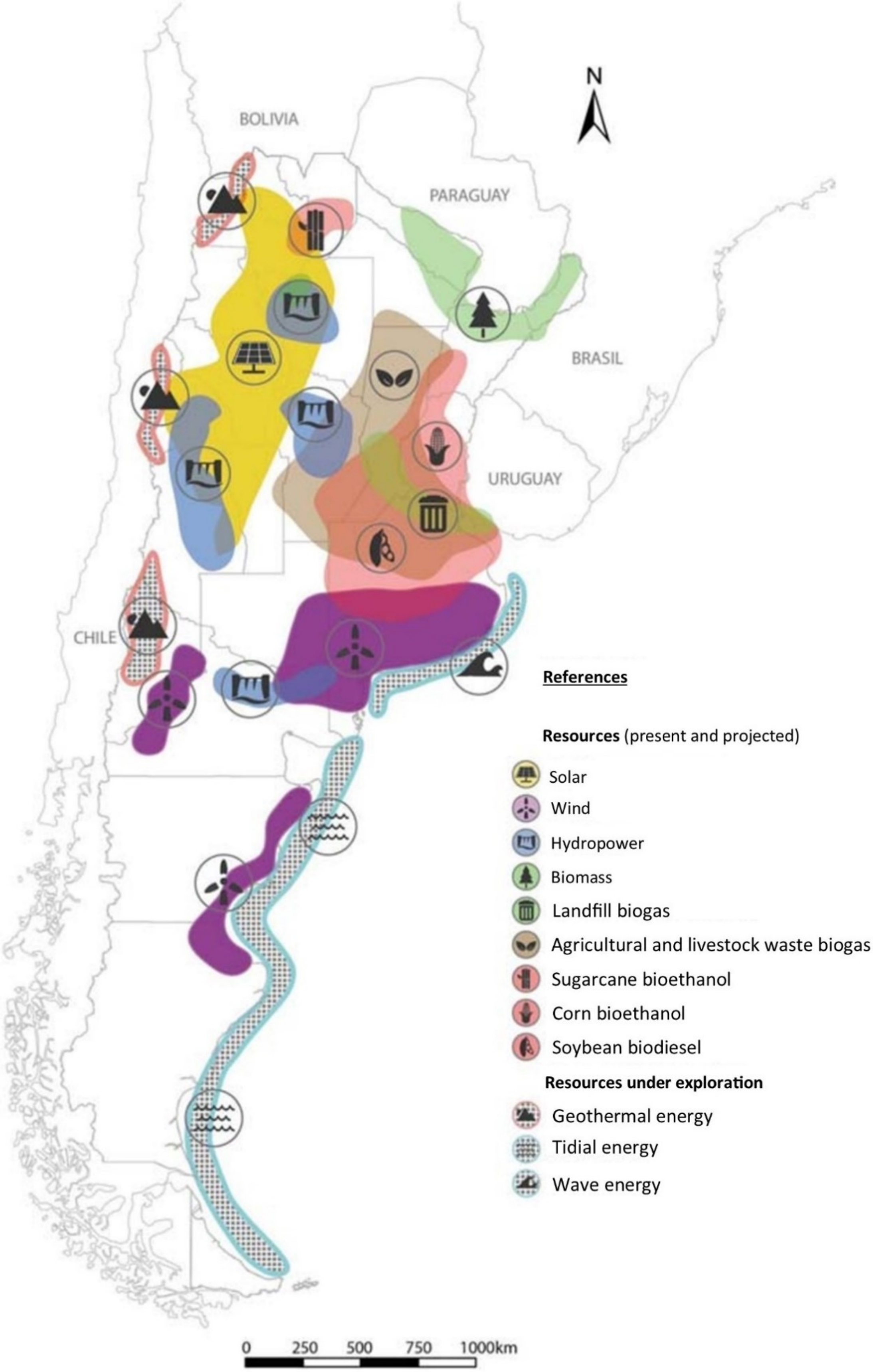

Figure 2-1: Renewable energy resources in Argentina
Source: Translated and used with permission from Luciana Clementi, based on Clementi et al. (2019)

2.3 Conclusion and research question

The diversity of national energy sources is one of the outstanding features of Argentina's power sector. The country has significant deposits of fossil energy sources, which have shaped the development of Argentina's power system. Since the end of the 1990s, natural gas has become the main source of power supply (Lampis et al., 2022). The exploration of unconventional gas in the last years further reinforced these path dependencies (Villalba et al., 2021). In addition, Argentina's geographical location offers ideal conditions for the use of renewable energy (Clementi et al., 2019). The country is particularly suited to the development of renewable energy projects due to high solar radiation, especially in the northern regions, and strong winds in Patagonia and along the coast (Clementi et al., 2019). Renewable energy has the potential to make a significant contribution to the country's energy supply, while also reducing the environmental impact (Murshed et al., 2022).

During the 1990s, Argentina was one of the pioneers of renewable energy development in South America. Early development was driven by the leading role of energy cooperatives in the wind energy sector and electrification programmes in remote rural areas. In the years that followed, the Argentinian government repeatedly set ambitious targets for the expansion of renewable energy. However, none of the targets have been met and by 2016 there had been no significant expansion of renewable energy, despite a wide range of support programmes. As illustrated in Figure 2-2, in the Argentinian context the development path of renewable energies has been extremely unstable in the aftermath of the sovereign default in 2001/02. Economic crises, political instability and changing regulatory frameworks led to structural changes in the Argentinian energy sector and shaped the investment environment for renewable energy in Argentina. Not much progress was made in expanding renewable energy until the Maurico Macri government (2015-2019) was elected. Under Maurico Macri, the government cut energy subsidies, introduced new support programmes for renewable energy such as the successful RenovAr programme, and set legal requirements for the share of renewable energy for large consumers.

To gain a deeper understanding of these complex and multi-dimensional relationships and the constant ups and downs (see Figure 2-2) associated with the diffusion of renewable energy in Argentina, this resaerch will distinguish between endogenous and exogenous factors. Endogenous factors refer to the internal dynamics within the socio-technical system of renewable energy in Argentina (F. W. Geels et al., 2018). These include structures and processes that are intrinsic to the social-technical system or that emerge from the system. Examples include social networks, learning processes, technological improvements and the development of value chains in the renewable energy sector in Argentina. This perspective is complemented by the consideration of exogenous factors, which are external influences arising from the existing country-specific context in which the development of a new technology is embedded (Edsand, 2019; F. W. Geels et al., 2018). These are, for example, the existing social, political, economic and energy sector context. This distinction between endogenous and exogenous factors underscores the complex interplay of dynamics shaping the development path of low-carbon innovations. Therefore, the objective of this dissertation is to explore the relevant factors influencing the development of renewable energy in the country-specific context of Argentina. This is addressed by the following research question:

How do endogenous and exogenous factors influence the diffusion dynamics of the distinct renewable energy innovations in the context of the socio-technical transition of the Argentinian power system?

Recent studies on the diffusion of renewable energy in Argentina have mainly focused on assessing the technical capacity and the progress of installed capacity (Genchi et al., 2016; Labriola, 2020), as well as the role of specific regions such as the province of Buenos Aires and Salta (Camargo et al., 2016; Clementi, 2018; Escalante et al., 2013). Other research has been devoted to the question of how renewable energy can contribute to reducing carbon emissions in the Argentinian electricity sector (Murshed et al., 2022) and the production of hydrogen (Armijo & Philibert, 2020; Sigal et al., 2014). In addition, significant research efforts have been devoted to analysing the regulatory framework and the influence of macroeconomic conditions on the success of renewable energy initiatives in Argentina (Barrera et al., 2022; Giralt, 2011; M. Recalde, 2010; Ruggeri & Garrido, 2021). However, a holistic approach that takes into account the different factors influencing the diffusion of renewable energy in the Argentinian context is lacking. The aim of this research is to contribute to filling this research gap. Chapter 4.3 provides a comprehensive overview of how the individual scientific publications of this dissertation (see Appendices A-D) are positioned within the context of the overarching research framework. It also presents the specific contribution these publications make to answering the research question. Furthermore, a brief summary of these publications is presented in Chapter 5.

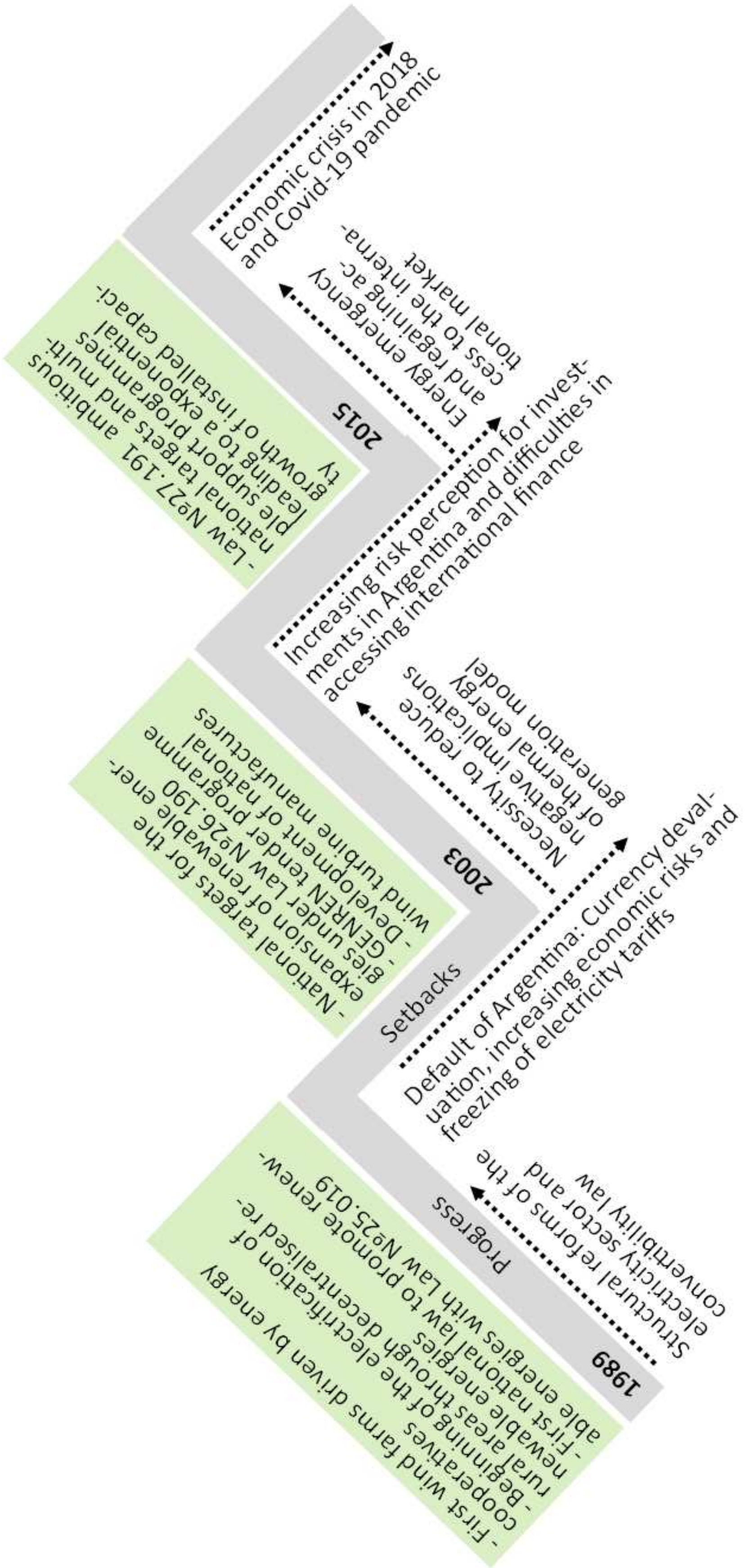

Figure 2-2: Development of renewable energy in Argentina within main context-specific dynamics
Source: Own illustration, inspired by Clementi (2018)

3 Theoretical background

3.1 Innovation and socio-technical transitions

Innovations play a central role in the scientific discourse of sustainability transitions research (STR), in which this dissertation is theoretically embedded. This research field is concerned with the complex processes through which societies in various domains can transition from environmentally harmful or unsustainable states to more sustainable alternative practices. In this context, innovations are perceived as the central driving forces that significantly influence the transition to sustainable societies. Sustainability transitions research is based on a broad understanding of innovation. On the one hand, innovations in the form of technological change (e.g., decarbonisation of the energy system through the dissemination of renewable energies) are perceived as a key aspect of sustainability transitions. On the other hand, changes in social practices (e.g., changes in social norms, consumer behaviour and lifestyles) are another relevant component of sustainability transitions. Thereby, the interaction between technological and social change is understood as a dynamic process that influence each other and jointly contribute to the realisation of sustainable developments.

Moreover, the suitability of alternative research frameworks for addressing the research question was explored at the beginning of the research journey. One example in this context is Rogers' Diffusion of Innovations Theory which examines the diffusion of new technologies from both a process-oriented and a market-oriented perspective (Veronika Karnowski, 2016). The theoretical framework was not considered appropriate for the purposes of this study due to the limitations of this approach identified by authors Kropp (2018) and MacVaugh & Schiavone (2010). Nevertheless, the basic ideas of this approach are embedded in the applied theories of STR, e.g., the TIS life cycle. The limitations of Rogers' Diffusion of Innovations Theory mentioned in the literature are its insufficient consideration of contextual factors in different areas of application and the interaction with the various levels of the socio-technical system as well as resulting path dependencies (Kropp, 2018; MacVaugh & Schiavone, 2010).

In order to take this complexity regarding innovation processes into account, various theoretical approaches have been developed in this field of research. Within the scope of this dissertation, the three main approaches are the Multi-Level Perspective (MLP), Strategic Niche Management (SNM) and Technological Innovation Systems (TIS). The Multi-Level Perspective of the MLP framework focuses on the change of socio-technical regimes through new innovations and external influences. The Strategic Niche Management perspective concentrates on the development processes of innovations in technological niches. The TIS analyses innovations at the level of technology systems and examines how novel technologies evolve within these systems within various dimensions of analysis. Overall, one can summarise by saying that the different frameworks provide different perspectives on the diffusion of renewable energy innovations. While the MLP approach broadens the perspective with regard to the holistic transformation process of socio-technical systems, the Strategic Niche Management and Technical Innovation System approaches focus on the specific development of individual technologies and fields with respect to their application niches.

Therefore, the following sections provide a brief overview and relate to the theoretical concepts of relevance within the scope of this investigation. Since a central guiding principle of this investigation is to assess the development of different renewable energy technologies in the context of the transition dynamics of Argentina's energy sector, this chapter first reviews the fundamental debates on the transition of socio-technical systems and niches. Thus, the first two sub-sections introduce the concepts of the Multi-Level Perspective and Strategic Niche Management. A further guiding principle of this investigation has been to provide a deeper insight into the processes of development within specific fields of technology in the wider Argentinian context. Therefore, subsection 3.2.3 introduces the Technical Innovation System framework, which provides a complementary perspective that enables a focus on the development dynamics within the trajectories of individual renewable energy technologies. Finally, section 3.3 brings together the different theoretical perspectives and identifies the relevant research gaps addressed in the course of this research journey.

3.2 Overview of the theoretical frameworks

Excerpts from the texts in section 3.2 have already been published in texts written by the author of this dissertation. These are extracts from the theory chapter of the author's Master's thesis[5] and from the four scientific publications (see Table 5-1) on which this thesis is based. These text passages are labelled in *italics*.

3.2.1 Multi-Level Perspecitve[6]

In order to analytically frame the development of new technologies inside a socio-technical system the Multi-Level Perspective (MLP) on a socio-technical transition has emerged as a heuristic framework. It conceptualizes a transition of a socio-technical system as a process being shaped by a dynamic interplay of three levels: Niches, regimes and landscapes. The regime is a dominant socio-technical configuration inside the socio-technical system which embodies the mainstream way of currently providing a societal function and contains its basic logic of functioning (Smith & Raven, 2012). *Linkages between interrelated heterogeneous elements lead to a dynamic social structure being constantly reproduced which has an auto-stabilizing effect on the regime and by this only leaves room to incremental innovation. In contrast radical innovations challenging the established regime structures arise in the niche level which is defined as "... protected spaces that allow the experimentation with the co-evolution of technology, user practices and regulatory structures"* (Johan & Geels, 2008, p. 537). *Niches and regimes are embedded in a broader landscape which provides the macro-level-structuring exogenous context which shapes the overall developments and can hardly be*

5 The Master thesis with the title "Dynamics of decentralized renewable energy niche building processes in Argentina" was handed at the "Bergische Universität Wuppertal" in 2017.

6 Subsection 3.2.1: Excerpts from the author's Master thesis with the title "Dynamics of decentralized renewable energy niche building processes in Argentina" and the theory section of the articles: Schaube (2024) and Schaube et al. (2018, 2022). These text passages are labelled in *italics*.

influenced by individuals or groups of actors. In this context Geels defines a transition as a shift from one regime to another, which does not only include physical changes in infrastructure or organization, but also can lead to a redefinition of norms and values (F. W. Geels, 2011; Schneidewind & Augenstein, 2012). *Consequently, this approach unites bottom-up and top-down dynamics which interrelate in the different phases of a transition process. Through a process of niche-accumulation these radical innovations can break out from the niche- to the regime level, "… when ongoing processes at the levels of the regime and landscape create a ´window of opportunity´"* (F. W. Geels, 2002, p. 1262). *However, regulation and norms, cognitive and normative rules, sunk-investments in artefacts, constancy of established infrastructure, and interdependent actor and material networks function on the regime level in existing trajectories as stabilization mechanisms and are hindering the development of novel alternatives developing at the micro level in socio-technical niches* (Johan & Geels, 2008; Viétor et al., 2015). *Therefore socio-technical regimes function as selection and retention mechanisms, so that the stability of socio-technical configurations is guaranteed which can led through path-dependency to a systemic resistance to change* (Elzen et al., 2002).

This particular understanding of the transition process is specific to the MLP and has its theoretical roots combining the concepts of institutional theory, evolutionary economics and the sociology of innovation (Köhler et al., 2019). The institutional theory emphasises the role of rules and norms in shaping innovation processes. Thereby, it explores how formal and informal rules influence the interaction between actors in a society and how these rules influence the trajectory of innovations (Grin, Rotmans, Schot, et al., 2010). Evolutionary economics views economic change as an evolutionary process and emphasises the importance of variation, selection and path dependence for the course of innovations (F. Geels, 2005). The sociology of innovation deals with the social and organisational aspects of innovation processes. It examines how social networks, actor constellations and cultural factors influence the emergence and diffusion of innovations (F. W. Geels, 2004). Combined, these theoretical approaches allow a comprehensive understanding of innovation dynamics in the context of sustainability transitions. They take into account the multiple interactions between actors, institutions, technologies and social norms that shape the process of introducing and diffusing sustainability innovations. Against this background, in order to provide a deeper understanding of the MLP framework, the following sections outline the core elements and premises of the MLP framework and relate them to the underlying theoretical foundations.

Socio-technical system: The framework of the MLP is based on a socio-technical system perspective which enables to analyse the complex interplay of social and technological elements within a specific sector (F. W. Geels, 2005). *In contrast to the concept of technology as an autonomous artefact, technology is seen as a product of social shaping which is a situated process of co-evolution and co-production of human and non-human actors* (F. W. Geels, 2005). *On the basis of this underlining considerations Geels comes to the conclusion that the "linkages between technical and social elements provide stability" and that "sociotechnical change… is a process of shifting assemblies of associations, substitutions and a reweaving of elements"* (F. W. Geels, 2002, p. 1259). *In his perspective technology itself does not have power, it just* *can function in interaction with human agency, social structures and organization* (F. W. Geels, 2002). *Each technological function, for instance transportation or provision of electricity, is embedded in a socio-technical configuration which is a heterogeneous set of elements being linked together* (F. W. Geels, 2002). *For instance regarding the transportation function, the vehicle as the artefact, the road- and fuel infrastructure, regulation and policies, culture and symbolic meaning of cars etc. can be identified as a set of elements that form the socio-technical configuration* (F. W. Geels, 2002). *This perspective can be led back to* Rip & Kemp (1998) *who conceptualize technology as configurations that work. This characterization of technology "… avoids the individualistic bias of a tools concept, and so can include large technical systems. Artifacts, procedures and humans can be part of this configuration*" (Rip & Kemp, 1998, p. 387). The term 'configuration' refers to the arrangement and interaction of various heterogeneous elements, and the addition 'that works' implies that this configuration serves to perform a specific function (Grin, Rotmans, Schot, et al., 2010). This understanding emphasises the interplay between technical and social components, as well as the inherent focus on utilitarian value and functional areas of application (Grin, Rotmans, & Schot, 2010). The socio-technical perspective thus emphasises that technologies are always situated in specific contexts and should be analysed against this background (Grin, Rotmans, Schot, et al., 2010).

Radical and incremental innovations: Our current understanding of innovations has been significantly influenced by Joseph Schumpeter's pioneering and comprehensive conceptualisation of innovation processes. He recognised that new combinations of production factors are the source of economic development (Blättel-Mink, 2020). Schumpeter emphasised that innovations encompass not only the introduction of new products but also new production processes and organisational forms (Burr, 2022). Another important facet of his findings is that innovations, unlike inventions, are novelties that have to prove their economic success in diffusion and application processes (Blättel-Mink, 2020). His distinction between radical innovations, which introduce fundamentally new ideas, and incremental innovations, which build on existing ideas and improve on them gradually, provides guidance in understanding the diversity and transformative potential of innovations in different contexts (Burr, 2022). One key differentiating characteristic is the novelty of the knowledge base on which the innovation is based. A radical innovation implies a high degree of discontinuity in the knowledge base, while incremental innovations are characterised by a greater continuity in the type of knowledge that is used (Bell, 2012). Second, the size and relevance of the economic (and other) consequences of the innovation are taken into account. In essence, the underlying assumption is that the impact and effects of radical innovations are much greater and more 'disruptive' than those of incremental innovations (Bell, 2012). The distinction between "radical innovation" and "incremental innovation" has been adopted by the MLP framework and is an essential aspect of the conceptualisation (Twomey & Gaziulusoy, 2016). Within the MLP concept, socio-technical niches act as places of origin for radical innovations, providing a protected space for their further development (F. W. Geels et al., 2017). Incremental innovations play a crucial role in maintaining the stability and continuity of an existing regime, thereby enabling a regime to adapt to changes in requirements without destabilising its fundamental and underlying patterns (F. W. Geels, 2004).

Socio-technical regimes and path dependency: Schumpeter's ideas have been adopted and advanced by evolutionary economics (Resch, 2022). With its conceptualisation of technical development processes, evolutionary economics constitutes an important contribution to the MLP framework (F. W. Geels, 2020). Decisive impetus for the understanding of innovation in sustainability transitions research lies in the insight that, under the key word "history matters", the sequence of events is relevant for the course of an innovation. This also means that individual events can lead to self-reinforcing effects. As a result, path dependencies can emerge and technologies prevail in the market (Häußling, 2019). Resulting possible log-in constellations are of particular interest in the context of transition research with regard to the question of how dominant socio-technical configurations, such as conventional energy production, persist over long periods of time (Klitkou et al., 2015). Another important impetus for the MLP framework is the role of uncertainty in the development of innovations. In this context, Nelson & Winter (1982) developed the concept of "technological regimes", which are particularly relevant in relation to pre-market technological trajectories. They act as "carriers of history" and play an important role as selective environments during technological development (Grin, Rotmans, Schot, et al., 2010). Technology regimes are based on the idea that existing search strategies and problem-solving approaches can be used to frame innovative research and development processes. Like paradigms, they define the field in which the search for a solution appears worthwhile and thus trajectories in the sense of technology-specific corridors are constituted over time (Weyer, 2008). In the market entry phase, the "selection environment" is responsible for the question of whether an innovation leads to the desired success. In this phase, social processes are crucial, e.g., market entry timing and convincing management and relevant market actors such as regulators and consumers. This highlights the importance of institutional factors, both market and non-market, in the development and implementation of innovative products (Häußling, 2019).

Geels adopted Nelson and Winter's concept and advanced it to the concept of socio-technical regimes by combining it with the sociological category of rules. By this he created the concept to socio-technical regimes (F. W. Geels, 2002). In this context Geels refers to Anthony Giddens' structuration theory, which states that human behaviour is at the one side determined by social structures, but on the other hand human agency can also actively influence and change these structures (Grin, Rotmans, & Schot, 2010). *While Nelson and Winter have focused on the engineering community, Geels extends the concept and notes that "... technical trajectories are not only influenced by engineers, but also by users, policy makers, societal groups, suppliers, scientist, capital banks etc."* (F. W. Geels, 2002, p. 1259). Geels builds on the idea of Nelson and Winter and argues that socio-technical regimes provide guidance to the actors involved, thereby promoting the stability of socio-technical configurations (F. W. Geels, 2002). *Examples for the stabilization in existing trajectories are regulation and norms, sunk-investments in machines, infrastructure, cognitive routines in the scientific world and lifestyles based on certain technology* (Geels and Schot 2007). *In this way the socio-technical regimes function as selection and retention mechanisms, so that the stability of socio-technical configurations is guaranteed* (F. W. Geels, 2002). However, a systematic literature review criticised the concept of regimes as not being applied coherently in the transition literature (Markard et al., 2012). With the differentiation between 'broad' and 'narrow' regime conceptualisations, it was shown that two distinct regime understandings have evolved in transition research (Holtz et al., 2008). While the narrow conceptualisation defines regimes as rule sets, a broad conceptualisation also integrates tangible elements, such as actors, infrastructure and technological artefacts (Holtz et al., 2008). However, as pointed out by Best et al. (2012), both regime understandings have in common that the boundaries of the conceptualisations are defined by the fulfilment of a specific societal function. In order to provide a clear theoretical basis for this dissertation, this research is based on a broad regime conceptualisation, following the regime definition of (Holtz et al., 2008):

"A regime comprises a coherent configuration of technological, institutional, economic, social, cognitive and physical elements and actors with individual goals, values and beliefs. A regime relates to one or several particular societal functions bearing on basic human needs. The expression, shaping and meeting of needs is an emergent feature of the interaction of many actors of the regime. The specific form of the regime is dynamically stable and not prescribed by external constraints but mainly shaped and maintained through adaptation and co-evolution of its actors and elements" (Holtz et al., 2008, p. 629).

Socio-technical niche and landscape: *As for Geels the regime level is characterized by a high level of stability and only can lead to incremental innovation, he states that radical sustainability innovation arises in the niche level.* The socio-technical niche in MLP differs from the market niche in evolutionary economics in the sense that market niches and user demand do not yet exist for many radical innovations, especially those with substantial sustainability improvements (Johan & Geels, 2008). In addition, many of these developments are not minor variations on existing technologies. Rather, they are radically different innovations (Johan & Geels, 2008). Johan & Geels (2008) distinguish between local socio-technical projects and the global niche level. The latter represents an emerging overarching structure characterized by the development of shared cognitive, formal, and normative rules (Johan & Geels, 2008). *In their view sequences of local projects may gradually add up to an emerging field at the global level and through the aggregation of the experiences, interaction between the actors and the stabilization of rules a niche is created* (Johan & Geels, 2008).

Alongside the dynamics of socio-technical niches, developments at the level of the macro-structural context, the so-called landscape, are relevant for the transition of socio-technical systems in the MLP framework (Johan & Geels, 2008). *Regarding the temporal dimension landscape factors refer to factors 1) that do not change, or evolve very slowly, such as the biophysical enviroment (e.g. availability of renewable energy potential in a certain region and climate), 2) long term developments (e.g., macroeconomics, demography, ideology) and 3) exogenous shocks (e.g., economic crises, drastic accidents, sudden political shifts)* (El Bilali, 2019; F. W. Geels et al., 2017; Grin, Rotmans, Schot, et al., 2010). However, this does not mean that landscape developments are not affected by human agency (Grin, Rotmans, & Schot, 2010). Developments such as climate change and urbanisation result from the interaction of a large number of actors over a long period of time. The essential difference from the perspective of the MLP framework, however, is that niche or regime actors have no, or if any, very little influence on the landscape level, which in turn provides the exogenous context in which the trajectory of technologies is embedded (F. W. Geels & Kemp, 2007). However, regarding the regime-landscape interaction, the results of this dissertation suggest a more differentiated view, which will be outlined in detail in the last chapter.

Transition pathway and socio-technical change: The central idea of the MLP framework is that socio-technical change is the result of the interaction between three different levels: *'niche innovations', 'socio-technical regime' and the 'socio-technical landscape' as an exogenous context* (F. W. Geels, 2002). *For* F. W. Geels (2011) *the regime-level is crucial because he defines transitions as a shift from one regime to another regime and by this it is an outcome of the linkages between the processes at the different levels. Consequently, regarding the regime level this concept unites the bottom-up and top-down dynamics which interrelate in the different phases of a transition process and therefore the niche and the landscape level have to been seen in relation to the regime level. Thus, each level refers to a heterogeneous configuration of elements with a different degree of structuration and stability* (F. W. Geels, 2011). However, the individual outcome of a development is not solely dependent on the specific configurations, but rather is significantly determined by the temporal sequence of multi-level interactions (Grin, Rotmans, Schot, et al., 2010). Depending on the characteristics and temporal interplay of developments, five archetypal transition pathways are outlined in the transition literature, which are summarised in Table 3-1.

Table 3-1: Transition pathways
Source: Based on Grin, Rotmans, Schot, et al. (2010), Gudbrandsdottir et al. (2021) and Häußling (2019)

Transition pathways	Nature of interaction		Characteristics
	Landscape pressure	Niche-regime relationship	
Reproduction	No	Not relevant	Without external pressure from the overarching landscape level, socio-technical regimes are in a state of dynamic stability independent of the degree of maturity of the niche innovation. Under these conditions, a niche innovation, regardless of its degree of maturity, has only limited prospects of becoming the dominant technology. Minor challenges at the level of the existing regime tend to be solved by incremental innovations from the research and development community. Typically, this community is strongly oriented towards the prevailing socio-technical regime, which means that radical innovations developed by "outsiders" in niches are often marginalised and do not receive the attention they require.
Transformation	Yes (moderate)	Competing or symbiotic	In cases where the pressure at the landscape level is moderate and the niche innovation is at an early stage of development, its successful diffusion becomes more difficult. In contrast, established socio-technical regimes show the ability to adapt their structures, and to reorient and integrate the advantageous elements of emerging niche innovations to maintain both their resilience to external influences and their ability to evolve.
Reconfiguration	Yes (moderate)	Symbiotic	This development path is characterised by the presence of a niche innovation that does not compete with the established socio-technical regime but is compatible with it. The niche innovation is integrated into the respective regime, usually in the form of an add-on or component replacement. This integration triggers a gradual adaptation of the regime structure, which substantially transforms it and results in a reconfiguration of the regime.
De-alignment and re-alignment	Yes (strong or shock)	Competing	This development path is characterised by sudden and strong pressure for change that originates from the landscape level. This destabilises the prevailing socio-technical regime, which is not in a position to react due to internal challenges. As a result, this regime erodes and becomes de-aligned, opening a development space for existing but insufficiently developed niche innovations. Finally, a dominant niche innovation prevails, leading to a re-alignment and the establishment of a new socio-technical regime.
Technological substitution	Yes (strong or shock)	Competing	*Through a niche accumulation process, radical innovations can break through from the niche to the regime level. This happens when ongoing processes at the regime and landscape levels create a "window of opportunity". These windows of opportunity for niche innovations arise through interactions between different processes: a) the innovation has developed sufficiently at the niche level (e.g., through learning processes, technical improvements, cost reductions) and creates momentum, b) new developments at the landscape level exert pressure on the regime, and c) symptoms of destabilisation occur at the regime level.*

3.2.2 Strategic Niche Management[7]

The MLP is a fruitful heuristic for analysing transition processes within large socio-technical systems such as the Argentinian electricity system, which is the subject of this thesis. Strategic Niche Management is a complementary framework that is appropriate for a closer look at individual innovations such as renewable energies, because it *focuses on the role of protected 'niche' spaces as seedbeds of radical innovation and thereby analyses ongoing processes within niches and the conditions for their successful development. The rationale behind this approach is that new innovations require the niche as a protected environment to potentially become robust enough to compete with and displace the existing socio-technical regime.* Kemp et al. (1998) *postulate that the established regime is characterised by dominant rules and guiding principles, and the resulting adversary selection pressure negatively effects the development of the emerging technology. The niche is therefore necessary as a protective space in which the emergent technology can mature and the learning processes necessary to further develop and use the new technology can be initiated* (Kemp et al., 1998). Therefore, the development trajectory of a niche, as outlined in Table 3-2, is driven by the interplay of shielding, nurturing and empowerment processes (Smith & Raven, 2012).

Table 3-2: Summary of niche building processes
Source: see citations in the table

Shielding	Active shielding: Active protective spaces are deliberately created by supporters of innovation to shield it from the selective environment of the socio-technical regime. Political and regulatory support instruments play a crucial role in this context (Smith & Raven, 2012).
	Passive shielding: Passive protective spaces are application contexts that already existed before the development of the innovation, but which by their very composition create a space that protects the innovation from the selection pressure of the socio-technical regime (Smith & Raven, 2012).
Nurturing	*Shaping of expectations: In the early stages of the niche development, the competitive advantages of a new technology are often not evident. Kemp points out that expectations function as a promise for the future and are "…especially powerful if they are shared, credible (supported by facts and tests), specific (with respect to technological, economic and social aspects) and coupled to certain societal problems…" (Kemp et al., 1998, p. 189). Therefore, the coupling of expectations among the different actors is an important factor in the niche development process.*
	Network formation: In the trajectory of the niche development process, the formation of actor networks is essential. What are particularly valuable are networks with a broad member structure, which allows the integration of a broad spectrum of views on the one hand, and on the other hand has deep (resource intensive) commitment from the participating actors (Seyfang et al., 2014). An important function of the networks is the exchange of knowledge and coordination of the strategies of different actor groups as technology developers, investors, regulators and users (Kemp et al., 1998). When networks are composed of niche internal and external actors, they can play an important role in the expansion of a niche into a regime (Augenstein, 2014).

[7] Subsection 3.2.2: Excerpts from the author's Master thesis with the title "Dynamics of decentralized renewable energy niche building processes in Argentina" and the theory section of the article: Schaube et al. (2018). These text passages are labelled in *italics*.

	Learning processes: During the various stages of the niche development process, learning and knowledge sharing processes regarding the requirements, challenges and opportunities of the new technology play a key role (Kemp et al., 1998). First-order learning processes, oriented towards the accumulation of facts and data, take place when the new technology is applied in the field within local projects. Based on the surface features of a socio-technical practice, this is characterised by "…instrumental learning, concerned with the functioning of technologies, not with the assumptions on which their use rests" (Grin, Rotmans, Schot, et al., 2010; Urban & Nordensvärd, 2013, p. 243)*. Second-order learning questions the underlying values and assumptions about the present dominant approaches that fulfil the socio-technical function (Smith, 2007). This deeper reflection enables changes in cognitive frameworks and helps to identify problems within the socio-technical configuration of the dominant socio-technical regime* (Grin & Graaf, 1996; Johan & Geels, 2008)*. During niche development, these insights contribute to the development of diverse core values and norms (Smith, 2007).*
Empower-ment	Stretch and transform empowerment transforms different parts of the prevailing selection environment by enforcing and adopting elements of the institutional framework that developed through the shielding process of the socio-technical niche (Smith & Raven, 2012).
	Fit and conform empowerment is characterised by innovation becoming competitive, whereas the dominant socio-technical practices do not change (Smith & Raven, 2012).

As shown in Figure 3-1, F. W. Geels & Deuten (2006) *conceptualize the niche development process as an interplay between the cosmopolitan level and local practices. A global niche emerges when the technology is applied in multiple on-the-ground local projects which are linked together by networks and intermediary actors* (Seyfang et al., 2014). *In this context* F. W. Geels & Deuten (2006) *are subdividing the process into an ideal typical four-phased pattern.*

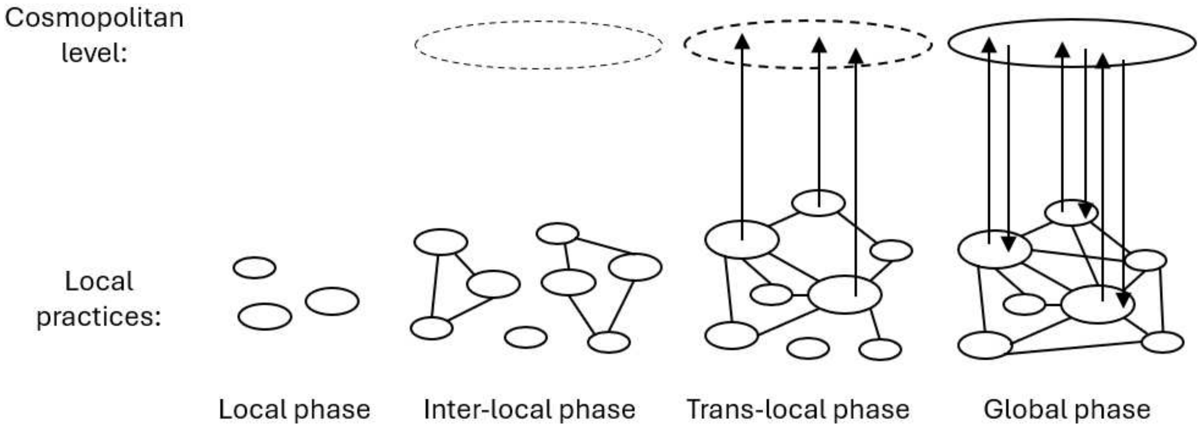

Figure 3-1: Niche development phases
Source: Own illustration, based on F. W. Geels & Deuten (2006)

The first phase is referred to as the local phase. It can be characterized by the existence of a group of local individual isolated projects developing novelties in response to local problems and demand. Therefore, the local variety in technological application possibilities is high and because of limited interactions between the actors the generated knowledge tends not to be shared with others (F. W. Geels & Deuten, 2006). *When the actors begin to share their knowledge and experiences across the project boundaries, a socio-technical niche is beginning to emerge. This* *stage is referred to as the inter-local phase. It is "… characterised by increasing circulation of technological knowledge within networks, alliances and supplier–producer relations"* (F. W. Geels & Deuten, 2006, p. 268). *Moreover, this phase distinguish itself by the existence of different technical designs which are engaged in competition with one another. In this context the actors use the emerging networks to raise the reputation of the specific technical designs in order entail a competitive advantage. At the same time the manufactures of the emerging technology interact with an increasing circle of actor groups and therefore exchange not only with other producers, however also with suppliers, users and regulators* (F. W. Geels & Deuten, 2006). *Furthermore, the knowledge gathered creates experts who begin to hold presentations at gatherings outside their local practices, representing the emerging technology to new groups of actors. The cumulative result of these various processes can lead to small emerging markets, which contribute to stabilising knowledge and quality standards of the innovation* (F. W. Geels & Deuten, 2006). *This, in turn, is followed by the trans-local phase which is characterized by the aggregation of local experiences and the production of knowledge "… that is not intended for use in specific local practices, but rather for the field as a whole"* (F. W. Geels & Deuten, 2006, p. 268). *An additional feature of this phase is that groups of actors start to form associations for the representation of collective interests and on the global level intermediary actors appear who are dedicated to knowledge creating and distributing activities* (Seyfang et al., 2014). *In the final phase, called the global phase, actors are engaged in coordinating projects and making knowledge robust and thereby available for others* (Seyfang et al., 2014). *A collective knowledge reservoir is created when the aggregated knowledge of a broad actor network results in the establishment of dominant cognitive rules and standards. In doing so, knowledge is not only aggregated at the global level but also becomes guiding for local-level practices. Simultaneously institutionalisation processes are taking place which manifest themselves i.e. in the circumstance that specialized courses and training programs are offered* (F. W. Geels & Deuten, 2006). As described in more detail in the previous subchapter on the possible trajectories of a transition process (see Table 3-1), the degree of maturity of the niche plays a decisive role in the course of the development processes. *In the global phase, the niche is robust enough to influence or replace the dominant socio-technical system.*

3.2.3 Technical Innovation System[8]

A third complementary perspective is the Technical Innovation System (TIS) framework *which is capable of breaking down the complex and multi-dimensional nature of the emergence and dissemination of novel energy technologies. The reasoning of the TIS framework builds on the work of* Carlsson & Stankiewicz (1991) *and evolutionary and institutional economics* (Nelson & Winter, 1982; Schout & North, 1991). *The underlying causal mechanism implies that the close interaction of system elements generates positive feedback effects that foster the emergence of interdependencies from which various forms of systemic synergies can evolve*

[8] Subsection 3.2.3: Excerpts from the theory section of the articles: Schaube et al. (2022) and Schaube (2024). These text passages are labelled in *italics*.

(Markard, 2018; Markard & Worch, 2009). *The framework is a fruitful heuristic for the purpose of this research as it not only focuses on novel technologies, but also provides insights into the institutional and organisational changes required for the evolution of emerging technological fields* (Hellsmark et al., 2016).

One of the main advantages of the TIS framework is that it combines structural and functional analysis, which leads towards a dynamic view of innovation systems. A TIS conceptualises the development, diffusion and use of new products (goods and services) and processes as a result of the systemic interplay of actors, networks, institutions and technologies in a particular technological domain (S. Jacobsson & Bergek, 2011; Mäkitie et al., 2018; Markard et al., 2012). *In this context, networks (formal associations, communities, etc.), institutions (regulations, norms, cognitive rules, etc.) and infrastructure/materials (physical surroundings, financial systems, etc.) form the structural environment in which the actors' activities take place* (De Oliveira & Negro, 2019; Wieczorek & Hekkert, 2012). *The complementary analysis of system functions allows for a better understanding of the performance of the innovation system, which should be seen as an emergent property resulting from the interplay between the structural elements and the wider context* (Markard & Truffer, 2008). *Hence, the system functions are emergent sub-processes of the overall innovation dynamic and, moreover, intermediate variables between the structure and the overall system performance* (Bergek, 2019; S. Jacobsson & Bergek, 2011; T. Jacobsson & Jacobsson, 2014). *The analysis of the performance of each system function allows to obtain a dynamic view of the diffusion of novel technologies and to identify the factors that inhibit the diffusion of the technology. In recent years, an increasing volume of literature has provided evidence that the relevance of key processes differs during the distinct development phases of a TIS* (De Oliveira & Negro, 2019; Suurs et al., 2010; Suurs & Hekkert, 2009). *Based on previous findings from the industry and technology lifecycle literature, Markard (2018) developed a TIS lifecycle framework that distinguishes between four key phases of TIS development: emergence, growth, maturity and decline. Moreover, the functions of a TIS do not develop independently of each other, but rather interact with each other in positive or negative feedback loops (Suurs, 2009; van der Loos et al., 2021). Changes in the TIS can induce variations in other areas, resulting in a series of actions and reactions that can either drive the system forward or cause it to fail* (S. Jacobsson & Bergek, 2011). *In the foregoing studies, the specific functions in the TIS analysis vary slightly. This study builds on the definition of system functions as developed by Hekkert et al. (2007)* (defined in Table 3-3):

Table 3-3: The seven TIS functions
Source: Definitions of Hekkert et al. (2007)

Functions	Definitions
Knowledge development	*Encompasses R&D and knowledge development in the form of 'learning by searching' and 'learning by doing'.*
Knowledge diffusion through networks	*Exchange of information in networks. Includes 'learning by interacting' and 'learning by using'.*
Entrepreneurial activities	*Turns the potential of new knowledge networks and markets into concrete action to generate – and take advantage of – new business opportunities.*
Guidance of search	*Those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users. Represents the process of selection between various technological options.*
Market formation	*Creation of a protected space for new technologies.*
Creation of legitimacy	*Creation of legitimacy for a technological trajectory by advocacy coalitions putting the new technology on the agenda and lobbying for resources and favourable tax regimes.*
Resource mobilisation	*Allocation of sufficient resources; both financial and human capital.*

A systematic literature review by Bergek (2019) *on the TIS framework found that the length of the published studies are empirically dominated by case studies in the European context. Furthermore,* Bergek (2019) *concludes that the TIS framework should be adapted and further developed to adequately address the context of developing and emerging countries. The relatively few recent studies that have used the TIS framework to examine technology diffusion in developing countries all highlight the relevance of national specific context factors* (De Oliveira & Negro, 2019; Edsand, 2017; Esmailzadeh et al., 2020; Tigabu et al., 2015). *Since innovation systems do not develop in a vacuum but are embedded in existing configurations of socio-technical systems, the analysis of contextual relationships plays a crucial role in deepening the understanding of TIS dynamics* (De Oliveira & Negro, 2019). *The lack of consideration of these contextual interactions is a recurring criticism of the TIS approach* (Mäkitie et al., 2018; Markard et al., 2015). *In response to this criticism, TIS scholars have recently proposed a classification of context interaction patterns enabling a differentiated analysis of TIS influencing factors: politics, established sectors, other TISs and geographical context* (Bergek et al., 2015).

Guided by the question of the extent to which actors in a TIS can or cannot influence the underlying context elements, a distinction is made in the literature between two types of TIS-context interactions (Bergek et al., 2015). *By differentiating between "external links" and "structural couplings", attention is drawn to the varying degrees of interdependence between the elements of the TIS and the context. Structural couplings describe interactions in which TIS elements are typically embedded in several different contexts simultaneously* (Bergek et al., 2015). *In terms of a two-way interaction, structural couplings can lead to interdependent dynamics between a focal TIS and different context structures* (Mäkitie et al., 2018). *In this respect, developmental dynamics within the context can lead to changes in the TIS and vice versa. External links, on the other hand, describe monodirectional influences from a* *contextual element on the developmental dynamics of the TIS. An additional characteristic of this interaction pattern is that this influence cannot be affected by the agency of the TIS actors* (Bergek et al., 2015). *In this case the performance of the TIS is influenced by shifts on the macro level, such as financial crises or changes in government.*

In the course of this research, these theoretical considerations of the interaction between the context and the TIS are incorporated into the analysis which identifies the endogenous and exogenous factors that determine the performance of the TIS with respect to the key processes presented in Table 3-3 (Markard et al., 2015). *In order to better understand the performance of the individual functions, a central focus of analysis in the TIS approach is the identification of both system strengths and weaknesses. In line with* S. Jacobsson & Bergek (2011a)*, the concept of "system weakness" is applied in this research in order to describe endogenous and exogenous factors that have a negative impact on various functions. Inspired by the approach of* Hellsmark et al. (2016)*, another focus of investigation is the identification of "system strengths". On the one hand, it is acknowledged that system strengths reflect what actors can individually achieve within the system* (Hellsmark et al., 2016). *On the other hand, examples such as "passive protective spaces" or the prominent role of incumbents from transition research show that exogenous factors can also positively influence the diffusion of new technologies* (Smith & Raven, 2012; Sovacool et al., 2020). *Therefore, both endogenous and exogenous factors are included in the analysis of system strengths in the context of this research.*

In this research, a further distinction is made between the focal TIS and the Global Innovation System (GIS). Figure 3-2 provides an overview of the distinct concepts of innovation systems. The GIS is a concept to capture the multi-scalar dynamics of technological development on a global level (e.g., global value chain creation and international competition) (Binz & Truffer, 2017). *In contrast, the focal TIS is a concept used to analyse a specific object of study within a defined boundary* (Bergek et al., 2015). *In the context of this research, e.g., the focal TIS is the diffusion processes of onshore wind energy within the geographic boundary of Argentina.*

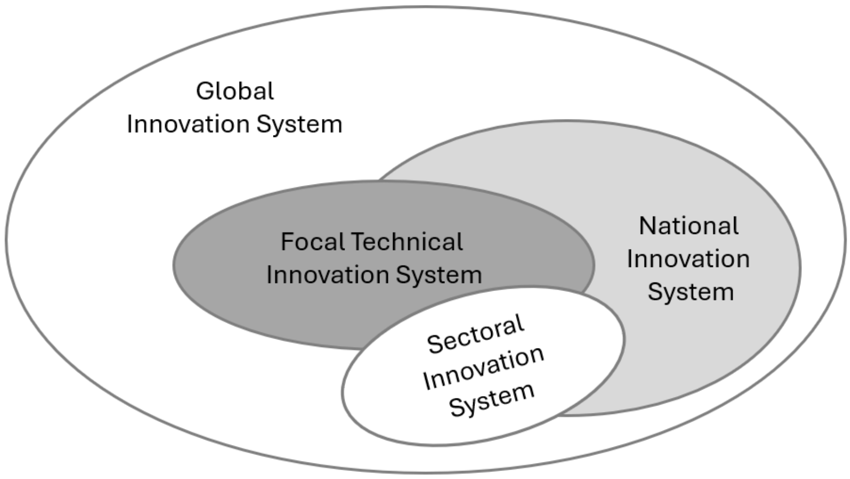

Figure 3-2: Visualisation of the intersections of the different concepts of innovation systems
Source: Own illustration, inspired by Van Lancker et al. (2016)

3.3 Conclusion and positioning the research within the theoretical context

In the course of this dissertation, the development of renewable energies in Argentina is framed on the basis of the theoretical concepts of Sustainability Transition Research. The different theoretical approaches provide insights into different facets of the development dynamics of renewable energy in Argentina, as the comparative analysis in Table 3-4 highlights. With regard to the research question, complementary perspectives emerge that, on the one hand, take a technology-specific view and, on the other, focus on interactions with the power system and the wider contextual framework conditions.

In term of the analysis of endogenous and exogenous factors influencing the development paths of renewable energies in Argentina, the different analytical focuses of the respective frameworks provide supplementary insights. Especially with respect to the endogenous constitution, the Strategic Niche Management perspective offers relevant insights, as it allows individual technological niches to be specified and niche-internal development dynamics, such as niche formation processes, to be examined in greater detail (R.Mourik & Raven, 2006). The identification of drivers and barriers for the development of decentralised renewable energies is intended to provide a better understanding of the selection environment and thus to enable exogenous factors to be identified in more detail (Schaube et al., 2018). The Multi-Level Perspective, focusing on socio-technical transition processes, contributes to this research by analysing endogenous niche dynamics and interactions with the exogenous regime and landscape factors (F. W. Geels et al., 2016, 2017). In the context of this research, the combined application of the SNM and MLP famework allowed an in-depth exploration of the socio-technical configurations that enable and constrain the development and diffusion of small wind in the Argentinian region of Chubut (Schaube et al., 2022). The TIS focuses on the development of a specific technology area (S. Jacobsson & Bergek, 2011). The performance of diffusion-relevant processes, and consequently the endogenous constitution, can be deeply understood through an analysis of the different system functions (Bergek et al., 2015). This has led to criticism that TIS is overly focused on endogenous processes (Bergek, 2019). For this reason, the approach of endogenous and exogenous system strengths and weaknesses of TIS proposed by Bergek et al. (2015) is applied to the analysis of PV development in Argentina and further developed in this research (Schaube et al., 2022). In addition, the combined MLP-TIS framework proposed by Markard & Truffer (2008) (complemented by the GIS) is used to analyse the development path of wind energy in Argentina. This provides the basis for analysing the exogenous contextual factors influencing the development of the focal onshore wind TIS in Argentina.

Furthermore, this dissertation study contributes to the current scientific theoretical discourse of the research field. In 2019, 29 leading scientists in the field of Sustainability Transition Research wrote a paper which proposed a differentiated research agenda for the further development of the research field. In addition to its empirical insights into the development dynamics of renewable energies in the context of the Argentinian power system, this research contributes to individual points on this research agenda (Köhler et al., 2019). Moreover, this research connects with the study by Bergek (2019), who identified open research gaps in her review of the current state of research on the TIS framework. In sum, the following three research gaps are addressed in this research:

1. Research gap: Transfer of the theoretical frameworks to new fields (e.g., technical and geographical nature) and gaining insight into how specific contexts influence the diffusion of new innovations (Bergek, 2019).

2. Research gap: Gaining insights into the question of whether sustainability transitions in the context of developing countries are also premised on the assumption that they are accompanied by the destabilisation of the socio-technical regime and its technological substitution (Köhler et al., 2019).

3. Research gap: Development of approaches to deal with the micro vs. macro methodological dilemma (Köhler et al., 2019).

Table 3-4: Positioning the theoretical frameworks in the context of this research endeavour
Source: Own summary

Framework	Characteristics	Relevance in the context of this research	Limitations
Multi-Level Perspective (MLP)	▪ Analyses the transition dynamics in socio-technical systems against the background of co-evolutionary processes ▪ Conceptualises the transition of a socio-technical system as a process being shaped by a dynamic interplay of three levels: Niches, regimes and landscapes ▪ Depending on the characteristics and temporal interplay of developments, different transition pathways are possible	▪ Illustrates the big picture regarding transition processes of the Argentinian power system ▪ Helpful to understand in depth how the interaction of the micro (niche), meso (regime) and macro (landscape) levels influences the development of renewable energy in Argentina ▪ Deeper insights into relevant contextual factors in which renewable energy development in Argentina is embedded	▪ Superficial analysis of dynamics within niches ▪ Difficulty in capturing multi-geographic dynamics of technology development
Strategic Niche Management (SNM)	▪ Protected 'niche' spaces are essential to shield the development of innovations from the initial selective pressure of the dominant regime and enable their development ▪ Thus, the interplay of shielding, nurturing and empowerment processes is relevant ▪ The development trajectory of a niche is shaped by the interaction between the local project and a global niche level	▪ Identification of specific sub-niches, e.g., fields of application for decentralised renewable energies in Argentina ▪ In-depth understanding of the associated selection environment ▪ Insights into the internal dynamics of niche development processes and thus the development status of sub-niches	▪ The focus on internal niche development dynamics makes it less suitable to providing insights into overall transition dynamics of the Argentinian power system
Technological Innovation System (TIS)	▪ Conceptualises a technological field as an innovation system and combines structural and functional analyses ▪ Structural analysis: Interaction of actors, networks, institutions and technologies ▪ Functional analysis: Analysis of various system functions	▪ Enables the targeted analysis of dynamic processes that affect the development and diffusion of a specific renewable energy technology, such as photovoltaics in Argentina ▪ In-depth understanding of the performance of different system functions and thus the interaction with structural and contextual framework conditions	▪ Due to the focus on one technology, no insights into the interaction of different renewable energy technologies in the context of the transformation processes of the Argentinian power system
Global Innovation System (GIS)	▪ Investigation of multi-scale dynamics to analyse technical innovation processes in a transnational context	▪ Important for understanding how global developments in a technology field, such as wind energy, influence the development path in Argentina	▪ Analysing the complexity of the overall global development context in a technological field is beyond the scope of the research, which is limited to the interaction of global dynamics with developments in Argentina

4 Research approach and methodology

4.1 Research framework

Building on the previous elaborations on the theoretical background, the analytical research framework of this dissertation (Figure 4-1) is outlined in this chapter. The different frameworks of Sustainability Transition Research have distinct analytical focuses, as summarised in Table 3-4. Taken together, they contribute to obtaining a comprehensive picture of the endogenous and exogenous factors that influence the diffusion dynamics of individual renewable energy innovations in the context of the socio-technical transition of the Argentinian power system. Against this background, and in order to illustrate the interplay of the central elements, Figure 4-1 presents the research framework on which this dissertation is based.

Following the structure of the MLP framework, a distinction is made between the renewable energy niche as the micro level, the power system regime as the meso level, and its specific contextual embedding as the macro level. As explained in more detail in the previous chapter, this research adopts a broad definition of the regime level. Therefore, the regime refers to the socio-technical elements that contain the dominant configuration for the fulfilment of a societal function. In the context of this investigation, this refers to the dominant configuration of electricity generation in Argentina, which is characterised by fossil fuel-fired power generation. Based on the insights of Strategic Niche Management, the development of the renewable energy niche is divided into a global and a local, project-related niche level. Due to variations in the actor structure, technical concepts, infrastructural prerequisites and institutional framework, a further distinction is made at the global niche level between the application areas of "large-scale" and "small-scale decentralised" application[9]. Within each application area, different renewable generation technologies are utilised, some of which are specifically analysed in this research.

The previous elements of the research framework are specified in the context of this dissertation by the particular empirical focus on the country of Argentina. However, the development of renewable energy, such as value chains and R&D, has a transnational dimension. The Global Innovation System element addresses these multi-scalar dynamics at the technology level. Within this context, the development dynamics of individual technologies are analysed using the Technical Innovation System framework approach. The analysis boundary of each focal TIS refers to the respective renewable energy generation option within the geographical borders of Argentina.

The preceding theoretical concepts all stress that the development of the innovations does not occur in a vacuum but rather is shaped by the specific context. In the MLP conceptualisation, this circumstance is considered at the macro level through landscape factors and the socio-technical regime. Since the TIS focuses on the dynamics of the specific Technical Innovation System, the extension proposed by

[9] For the purposes of this research journey, decentralised energy systems are understood to be modular power generation plants situated close to energy consumers, in contrast to centralised power plants where electricity often has to be transmitted over long distances (Leary et al., 2019; Schaube, 2024; Schaube et al., 2018, 2022).

contextual structures and interaction dynamics is adopted and further developed in this research. The interaction of the micro, meso and macro levels results in socio-technical transition dynamics. As explained in more detail in the theory chapter, different transition paths emerge depending on the characteristics and interplay of developments and events.

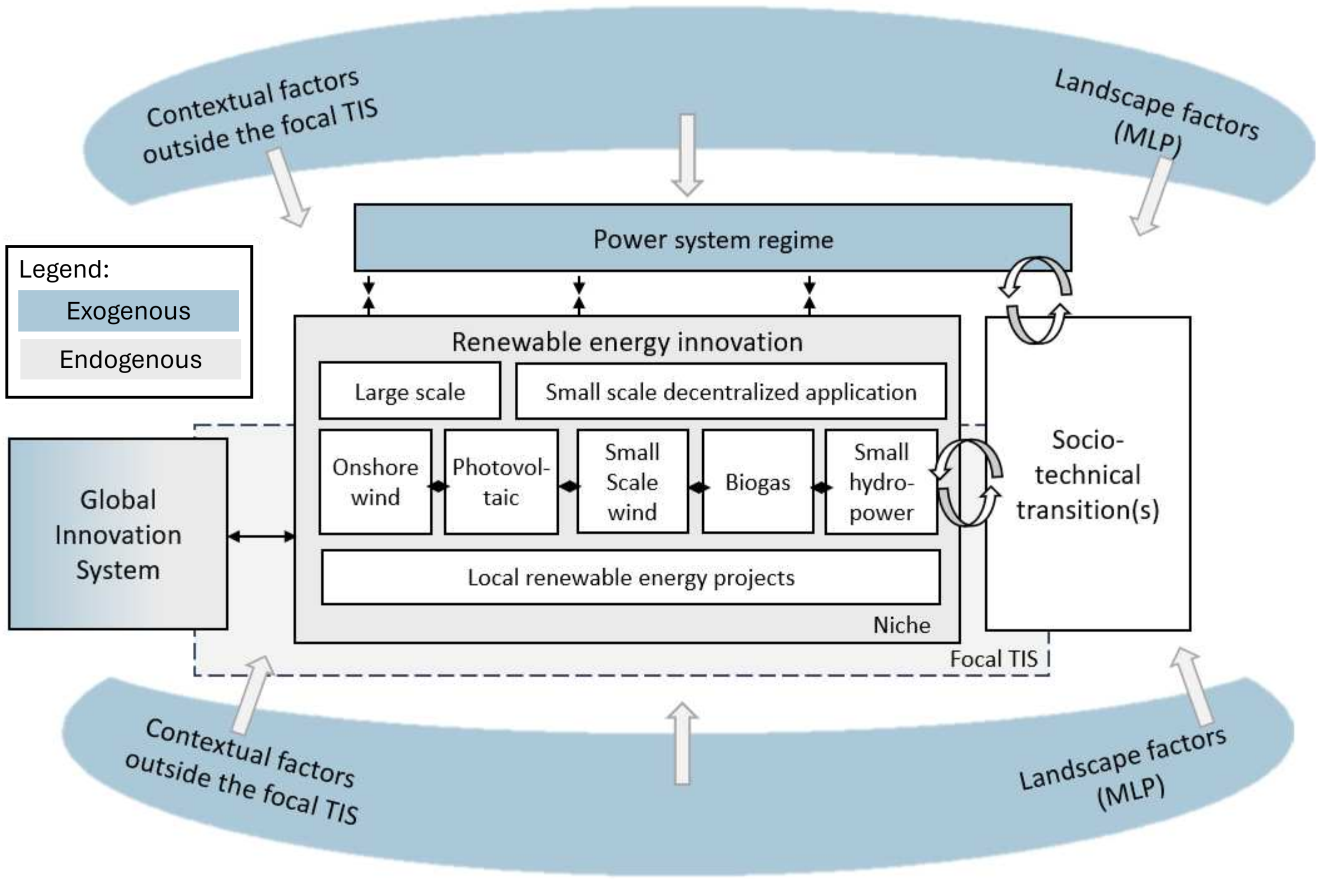

Figure 4-1: Research framework
Source: Own illustration

4.2 Methodological approach

Based on the results of a literature review on methods and theoretical frameworks of Sustainable Transition Research, Zolfagharian et al. (2019) propose the "Transition research onion" (Figure 4-2), which serves as a guideline for prospective research. To explore the research questions, address the complexity of the empirical topics, and operationalise the respective theoretical frameworks, different methodological approaches were chosen during the research journey for this dissertation. However, as the comparative overview in Table 4-1 shows, all of the contributions are based on explorative methodological approaches that explore the complex dynamics of socio-technical systems. As already explained in greater detail, the articles in this dissertation used specific Sustainability Transition Research frameworks, depending on the object of investigation. The research on the dynamics of the decentralised renewable energy niche, the PV-TIS and rural electrification with domestic wind turbines in windy regions can be classified as cross-sectional studies, as they analyse the respective object of investigation at the current point in time. The study of the contextual factors influencing the expansion of wind energy can be classified as a 'longitudinal study', as it examines development trajectories using constellation analysis.

What all of the articles have in common is that semi-structured expert interviews in various forms were part of the research design. A total of 49 expert interviews were conducted. In order to meet the requirements of the different research objectives, interview guidelines with between 11 and 19 questions were developed for the research endeavours. Specialised software such as MAXQDA and ATLAS.ti was used to analyse the content of the transcribed interviews. Another similarity between most of the articles is that the qualitative text analysis was guided by the considerations of deductive and inductive coding according to Gibson & Brown (2009).[10] In this context, a priori codes represent categories predefined by the researcher. They serve as a general analytical framework to guide the qualitative data analysis deductively as an initial basic structure. In the context of this research, the a priori codes in the systematisation were based on the underlying theoretical frameworks specific to the particular articles. In the case of the analysis of the Argentinian distributed PV-TIS, for example, these included the seven functions of the TIS, categories describing its contextual embeddedness, such as 'interaction with relevant sectors', and the categories of 'system strengths' and 'system weaknesses' (Schaube et al., 2022). The empirical codes, on the other hand, were derived inductively from the content of the data. They either formed new main categories on their own or were assigned to existing a priori codes. This iterative process between a priori and empirical codes resulted in a further development of the analytical framework. To operationalise the approach of inductive and deductive code development, the research was guided by the 'thematic qualitative text analysis' method developed by Kuckartz (2016). Initially, all of the interview material was classified using the a priori codes. Based on the outcome, the need for further differentiation of the main categories was assessed and definitions for the main categories were elaborated upon. In the case of the PV-TIS study in Argentina, for example, two main categories were added: 'macroeconomic context' and 'education system' (Schaube et al., 2022). In a subsequent step, the subcategories were elaborated upon by re-coding the material, so that at the end of the process a final coding scheme was generated as part of a double blind author analysis.

Depending on the focus of the paper, additional methodological approaches were applied to obtain additional relevant insights or to triangulate the results of the expert interviews. As part of the case study on "Rural electrification with household wind systems in remote high-wind regions", 43 observational field visits were carried out to gain an insight into the on-site reality and to obtain specific data regarding the operation of the individual small wind turbines. In addition, the findings from these field visits and expert interviews were validated and discussed in a workshop with a number of experts (Leary et al., 2019). In order to explore the status of decentralised PV-TIS in Argentina and the factors influencing its development, as well as to quantitatively consolidate and enrich the findings, a mixed-method sequential

[10] The approach of inductive and deductive category development was not applied in the article "The influence of context-specific factors on the diffusion of onshore wind energy in Argentina". The findings from the expert interviews were further explored with the application of the constellation analysis.

research design was used. The exploratory factors were first quantitatively validated with an independent expert control group. The remaining factors were assessed regarding their grade of relevance and influence by another independent control group in a further quantitative survey (Schaube et al., 2022). A 'convergent research design' was followed in the study of the contextual factors influencing the diffusion of wind energy in Argentina as part of a mixed-methods approach. The research methodology was based on constellation analysis, which served as a bridging concept to synthesise the results of the literature review and the expert interviews. To ensure the consistency of the findings, the visualisations of each stage were discussed with further experts and their remarks were iteratively adapted in an iterative process.

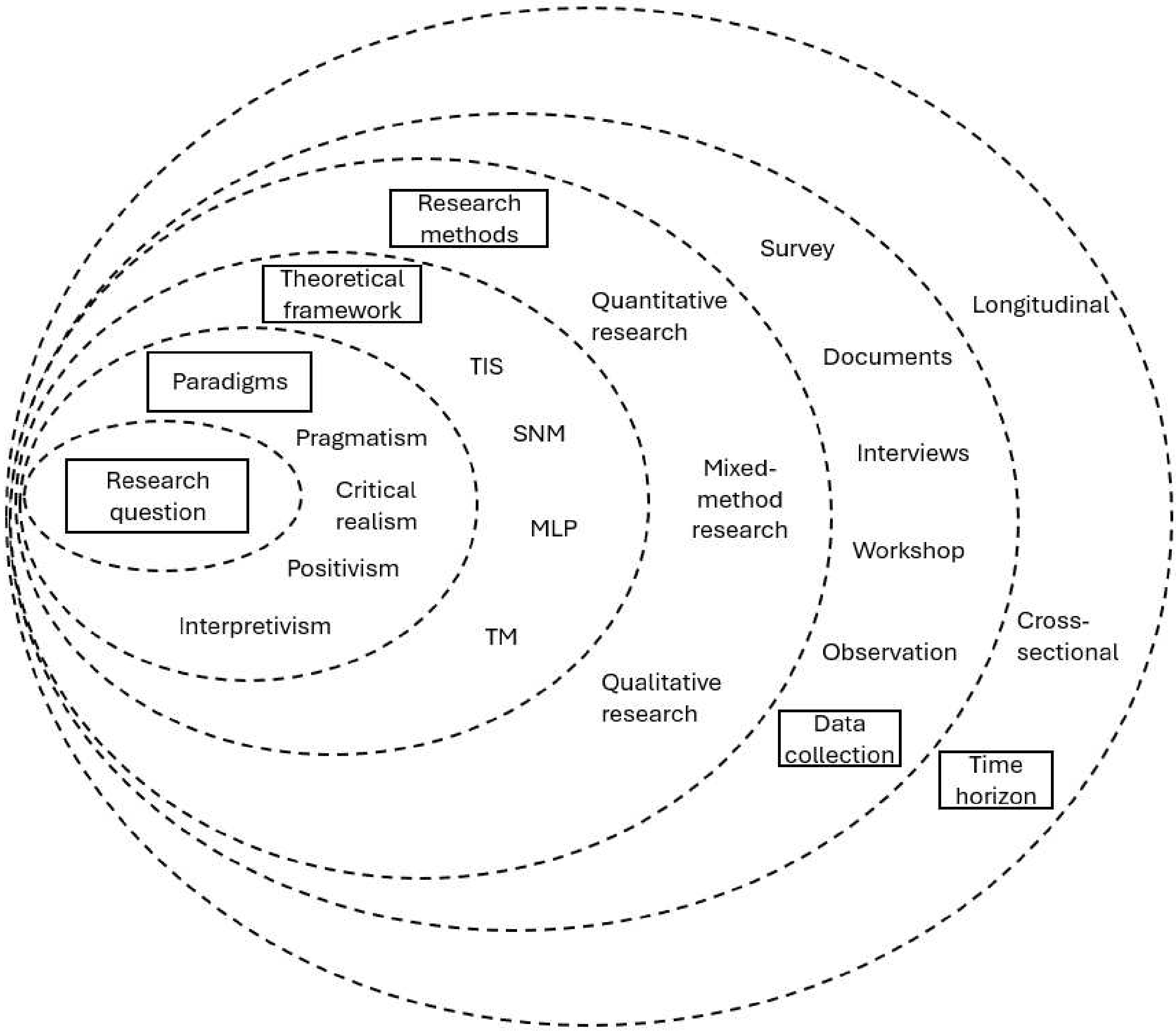

Figure 4-2: Transition research onion,
Source: Own illustration, based on Zolfagharian et al. (2019)

Table 4-1: Overview of the methodology of the distinct articles
Source: Own summary

Title	Theoretical framework and time horizon	Data collection	Data analysis
Status and future dynamics of decentralised renewable energy niche building processes in Argentina	▪ MLP and SNM ▪ Cross-sectional study	▪ Semi-structured interviews with 15 experts (qualitative data)	▪ Qualitative text analysis and process of deductive category application (a priori codes) and inductive category development (empirical codes) based on Gibson & Brown (2009) ▪ ATLAS.ti computer programme
Rural electrification with household wind systems in remote high-wind regions	▪ MLP and SNM ▪ Cross-sectional study	▪ Semi-structured interviews with twelve key stakeholders (qualitative data) ▪ 43 observational field visits (participatory field research with qualitative and quantitative data) ▪ Workshop with key stakeholders to validate results	▪ Multi-stage process of the thematic qualitative text analysis based on Kuckartz (2016) using the ATLAS.ti computer programme ▪ Workshop with key participants to validate results
Distributed photovoltaic generation in Argentina: An analysis based on the Technical Innovation System framework	▪ TIS ▪ Cross-sectional study	▪ Mixed-method exploratory sequential research design ▪ Semi-structured research interviews with 14 experts (qualitative data) ▪ Validation of factors with heterogeneous expert control group comprising 13 participants (quantitative data) ▪ Structured questionnaire with 32 participants (quantitative data)	▪ Multi-stage process of the thematic qualitative text analysis based on Kuckartz (2016) using the MAXQDA computer programme ▪ Quantitative: Statistical evaluation of the Likert scale on the basis of frequencies and calculation of mean values
The influence of context-specific factors on the diffusion dynamics of onshore wind energy in Argentina	▪ Combined MLP-TIS framework complemented by the GIS ▪ Longitudinal study	▪ Mixed-method convergent research design in the context of the constellation analysis ▪ Literature review ▪ Semi-structured research interviews with eight experts (qualitative data)	▪ Constellation Analysis as a method of graphical mapping which served as a bridging concept to synthesise and triangulate the findings from the literature review and the expert interviews

4.3 Conclusion and research strategy

In the context of the socio-technical transition of the Argentinian power system, the dissertation focuses on the diffusion dynamics of renewable energy. To analyse the relevant endogenous and exogenous factors in detail from different perspectives, the various contributions within this dissertation draw on specific frameworks of sustainability transition research. As shown in Table 3-4, each of these frameworks illuminates certain aspects of the research framework and operationalises these through specific methodological approaches. The coloured magnifying glasses in Figure 4-3 illustrate the emphases of each article. However, two aspects are crucial to comprehending the overview: First, the analysis of socio-technical transitions is addressed in all contributions, whether at the project level (e.g., case study small wind) or at the power system level. Second, the magnifying glasses represent the respective focus. As they are explorative in nature, the respective contributions also uncover broader implications. For example, the impact of import restrictions is thematised in the article about the decentralised renewable niche. However, as it is not the direct focus of this article, the GIS field is not marked with a magnifying glass in the overview figure.

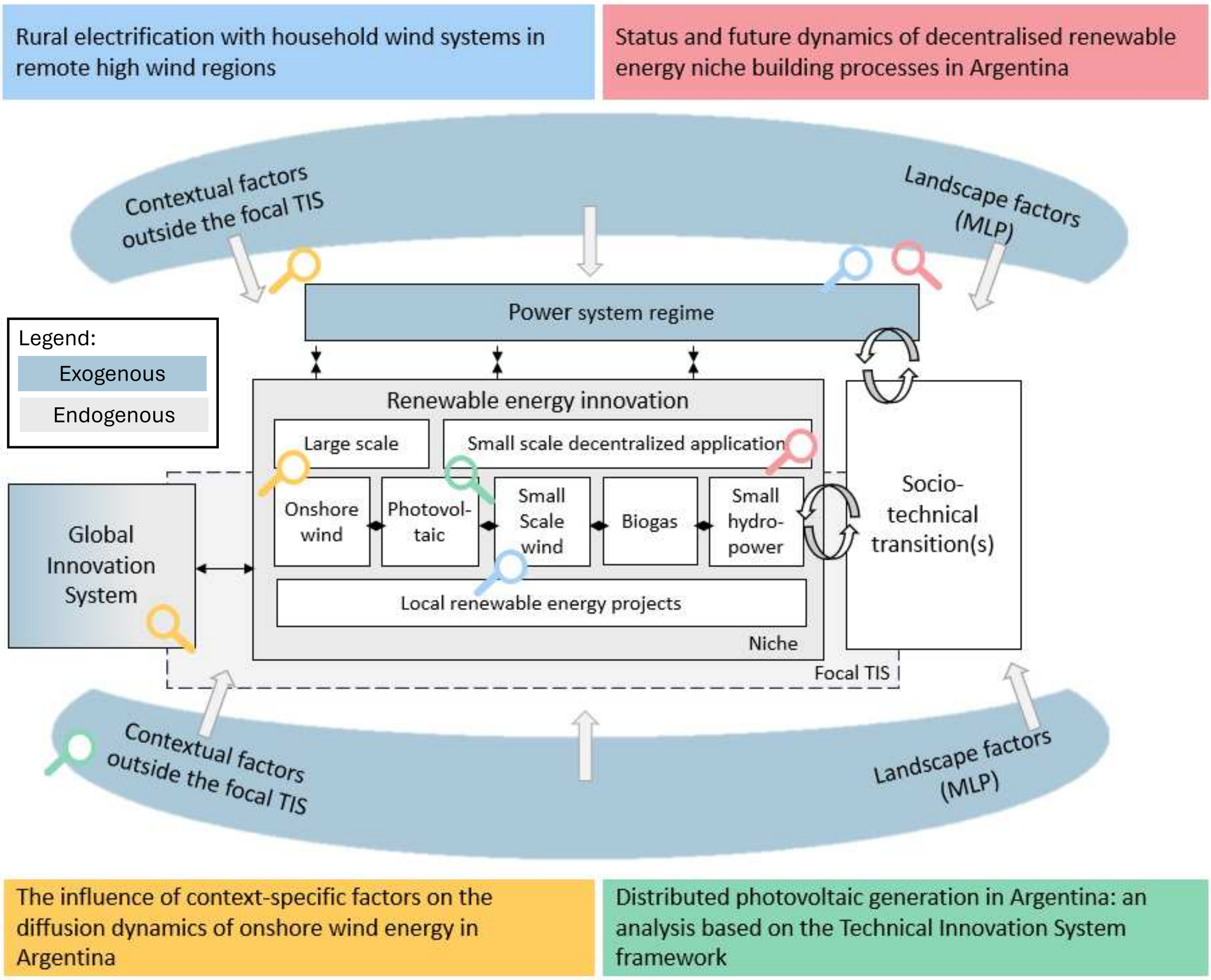

Figure 4-3: The research framework and its alignment with the individual research contributions
Source: Own visualisation

The first paper, "Status and future dynamics of decentralised renewable energy niche building processes in Argentina", focuses on the internal niche dynamics and contextual factors that have hindered or promoted the development of the decentralised renewable energy niche in Argentina. Based on the MLP and SNM frameworks, it applies conceptualisations of socio-technical niche development. As part of the study, 15 expert interviews were conducted and analysed using qualitative research techniques. Embedded in the overall context of this dissertation, this research contributes to a deeper understanding of the constitution of the decentralised renewable energy niche. In addition, the analysis of the drivers and barriers provides a profound insight into the endogenous influencing factors resulting from the dynamics of the niche as well as the exogenous influencing factors resulting from the interaction of regime and landscape.

The second article, "Rural electrification with household wind systems in remote high-wind regions", focuses on the project level of small wind electrification programmes. Empirically, the study is based on semi-structured expert interviews, participatory field research and a workshop to discuss the findings. The comparative analysis of the case studies in Patagonia (Argentina) and the Falkland Islands/Islas Malvinas allows endogenous critical success factors for small wind electrification programmes to be identified. Against this background, the opportunities and challenges of socio-technical transition at local level are outlined. Furthermore, based on the application of the SNM and MLP frameworks, the article contributes to this dissertation by pointing out how exogenous contextual conditions, such as access to finance, influence the diffusion of decentralised renewable energy systems.

The third article, "Distributed photovoltaic generation in Argentina: an analysis based on the Technical Innovation System framework" is based on an "exploratory sequential mixed-methods approach". In the overall context of this research work, the extended function analysis of the TIS provides a clear picture of how endogenous and exogenous system strengths and weaknesses shape the diffusion of distributed photovoltaic generation in Argentina. This approach allows the state of development of decentralised PV generation to be assessed and shows how energy systems and, in particular, general country-specific factors influence its diffusion.

The fourth paper, "The influence of context-specific factors on the diffusion dynamics of onshore wind energy in Argentina", is based on the constellation analysis, which facilitates the mapping and discussion of findings from expert interviews and existing literature in an iterative process. Based on the integrated MLP-TIS framework, complemented by GIS, the development of wind energy in Argentina since 1990 is analysed and divided into different phases. The dissertation draws important insights from the investigation of how contextual conditions have influenced the development path of wind energy at different levels and how the technology is embedded in the socio-technical energy transition.

5 Chartering of the articles in the research

5.1 Synopsis of the research articles

Excerpts from the texts in section 5.1 have already been published in texts written by the author of this dissertation. These are extracts from the individual abstracts of the four scientific publications (see Table 5-1) on which this thesis is based.

5.1.1 Status and future dynamics of decentralised renewable energy niche building processes in Argentina[11]

The first paper of Schaube et al. (2018) investigates the state of development of Argentina's decentralised renewable energy sector and evaluates its potential role regarding the transition of the country's power system. It thereby conceptualises the diverse initiatives aimed at fostering the diffusion of decentralised renewable energy technologies in Argentina as an evolving socio-technical niche. *To that end, the paper builds on the concepts from Strategic Niche Management (SNM) and the Multi-Level Perspective (MLP) of socio-technical transitions. This approach makes it possible to evaluate the internal niche dynamics and the context-related factors that have either impeded or supported the development of the respective renewable energy niche in Argentina.*

Empirically, the study is based on a sample of 15 semi-structured interviews with experts from heterogeneous fields: equipment suppliers, engineering companies, government agencies, research institutions, and non-governmental organisations. Within the process of qualitative content analysis, the transcribed data was analysed on the basis of the cyclical interplay of a priori codes (based on the theoretical concepts) and evolving empirical codes (emerging topics from the data) within the scope of a double blind analysis.

The results of this study show that the decentralised renewable energy sector in Argentina acts like a highly-developed socio-technical niche, which is attributable to several characteristics: First, *a wide range of heterogeneous sub-niches were identified (backup systems in grid-connected regions, mining and telecommunications infrastructure in remote areas, rural population and businesses).* Second, the actions of the actors were guided by a shared a common vision independently of each other. Third, formal networks were identified that allow the systematic exchange of experiences from individual initiatives and contribute through bottom-up and top-down dynamics to the establishment of dominant cognitive rules and standards at the global niche level. One of the key findings of the article is that particularly contextual influencing factors such as economic and political instability in combination with restrictive political regulations (such as imports and subsidies for conventional energy sources) are amongst the most important obstacles to the

[11] Excerpts from the author's article:Schaube et al. (2018). These text passages are labelled in *italics*.

development of the decentralised renewable energy niche. In addition, specific sub-niche barriers were identified. In rural areas, the development of decentralised renewable energy systems is hampered by the lack of a long-term electrification strategy and limited access to finance. Furthermore, while the geographical spread of the country offers a broad potential for renewable energy, it also poses a challenge for companies in regard to maintaining and servicing widely dispersed plants. In urban areas, comparative economic disadvantages result from high subsidisation of electricity prices. In addition to this, development was hampered by the feed-in ban regarding renewable energy generated decentrally that was in force until 2017.

5.1.2 Rural electrification using household wind systems in remote high-wind regions[12]

The second paper, Leary et al. (2019), is a comparative case study of small wind electrification programmes in Argentinian Patagonia and the Falkland Islands/Islas Malvinas. In the broader context of the research journey, this research represents an in-depth exploration of the socio-technical configurations that enable and constrain the development and diffusion of small wind in the Argentinian Region of Chubut, where, as part of the PERMER project, around 1,600 Household Wind Systems (HWS) were installed.

In the study, HWS are perceived as a socio-technical system which provides a *technological solution to a social problem, namely the lack of access to energy services in remote areas. This socio-technical perspective at the local project level allows the disentanglement of the interwoven social, technical, economic, political and organisational factors that have contributed to the successes and failures of electrification programmes*. The applied frameworks of Strategic Niche Management and the MLP complement each other, which makes it possible to differentiate between the *internal influences (resulting from the niche level) and the external influences (resulting from the interaction with the broader regime and landscape level)*. The publication stands out on a theoretical level in that it represents one of the first attempts to apply the theoretical frameworks mentioned within the context of a field study that evaluates the effects of concrete applied projects.

Empirically, the study is based on semi-structured interviews with project-relevant actors, 43 field observation visits, and an analysis of previously published project reports. *The iterative process of deductive category application and inductive category development, based on the cyclical interaction of empirical and a priori codes, allowed for an in-depth exploration of the data using both theoretical insights from the literature on socio-technical transitions and the emerging insights from the two case studies*.

Regarding the dissemination of small wind turbines in rural Argentina, several relevant insights emerge from the comparative case study. A decisive landscape factor is the fact that Chubut is one of the windiest regions in the world. On the one hand, this results in excellent wind potential, but on the other hand it also places special demands on the technical robustness of the installed wind turbines. In the case study

[12] Excerpts from the author's article: Leary et al. (2019). These text passages are labelled in *italics*.

investigated, however, the turbines installed in Chubut proved to be unsuitable. This is due to three factors: An insufficient assessment of the technical requirements, the prioritisation of price over quality through the tender mechanism, and, as a regime influencing factor, the exclusion of proven foreign products through high import tariffs. Other crucial landscape factors are the scattered location of end users with poor transport infrastructure, as well as the historically poverty-stricken population and the associated high dependence of small wind turbines on external financing. Furthermore, the Argentinian case shows that, under these framework conditions, successful long-term operation of the systems heavily depends on reliable and long-term support through a sufficient budget at the political level. For the dissemination of small wind turbines for the electrification of rural areas, the paper provided further generally applicable insights. By combining small wind systems with other energy sources, the reliability and durability of the systems can be increased. In addition, the individual needs of end users should be identified and classified to enable the use of system components that are as standardised as possible. Especially in regions with dispersed settlement patterns, the establishment of decentralised maintenance networks is crucial for the sustainable operation of small wind turbines.

5.1.3 Distributed photovoltaic generation in Argentina: an analysis based on the Technical Innovation System framework[13]

The third article focused specifically on the endogenous and exogenous factors that are impeding or *facilitating the diffusion of decentralised photovoltaic systems in Argentina by using the Technical Innovation System (TIS) approach*. This study goes beyond a classical functional analysis of the TIS and *proposes a research approach that makes it possible to include the contextual influencing factors in the system analyses*. In order to investigate the contextual embedding of the PV-TIS, the concept of structural couplings and external connections proposed in Bergek et al. (2015) is empirically applied. Furthermore, *within this theoretical field, this study is one of the first attempts to apply an exploratory mixed-methods approach to the TIS analysis. The exploratory, sequential research design allows theory to be used as a guiding heuristic to simultaneously explore the strengths and weaknesses* related to the respective functions of the PV-TIS in a bottom-up process based on 14 expert interviews. In order to validate the influencing factors derived from the interviews, these were verified in a quantitative survey with a heterogeneous expert control group. Based on these results, in the final step, *a structured questionnaire asked experts to evaluate the relevance and degree of contextual embeddedness of the influencing factors* resulting from the previous steps and assess the performance of the different functions. In this way, *the study developed an important research approach that contributes to a more sophisticated understanding of the interdependencies of TIS with surrounding context* and helps to narrow this research gap in the literature. Based on the results of the study, proposals to extend the underlying theoretical model are furthermore elaborated upon.

[13] Excerpts from the author's article: Schaube et al. (2022). These text passages are labelled in *italics*.

By applying the TIS framework, this study found that, although decentralised photovoltaic systems account for only a small share of Argentina's electricity mix, a number of market segments with significantly distinct selection conditions have emerged. The market segment in the advanced state of development is off-grid PV systems for power supply in remote rural areas. Decentralised PV systems at grid nodes that contribute to grid stability and supply security in small towns (on-grid segment) are another application area. Since uniform national regulation was introduced in 2017, PV systems for self-power supply in urban areas have emerged as a further market segment (although not yet widespread). The findings show that the strengths of the PV-TIS derive both from the endogenous dynamics of the TIS (*e.g., knowledge development in pilot projects and market creation through provincial and national support programmes*) and from external contextual circumstances (relevance of existing technical education institutions for rapid knowledge diffusion and significance of rural regions as "protected spaces" for the implementation of photovoltaic systems). A central finding of the article is that the weaknesses of the PV-TIS are largely attributable to the challenging national contextual conditions. *The Argentinian example illustrates how problems within a country, such as political instability or macroeconomic uncertainty due to high inflation rates and devaluation of the national currency, hamper the breakthrough of sustainable energy production technologies.*

5.1.4 The influence of context-specific factors on the diffusion dynamics of onshore wind energy in Argentina[14]

This fourth article *aimed to provide insights into the contextual embeddedness of diffusion dynamics of onshore wind energy in Argentina based on the combined MLP/TIS framework. Through the application of a constellation analysis, this paper reviewed the different stages of development of onshore wind energy in Argentina since 1990, with the overall intention of identifying how exogenous dynamics have hindered or supported the diffusion of the new technology. Beyond the empirical findings, this study contributes to the growing body of transition research that aims to develop a deeper understanding of the contextual embeddedness of new innovations.* In doing so, the study contributes to the further development of the field on a theoretical level in two ways. On the one hand, the integrated MLP-TIS approach is extended to incorporate the GIS perspective in order to capture the multi-scalar dynamics of technology development. On the other hand, the constellation analysis presents a methodology that enables the approach to be operationalised and, in doing so, triangulates the results of the literature research with experts as a bridge concept and enables new aspects to be explored.

Across the five development phases of the focal TIS, the findings provide evidence of a variety of socio-technical niches: pilot projects, self-generation by energy cooperatives, projects based on feed-in tariffs, publicly financed and operated wind farms, hydrogen generation and compliance with legal requirements for large users. In the context of the constellation analysis, a significant conclusion drawn in this

[14] Excerpts from the author's article: Schaube (2024) and the corresponding abstract. These text passages are labelled in *italics*.

study is that the classification of the development phases of the trajectory of onshore wind energy in Argentina was, in particular, related to the effects of contextual factors. With the construction of South America's first wind farm in 1990, Argentina was the pioneer of wind energy in Latin America for almost a decade. This initial positive development was favoured by a constellation of specific framework conditions: stable exchange rates, liberalisation and privatisation of electricity markets, and subsequently wind energy as a business model for energy cooperatives to reduce rising electricity purchase costs. The structural problems of the Argentinian electricity system were identified as another important contextual influencing factor at the regime level. Since the 2000s, renewable energy has been perceived as part of the solution to the national energy crisis, contributing to covering capacity deficits and reducing energy imports. However, the Argentinian case also shows how, in later development periods, problems within a country, such as political instability or macroeconomic uncertainties due to high inflation rates and strong exchange rate fluctuations, hampered access to international project finance, thereby severely affecting the further development of wind energy. Another important contextual factor at the country level comprised discontinuities in the fundamental economic policy orientation of the country caused by changes in government. *The Kirchner government set the impetus to promote domestic manufacturers of wind turbines through targeted research programmes and project financing for wind farm projects*. Under the aegis of Mauricio Macri, an impressively rapid expansion of wind energy was achieved. However, this expansion was characterised by the dominance of globally operating wind turbine manufacturers, as low prices and fast installation times were the main focus.

5.2 Overview of the research papers

Table 5-1: Tabular overview of the publications with regard to authorship, leading research questions and key highlights
Source: Own summary

Title	Publication & Authors	Research question	Highlights
Status and future dynamics of decentralised renewable energy niche building processes in Argentina	Energy Research & Social Science Philipp Schaube 78 % Willington Ortiz 15 % Marina Recalde 7 %	What are the internal niche dynamics and the context-related factors that have been hindering or supporting the development of the decentralised renewable energy niche in Argentina?	▪ Evaluation of the decentralised renewable energy initiatives as an evolving socio-technical niche using Strategic Niche Management and the Multi-Level Perspective ▪ Identification of multiple sub-niches, nurturing an evolving global niche with a shared vision among actors and formal networks for systematic experience exchange ▪ Key barriers include economic and political instability, restrictive regulations, the lack of a long-term strategy, limited access to finance, and the challenges posed by geographical dispersion and high levels of conventional energy subsidies
Rural electrification using household wind systems in remote high-wind regions	Energy for Sustainable Development Jon Leary 44 % Philipp Schaube 44 % Luciana Clementi 12 %	What are the key socio-technical factors that can lead to the establishment of sustainable social infrastructure to support small wind electrification programmes in remote high-wind regions?	▪ Socio-technical approaches are applied to analyse small wind electrification projects in remote high-wind regions. ▪ Maintenance was found to be the major challenge. ▪ A centralised organisational model is fundamentally incompatible with remote decentralised power generation systems.

Title	Publication & Authors		Research question	Highlights
Distributed photovoltaic generation in Argentina: an analysis based on the Technical Innovation System framework	Technology in Society Philipp Schaube Luciana Clementi Alejandra Ise	 64 % 18 % 18 %	How do the functional dynamics and the related endogenous/exogenous system strengths and weaknesses influence the diffusion of decentralised photovoltaic systems in Argentina?	▪ Inclusion of a wide range of perspectives from Argentinian practitioners through an exploratory sequential research design ▪ Proposal of an analytical method and two additional analytical categories for the TIS/context framework ▪ Novel analysis of relevant endogenous and exogenous system strength and weaknesses ▪ Contextual factors, e.g., energy subsidies and high inflation rates, were identified as a major barrier
The influence of context-specific factors on the diffusion dynamics of onshore wind energy in Argentina	Wuppertal Papers Philipp Schaube	 100 %	How have context-specific factors influenced the diffusion of onshore wind energy in Argentina?	▪ Methododical advacment: Aplication of the Constellation Anlysis to operationalise the combined MLP/TIS framework in order to highlight how exogenous factors have influenced the diffusion dynamics of onshore wind energy in Argentina since 1990 ▪ Findings reveal various socio-technical niches across five development phases ▪ Significant obstacles to wind energy development include political instability, macroeconomic uncertainties, and discontinuities in economic policies, which have impacted access to international finance

6 Discussion & conclusion

6.1 From a practical perspective

This dissertation investigated the endogenous and exogenous factors influencing the diffusion of renewable energy in Argentina against the background of the socio-technical transition of the Argentinian power system. This chapter summarises and reflects on the main findings of the four articles against the background of the guiding research question. The individual articles focused on distinct empirical aspects and illuminated a number of different facets. In this way, it was possible to analyse the development of the distinct renewable energy technologies at different levels of aggregation. The results of the research show that the development of renewable energy in Argentina is strongly influenced by general national structural challenges such as political and economic instability. Furthermore, the results also illustrate that the different technologies have followed different development trajectories in the context of decentralised and large-scale energy generation, due to their distinct fields of application.

6.1.1 Main exogenous influencing factors

Before going into the specifics of the endogenous forces and the different application contexts, the following sections outline the exogenous factors that broadly shape the context for the diffusion of renewable energy in the Argentinian context. As it has become particularly clear in the analysis of the development of wind energy since 1990, one should not overlook the fact that these factors can also change in terms of their characteristics during the course of their development. In particular, this chapter focuses on exogenous factors that occurred repeatedly or had a long-term impact and had a significant influence on the course of development, be it positive or negative. Thus, four overarching thematic clusters can be identified:

Ambivalent interaction with the socio-technical regime

The results of this research have clearly revealed an ambivalent influence of the existing socio-technical system on the diffusion of renewable energies in Argentina. In general, the socio-technical regime is characterised by a thermal generation logic and heavy subsidisation of retail prices. Since mid-2010s, against a backdrop of declining natural gas production, this led to a heavy burden on the national budget on the one hand, and to increasing pressure on Argentina's scarce foreign exchange reserves due to natural gas imports on the other. Insufficient generation capacity and grid expansion have also led to problems with security of supply, particularly during the summer months. This has resulted in the following ambivalent interaction dynamics:

- **Positive influence:** On the one hand, the instability of the socio-technical regime opens up opportunities for renewable energy in Argentina. This is due to the fact that their diffusion contributes to security of supply and achievement of the Paris climate goals, as well as to overcoming the structural challenges mentioned above. Therefore, the dysfunctionality of the dominant socio-technical regime was a driving force behind the ambitious policy goals of Argentinian governments since 2006, accompanied by extensive support programmes (though with varying impact).

- **Negative influence:** On the other hand, the interaction with the socio-technical regime results in inhibiting exogenous framework conditions: a) the high subsidisation of electricity has a strong negative impact on profitability and thus on investment decisions in decentralised renewable energies, b) the over-indebtedness of central energy industry players resulting from the subsidy policy has had a negative impact on the risk assessment of investors in the context of support programmes, such as the GENREN programme), c) the increasing government spending on energy subsidies has reduced the ability of the Argentinian state to economically support energy industry investments against the backdrop of a tight fiscal situation, and d) the capacity of the transmission grid, which was fully utilised after the first RenovAr tendering rounds, is a technically limiting factor.

It can therefore be stated that, on the one hand, the dysfunctionalities of the socio-technical regime level strengthen the political ambitions to promote renewable energies and thus the development opportunities, but at the same time these function as indirect or direct obstacles (energy subsidies, fossil path dependencies and insufficient grid expansion) to the diffusion of renewable energies in Argentina. This circumstance is conceptually analysed in greater detail in the following theory chapter.

Macroeconomic instability & discontinuities in macro-political premises:

A key structural challenge in Argentina is the country's economic instability, which is rooted in high inflation rates, an unstable currency, high public debt, and a chronic budget deficit. Past macroeconomic crises have also stalled the positive development dynamics of renewable energy many times, as shown in the analysis of contextual factors influencing the diffusion of wind energy. Two examples are the economic crises in 2001/2 and 2018. In addition, discontinuities in the country's economic policy orientation had a negative impact on the development of renewable energies. In the past two decades, changes in government in Argentina have frequently been accompanied by significant shifts in the fundamental principles of economic policy (e.g., free market or protectionism & free or fixed exchange rate). As explained in greater detail in the article about the diffusion of decentralised solar energy, these economic policy disruptions have had a negative impact on development dynamics due to increased perceived uncertainty. In addition, the article on the trajectory of wind energy explained how the Macri government's ‘neoliberal energy policy’ was able to initiate a rapid expansion of wind energy through tenders and foreign wind energy producers (until the 2018 economic crisis). At the same time, however, it becomes apparent in the article that this represented a discontinuation of the ‘neo-developmentalist strategy’ of the Kirchner government, which promoted the formation of a national value chain for wind energy. Due to their long-term nature, however, investments in renewable energies and the development of upstream local value chains require stable and reliable framework conditions. Therefore, the results of this research highlight that the structural challenges faced by Argentina have a significant negative exogenous influence on the development of renewable energy, whereby the risk assessment of investments and access to project financing in particular can be highlighted as decisive factors. For the future development of renewable energies, it is crucial to create an environment that ensures planning security through a cross-party, overarching energy sector plan for mid- and long-term development.

The Argentinian education system:

An important positive exogenous influencing factor is the Argentinian education system. In Argentina, a wide range of educational opportunities exist for specialists to qualify in the field of renewable energies within the various areas of application. In addition to the public universities, industry-oriented research institutes such as the INTI [15] generate important impetus for the research landscape. Examples in this context are the IRESUD[16] research project in 2012 (development of regulations for the grid-connected installation of decentralised photovoltaic systems as part of pilot projects) and the Fits 2013 research programme (technical research projects to strengthen the national value chain in the wind energy sector). Furthermore, the analysis of the diffusion dynamics of decentralised photovoltaics showed that a wide range of training courses for non-academic professionals has already been developed. This in turn builds on the existing programmes and infrastructure offered by established institutions such as INET[17]. As such, the Argentinian education system is making a fundamental contribution to the development of renewable energies. It offers a wide range of opportunities for specialists to earn qualifications and supports the development of the renewable energy sector in Argentina through research projects at state universities and research institutes.

The federal structure of the country:

As Argentina is a federal state, the provinces enjoy a degree of autonomy in energy matters. The pioneering role of the province of Chubut, with its own legal framework, subsidy incentives and renewable energy agencies, laid the foundations for Argentina's pioneering role in wind energy in the 1990s. Moreover, as detailed in the case study on the electrification programmes involving small wind turbines, the Chubut Province initiative paved the way for the installation of more than 1,500 small wind turbines. In the photovoltaic field, it was the provinces of Santa Fe and Salta that allowed grid-connected distributed generation systems and supported them with funding programmes several years before the national regulation in 2017. The pioneering role of the provinces is therefore important for the development of renewable energy at the national level, as they serve as experimental fields. Successful strategies and policies were tested and identified, and then adapted and scaled up at national level.

6.1.2 Main endogenous influencing factors

Based on the research framework, the most relevant endogenous drivers in the context of large-scale and small-scale applications are presented below. An important general finding of the research is that, as a product of endogenous bottom-up and top-down processes, the niche of distributed renewable energy is sufficiently developed and consolidated for wider diffusion of distributed renewable energy. A relevant endogenous factor is that, guided by shared visions, a broad spectrum of

[15] INTI - Instituto Nacional de Tecnología Industrial (National Institute of Industrial Technology)

[16] Proyecto De Interconexión De Sistemas Fotovoltaicos A La Red Eléctrica En Ambientes Urbanos (Project for the Interconnection of Photovoltaic Systems to the Electricity Grid in Urban Environments).

[17] Instituto Nacional de Educación Tecnológica (National Institute of Technical Education)

heterogeneous networks has developed. These contribute to the exchange of knowledge between actors from different sub-niches and thus positively influence the formation of the global niche. The global niche manifests itself in the development of technical standards and participation in processes to define the legal framework. However, in this regard, the article that dealt specifically with the dissemination of PV energy also identified a number of shortcomings. a) Due to the size of the country, the exchange networks tend to be regional in nature and there is a lack of exchange at national and international level. b) In addition, it was critically noted that some of the actors do not feel represented by the work of the existing associations in the field of renewable energies.

Another key endogenous influencing factor that can be identified is the fact that the trajectory of the decentralised and large-scale renewable energy niche is sustained by a wide range of sub-niches. However, these differ considerably in terms of their specific selection environment. The rural application context represents a distinctive sub-niche within the decentralised renewable energy niche. In particular, regions without a connection to the power grid serve as a 'passive protected space'. Since the 1990s, this application context has been decisive for the initiation of projects in the context of electrification projects, particularly in the field of photovoltaics and small wind turbines. The off-grid segment comprises various user contexts (rural population and public buildings, the manufacturing sector, mining and telecommunications infrastructure), which has favoured the formation of value chains and learning processes. In contrast, the results of the investigation indicate that the sub-niche of decentralised grid-connected systems is still at an early stage of development. This is due to the fact that regulation and authorisation of the feed-in of electricity from decentralised renewable energy sources was only implemented at national level from 2018. Before then, renewable energies in the on-grid context primarily fulfilled the function of a backup system to bridge power outages in an unreliable supply situation. In addition, energy cooperatives were identified as an important actor that shaped the trajectories of the 'decentralised renewable' and 'large-scale' niches at different points in time. In the 1990s, energy cooperatives were the driving force and pioneers behind the expansion of wind energy against the backdrop of energy industry reforms. This development was only halted by the effects of the economic crisis in 2001/02. Since the mid-2010s, energy cooperatives have once again become a relevant actor, however this time in the field of decentralised photovoltaic generation. This is illustrated by the 'electric cooperative of Armstrong' presented in the article on PV diffusion.

As outlined in detail in the article on the spread of photovoltaics, this broad spectrum of different application contexts has fuelled the development of national manufacturers of solar cells, inverters and battery chargers. The experts interviewed as part of this research pointed out that the diffusion of photovoltaics in Argentina also benefits from the efficiency gains and cost reductions achieved through economies of scale and technological progress at the level of the global photovoltaic innovation system. However, as the import of relevant components was temporarily restricted due to changes in economic policy premises, the development of local value chains was identified as an important endogenous influencing factor. As part of the research, an insufficiently developed after-sales service was identified as an endogenous obstacle in the field of decentralised renewable energies. As described in detail in the case study on small wind turbines, one challenge is that the provision of maintenance services over long distances in the country is difficult. However, the various decentralised renewable energy technologies are associated with different maintenance requirements. Nevertheless, the research results clearly demonstrate how inadequately maintained small wind systems lead to technical failures with corresponding downtimes. In the long term, this leads to a loss of acceptance and therefore has a negative impact on the spread of this technology.

Having described the influence of endogenous dynamics on the development of small distributed systems, the following sections address the application area of large systems. The analysis of the development trajectory of large-scale onshore wind energy revealed a wide range of different sub-niches, each characterised by different actor structures: pilot projects, self-generation by energy cooperatives, feed-in tariff-based projects, publicly financed and operated wind farms, generation of hydrogen, and self-generation by large-scale users. From 2015, the expansion of renewable energies, particularly onshore wind energy, led to a significant increase in their share of the energy mix. This rose from 1.9% in 2015 to 14.3% in 2023 (CAMMESA, 2023a). As a result of large capacity increases in the ‘feed-in tariff-based projects’ (RenovAr & Resolution No. 202/16) and ‘self-generation by large-scale users’ (MATER) niches, wind energy accounts for 72.1% of renewable energy generation in 2023 (CAMMESA, 2023a). An essential insight of this investigation is that this positive endogenous development dynamic was only made possible by the creation of favourable conditions through exogenous changes: the declaration of a state of energy emergency and the associated need for rapid expansion of new power generation capacity, the regaining of access to the international capital market, and the introduction of a floating exchange rate system. It is significant that an important key to the success of the RenovAr programme was that, with a three-tier safety net of payment and solvency guarantees, the Argentinian context-specific factors were considered in the programme design. In this respect, the RenovAr programme was based on the strategy of rapid and cost-effective expansion of renewable energies with the backing of international financing.

Since this rapid expansion was carried out by international wind turbine manufacturers, this development also marked a missed opportunity for the Argentinian wind energy sector. At the end of the 2000s, Argentina was one of the few countries in South America in which national manufacturers of wind turbines had emerged. This development was facilitated by the economic policy of the Kirchner governments, which, on the one hand, promoted industrial research projects to establish a national value chain and, on the other hand, indirectly enabled wind farms to use Argentinian wind turbines through the provision of financing. The national wind turbine manufacturers were unable to benefit from the development under the Macri government, which promoted the rapid and cost-effective expansion of renewable energies. Several conclusions can be drawn from this. 1) Firstly, the development of national wind turbine manufacturers can be seen as an endogenous strength. Technical expertise has been developed locally and jobs and added value have been created. The contribution to Argentina's economic development is in turn relevant for the legitimacy of the technology. 2) In the last decade, however, wind energy has developed into a standardised and price-sensitive product at the level of the Global Innovation System which is subject to international competition. The result of this process can be seen in Argentina's development since 2015. This has been dominated by internationally active wind turbine manufacturers. These have been able to meet the predetermined tendering logic of rapid expansion through high production capacities and low prices through economies of scale.

Nevertheless, tax incentives that favoured the share of domestic value added in Argentina induced positive endogenous developments. As a result, well-known manufacturers such as Nordex and Vestas established assembly plants for wind turbines or joint ventures for the production of towers in Argentina. It can be concluded that international manufacturers have played an important role as a driving force. Without their technical expertise and production capacity, the rapid expansion of wind energy would not have been possible. At the same time, the results indicate that the strategy pursued by the Kirchner governments of creating an integrated national value chain was not an adequate approach. Instead, an industrial policy that focused on stages of the value chain with comparative cost advantages would probably have been more successful. The experts interviewed during the research noted that it would have been advisable under the Macri government to introduce special support programmes to enable the organic growth of these previously supported industries at a realistic level.

In conclusion, it can be said that the spread of renewable energies has played an important role in the socio-technical transition of Argentina's power system at various levels in recent years. As early as the 1990s, they made a decisive contribution to rural electrification in regions where grid expansion was not possible. However, the targets set by the Argentinian government for the expansion of renewable energies in conjunction with grid-connected systems have not yet been achieved. Nevertheless, the support programmes initiated in 2015/16 triggered drastic development that led to a tenfold increase in electricity generated from renewable energy sources from 1.98 TWh in 2013 to 20.08 TWh in 2023 (CAMMESA, 2023a). Achieving the 18% (14.3% renewable share in 2023) target would have been possible if the diffusion dynamics had not been severely slowed down by exogenous influences (CAMMESA, 2023a). This was illustrated in detail in the article on wind energy diffusion based on the example of unrealised projects in the RenovAr 2 tender round. The relevance of the political and macroeconomic environment is reflected in the developments from 2018 onwards, which had a negative impact on the momentum for renewable energies. Due to a massive economic crisis in combination with the IMF aid programme, the capital costs for wind energy projects increased, which considerably slowed down the implementation of wind energy projects from the last tender rounds. These effects were reinforced by the impacts of the Covid-19 pandemic.

Another limiting factor that became apparent in the course of the research is the fact that the rapid expansion of renewable energies in recent years has significantly reduced the availability of free grid connection capacities. As already implemented within the MATER programme for the first time, in the future the expansion of renewable energies needs to be planned and implemented in conjunction with grid expansion. In addition, the expected increasing demand for green hydrogen in the future can play a decisive role in the further development of renewable energies. Argentina, particularly with its abundant wind energy potential in coastal regions, offers significant potential for hydrogen production. The development of a hydrogen economy could not only contribute to decarbonisation, but also creates economic opportunities and could contribute to overcome Argentina's macroeconomic structural challenges through the export of hydrogen.

6.2 From a theoretical perspective

In order to study the complex interactions involved in the diffusion of renewable energies in Argentina, a research framework (detailed in chapter 4.1) was developed within the scope of this dissertation which is grounded in the concepts of sustainability transition research. The integration of diverse approaches thus enables complementary perspectives from various frameworks to be combined, providing a comprehensive understanding of the endogenous and exogenous factors that are decisive for the diffusion of renewable energies in Argentina. Based on specific empirical foci and theoretical and methodological approaches, this research strategy allowed a technology-specific perspective at different levels of aggregation to be adopted on the one hand, and insights into the interactions with the Argentinian energy system and the surrounding contextual conditions to be gained on the other hand. The resulting findings contribute to the current research discussion in the still relatively young field of sustainability transition research. In the following, the theoretical findings of the respective contributions are outlined in a structured manner in relation to the research gaps presented in chapter 3.3.

6.2.1 Contribution to research gap 1

Transfer of the theoretical frameworks to new fields (e.g., technical and geographical nature) and gaining insight into how specific contexts influence the diffusion of new innovations (Bergek, 2019).

Although the respective articles differ in terms of their specific empirical focus, considering the contextual influencing factors specific to Argentina plays a prominent role in these articles. In the process, a range of theoretical and methodological approaches were selected and further developed. In general, it can be said that the contextual framework conditions in particular had a decisive, albeit very ambivalent, influence on the development of renewable energies in Argentina. a) On the one hand, as described in detail in the previous chapter, contextual changes acted as a window of opportunity and indicated positive development dynamics. Examples in this context include the effects of the energy reform of the 1990s on the practices of energy cooperatives and related wind energy projects, the promotion of renewable energies as a strategy to counter the inadequate energy supply in the context of the energy crisis and the remote rural regions without an electricity grid as a protected space for the development of decentralised renewable energies. b) On the other hand, the ambivalent influence of contextual factors becomes evident from the fact that Argentina-specific factors strongly inhibited the diffusion dynamics during certain phases and led to disruptions in the trajectory.

In the Argentinian case, the following aspects are of central importance in this regard: the country's economic and political instability, which increases perceived uncertainty for the activities of key actors (with negative implications for investments in energy projects and access to external finance, for example) as well as the negative effects of severe economic crises and their disruption effects on development dynamics (e.g., effects of the economic crises in 2001 and 2018). A comparison with current investigations undertaken in neighbouring Latin American countries shows that the development of renewable energies is shaped by country-specific factors. [18] This emphasises the appropriateness of the explorative methodological approach employed in this research to determine the factors influencing the development of renewable energies. This is relevant in light of the fact that the results of this research indicate that the theoretical approach developed by Edsand (2019) in his article 'Technological innovation system and the wider context: A framework for developing countries' regarding the ex-ante definition of landscape factors relevant for the diffusion of renewable energies in developing countries could not be confirmed. Indeed, the factors presented by Edsand (2019)—economic growth (e.g., increase in energy demand during positive economic development phases and thus exacerbation of the energy crisis), environmental awareness (e.g., positive effects on the niche of decentralised renewable energies), and climate change (e.g., ambitious CO2 reduction targets under the Paris Agreement)—play a direct or indirect role in the development of renewable energies in Argentina. However, the factors of 'Armed Conflicts', 'Corruption and Inequality' and 'Unequal Access to Higher Education' could not be empirically validated by this investigation. On the contrary, the Argentinian education system was even identified as a positive influencing factor due to free access to academic education with its specialisation opportunities in the field of renewable energies as well as technical training courses. The results of the study demonstrate that general guiding categories of analysis (e.g., in the form of a priori codes) derived from theoretical considerations can be adopted as a starting point for the analysis. The theoretical approaches of Bergek et al. (2015) proved to be more adequate for analysing the contextual embeddedness in greater depth. These were adopted and further developed in the present research endeavour. The contribution to the advancement of the research field is briefly summarised as follows:

- **Conception of 'endogenous' and 'exogenous' as a continuum:**

  As outlined in the theory chapter, this research builds on the idea of Bergek et al. (2015), who propose a distinction between 'structural couplings" and 'external links' to further investigate the contextual interactions and the degree of interdependence between the TIS and the surrounding context. In the course of this research, this conceptualisation has been applied and further developed in order to identify the key factors influencing the PV-TIS in Argentina. The 'endogenous and exogenous system strengths and weaknesses' could thereby be determined and specified.

[18] E.g., key contextual influencing factors in the analysis of wind TIS in Uruguay: reduction of import dependency in the electricity sector and a small and saturated market. Explicitly, it was emphasised that the factor of 'macroeconomic instability' is not relevant for the diffusion (Corrêa et al., 2022).

This assessment is founded on the perception that influencing factors can be positioned along a continuum between endogenous and exogenous influences, as shown on the Y-axis in Figure 6-1. The advantage of viewing exogenous and endogenous factors as a continuum is that it allows for a more comprehensive understanding of the complex interactions in the TIS. This distinction allows researchers to better analyse the dynamics between factors that are outside the actors' sphere of influence and those that are controlled by the actors themselves. Furthermore, it represents one of the first endeavours to operationalise the Bergek et al. (2015) theoretical constructs of 'structural coupling' and 'external links'. In order to illustrate the operationalisation, in Figure 6-1 the results of the research project on onshore wind energy (for the period 2015-2020) have been transferred to the overview diagram developed as part of the PV article. This conception of exogenous and endogenous factors as a continuum for determining monodirectional and interdependent interaction patterns and the proposed empirical approach represent an innovative contribution to the field of research. At the same time, the simultaneous analysis of the factors with regard to their relevance for the performance of TIS enables the identification of factors that have a particularly positive or negative influence on the development of TIS.

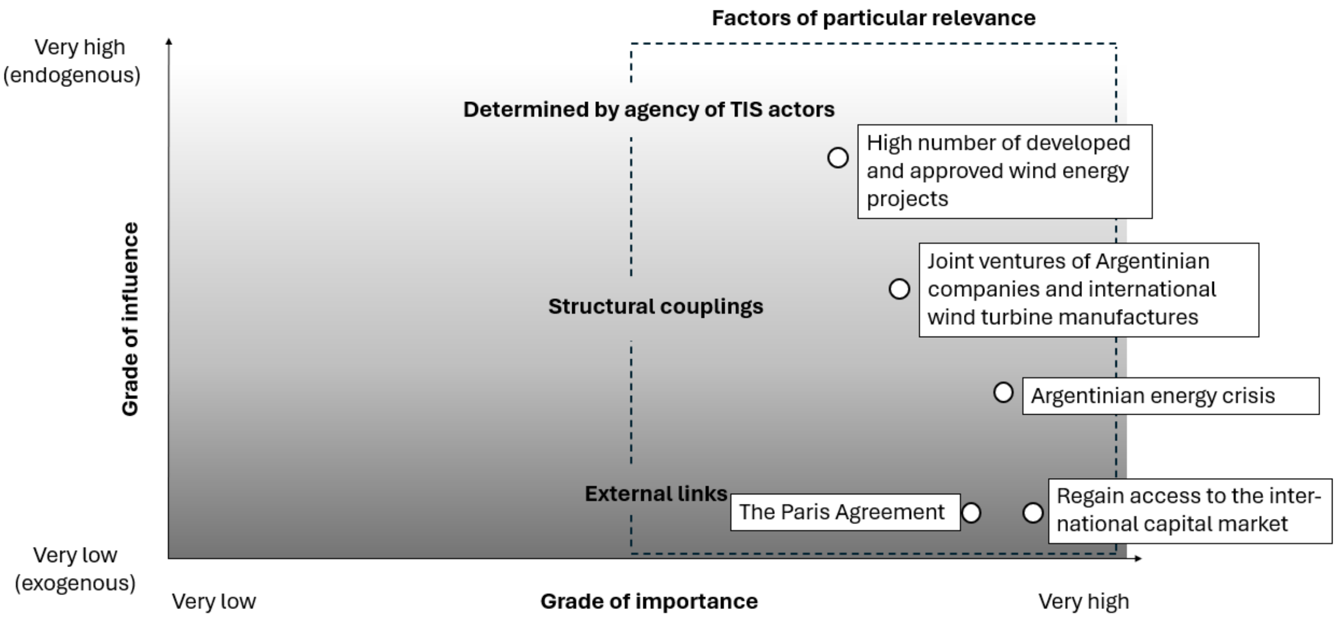

Figure 6-1: Illustrative example of endogenous and exogenous system strength: Mapping of key influential factors for the diffusion of onshore wind energy between 2015 and 2020
Source: Own illustration

■ Proposition of new analytical categories

The analysis of contextual factors influencing PV diffusion was based on the classification of TIS-context interaction patterns developed by Bergek et al. (2015). Within this classification, the following general context categories are distinguished: policy, established sectors, other TIS, and geographical context. As explained in detail in the discussion of the results in the article on PV diffusion, one recommendation derived from the empirical findings at the theoretical level is to add two further categories to the heuristics of Bergek et al. (2015): the ‘macroeconomic context’ and the ‘education system’. On the basis of the insides of the additional research papers on which this dissertation is based, the adoption of the National Innovation System (NIS) approach is proposed here, particularly for analysing TIS-context interactions in developing countries. As outlined in detail in the previous chapter, the diffusion of renewable energies in Argentina is significantly hindered by country-specific dysfunctionalities (e.g., macroeconomic instabilities and discontinuities in the macroeconomic policy framework). As mentioned previously, accompanying factors such as restricted access to the capital market, an unstable currency, high inflation rates, and a rapidly changing regulatory framework are generally having an impact on the innovation climate in the country. Based on these reflections, the consideration of the National Innovation System approach could provide a valuable contribution to future research in order to analyse the role of country-specific TIS-context interactions. The NIS approach assumes that the ability of a National Innovation System to develop and diffuse new innovations at the macro level is largely determined by the interdependent interaction of subsystems, in particular the research, education, legal and financial systems (Ebner, 2021).

On the basis of this approach, the "political" category, proposed by Bergek (et al., 2015), and the "macroeconomic environment" and "educational regime" categories, derived from the empirical data of this research project, can be considered as subsystems of the NIS. The functions of the subsystems of the NIS can therefore be considered to be a fundamental prerequisite for the development and diffusion of new innovations. The results of this research emphasise the importance of a functioning capital market, stable monetary policy, political stability, low inflation, confidence in investments, and political commitments for the development of renewable energies in developing countries. Based on the research results, in analogy to the NIS concept it is therefore proposed (see Figure 6-2) that the category of ‘national innovation environment’ should be introduced as a superordinate category for the TIS/context interaction.

Furthermore, the results of this research have demonstrated that a multi-scale approach is required to gain a deeper understanding of development dynamics and context interactions, which confirms the ‘geographical context structures’ category of analysis proposed by Bergek et al. (2015). The analysis of wind energy development has emphasised the relevance of the interaction between the focal TIS and the associated Global Innovation System (e.g., interaction dynamics of the global and Argentinian wind industry). On the other hand, the results have highlighted that, at the regional level, specific regions, such as the Chubut region with its excellent wind energy conditions, play a prominent role, which means that regional contexts should be specifically considered when analysing a TIS at the national level.

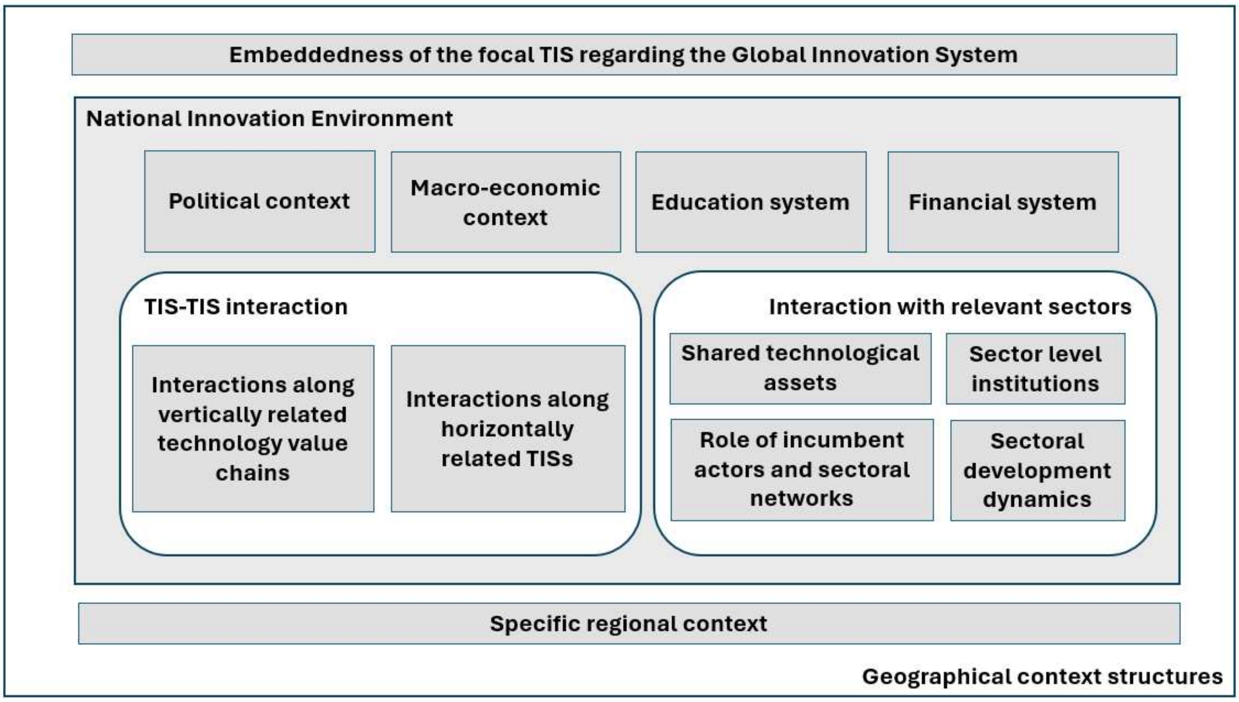

Figure 6-2: Enhancement of the TIS/context categorisation from Bergek et al. (2015a)
Source: Own illustration

6.2.2 Contribution to research gap 2

Gaining insights into the question of whether sustainability transitions in the context of developing countries are also premised on the assumption that they are accompanied by the destabilisation of the socio-technical regime and its technological substitution (Köhler et al., 2019).

Within the MLPs framework, socio-technical transitions are conceptualised as the product of dynamics occurring between the niche, regime and landscape levels. As described in detail in the theory chapter in Table 3-1, so far, five different types of transition pathways have been developed. The different typifications acknowledge that the course of the respective paths depends, on the one hand, on the temporal sequence of the interaction of the different levels, and on the specific constitution (e.g., the state of maturity of a specific niche) of the interacting elements. The inner constitution of the socio-technical regime plays a central role for the successful diffusion of new technologies that have developed at the niche level. It is assumed that instabilities in the dominant socio-technical regime, caused in particular by internal or external developments, create a window of opportunity for socio-technical transitions. The results of this study suggest that this conceptualisation does not fully apply to the Argentinian case, as partially interdependent patterns can be identified between the regime and landscape levels which have not yet been conceptually described in the literature on socio-technical transitions.

In Argentina, the socio-technical power system is affected by numerous instabilities which, however, resonate with instabilities in higher-level context structures. The resulting feedback loops in turn lead to path dependencies in the socio-technical regime. A further distinctive characteristic in this context is that these effects are so powerful that developments in the socio-technical regime also influence developments at the landscape level. This contrasts with the current understanding of the landscape level, which is characterised in the literature as being beyond the sphere of influence of the actors of the socio-technical regime and the niche level. In this context, instabilities within the socio-technical regime do not directly result in its replacement, as suggested in the literature. On one hand, these instabilities support the development of renewable energies in Argentina; on the other hand, their interaction with overarching country-specific instabilities simultaneously reinforces the fossil-based socio-technical regime's developmental pathway (see subsection 6.1.1.). In this context, it is suggested that the phenomenon can be described as 'path dependency from coupling-induced cross-system instabilities'.

These circumstances are illustrated by the following empirical example. Recurring macroeconomic crises and changes in the country's economic policy direction have led to increased uncertainty for long-term investments and restricted access to the international capital market. In the energy sector, this has led to insufficient investment in infrastructure and an increased dependence on imported natural gas, which has negatively impacted the country's already limited foreign currency reserves. The subsidisation of electricity as a political means of counteracting pauperisation negatively impacts the national fiscal budget and reduces the scope to provide financial resources in order to facilitate investments in the energy sector. This interdependency, in which macroeconomic instabilities and challenges within the energy sector influence each other, leads to a restriction of options for action and path dependency.

6.2.3 Contribution to research gap 3

Development of approaches to deal with the micro vs. macro methodological dilemma (Köhler et al., 2019).

The methodological micro vs. macro dilemma in Sustainability Transition Research refers to the challenge of analysing large-scale system transitions at the macro level (e.g., structural processes in the energy system and broader contextual development patterns), while simultaneously requiring an understanding of processes at the micro level (e.g., niche development, technological innovation systems (TIS) functions such as technological learning, and knowledge diffusion). In order to address the methodological micro vs. macro dilemma, distinct research strategies (see Table 4-1) were developed in the curse of this thesis. The contribution to the research field is summarised briefly in the following.

The four articles of this dissertation underline the strength of mixed-methods research approaches. On the one hand, these enable the explorative investigation of the research subject and, on the other, the triangulation and specification of the results. An overview over the selected methodological approaches has already been provided in the fourth chapter. Therefore, as an in-depth example of the consideration of micro/macro dynamics, the research work on ‘distributed photovoltaic generation’ in Argentina is outlined below. This article was based on a ‘mixed-method exploratory sequential research design’ research design. By conducting expert interviews, in the first step this approach enabled the explorative identification of factors that have an inhibiting or reinforcing effect on the performance of the individual functions of the focal TIS. By asking open-ended interview questions, both endogenous and exogenous relationships were revealed. This included considering dynamics at the micro level (e.g., creation of a training programme by PV experts) and at the macro level (influence of energy subsidies). This was complemented by a validation of the factors with an independent control group and the subsequent quantitative evaluation of these factors. This involved assessing the degree of influence of the actors in order to categorise the respective factors along the aforementioned scale of the endogenous-exogenous continuum. Against the background of the micro/macro dilemma, this made it possible to differentiate the influencing factors in terms of their origin. In doing so, for example, factors were identified that are of exogenous origin and can therefore be assigned to the macro level of the superordinate contextual environment. An additional example is the field study on the development of small wind turbines in Argentina. Here, the micro vs. macro dilemma was addressed by aggregating the findings from field observations and semi-structured expert interviews in a deductive and inductive categorisation process and discussing the results in a subsequent expert workshop. This multi-stage research process made it possible to precisely assess local dynamics and identify overall systemic relationships.

A further valuable methodological approach within this research is the constellation analysis. Building on the preliminary work of Best et al. (2012), it was applied for the first time in the course of this dissertation in order to operationalise the ‘combined MLP/TIS framework’. Constellation analysis represents an enrichment in terms of methodology for the research field of Sustainable Transition Research. This is rooted in the ability to map temporal dynamics (by recognising disruptions and the associated mapping of development phases) and to visualise the multidimensionality of development dynamics (e.g., niche developments and changes at the level of the socio-technical system). This approach has proven to be particularly suitable for exploring the influence of overarching contextual dynamics and demonstrating how these affect the respective sub-constellations in particular. In addition, the constellation analysis can be used in subsequent research to analyse individual sub-constellations in separate mappings (zooming-in), without neglecting overarching causal relationships (zooming-out).

6.3 Final remarks

Finally, based on the current state of knowledge, potential content adjustments and new areas of focus recommended for a revised version of the research project are reviewed. In addition, promising topics for future research are outlined.

Elaboration of an Argentina-specific definition of 'sustainability transitions' with a focus on normative drivers

In transition research, values and the associated objectives are considered to be normative drivers of sustainability transformations that trigger and guide the dynamics of change in a socio-technical system (Renn et al., 2007). Based on the results of the research, it can be concluded that the normative ecological dimension is a relevant, though not the key driving force for the diffusion of renewable energies in Argentina. In this context, decarbonising the energy sector is a key part of Argentina's commitment to ambitious targets under the Paris Climate Agreement. However, against the backdrop of the country's challenges, other normative motives play a major decisive role. At the level of the centralised energy system, the expansion of renewable energies is embedded in the goals of ensuring an affordable and secure energy supply. It is expected that the expansion of renewable energies will reduce the negative effects of the fossil energy system and thus alleviate the state's fiscal and monetary policy problems. Renewable energies are therefore seen as an opportunity to make an important contribution to the country's economic development. In the context of rural electrification through decentralised renewable energies, the underlying motive is the improvement of social justice and development opportunities through access to electricity. Therefore, if this research project were to be conducted once again, a key lesson would be to analyse more specifically the normative drivers and to elaborate on a definition of the term “sustainability transition in the energy sector” specific to Argentina. This definition, which is specific to Argentina, could then be compared with other definitions as part of a literature review. The current developments under the presidency of Javier Milei in 2024 demonstrate once again how strongly the development of renewable energies in Argentina is shaped by the specific contextual framework of the country. It is clear that a specific understanding and recognition of normative drivers and realities at the national level is crucial to achieving national renewable energy targets.

Analysing the impact of Argentina's National Innovation System on the diffusion of renewable energies

As outlined in the previous section 6.2.1, another insight of this research is that the development of a complementary research framework that analytically links the National Innovation System (NIS) and the Technological Innovation System (TIS) is a promising approach, especially in the context of analysing the diffusion of renewable energy in the Global South. If this work were to be re-done, this approach would be promising for example for the analysis of PV diffusion and exogenous system strengths and weaknesses. In future research projects, an approach could be developed in which a functional analysis of the NIS (complementary to the TIS analysis) is conducted based on the holistic NIS model. In this way, the impact of the functional fulfilment of NIS subsystems (e.g., financing) on the innovation dynamics of the focal TIS (e.g., resource mobilisation) could be explored, determining whether it inhibits or reinforces them. Therefore, in a revised version of the research, a general analysis of the Argentinian National Innovation System and its impact on the system function performance of the Technological Innovation System of a renewable energy technology would be a valuable approach to analyse exogenous influencing factors.

Complementary TIS analysis of hydrogen economy and wind energy

With regard to opening up development prospects for Argentina through sustainability transformations in the energy sector, the development of a hydrogen economy (based on renewable energies) is another promising field that would be considered in a new iteration of this research. The creation of jobs, diversification of export goods and the associated increase in foreign exchange reserves could offer the country considerable economic benefits. One important aspect for future research could be elaborating on scenarios for the development of a sustainable Argentinian hydrogen economy. A complementary TIS analysis of the current state of the hydrogen economy and wind energy in Argentina can serve as a foundation for these scenarios. These scenarios should take into account the specific Argentinian framework conditions as well as global influencing factors and identify development paths. In addition, concrete proposals should be developed on how the development of Argentina's hydrogen economy and the expansion of renewable energies can be successfully implemented in the long term against the background of Argentina's structural challenges. Such scenarios could provide valuable links to existing research and contribute to shaping a sustainable energy future in Argentina. Such research efforts would be a valuable addition to the current research and would contribute to the sustainable energy future in Argentina.

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Appendix: Full papers

The following pages of the printed version of this dissertation present the original versions of the published articles:

- Schaube, P., Ortiz, W., & Recalde, M. (2018). Status and future dynamics of decentralised renewable energy niche building processes in Argentina. Energy Research and Social Science. https://doi.org/10.1016/j.erss.2017.10.037
- Leary, J., Schaube, P., & Clementi, L. (2019). Rural electrification with household wind systems in remote high wind regions. Energy for Sustainable Development. https://doi.org/10.1016/j.esd.2019.07.008
- Schaube, P., Ise, A., & Clementi, L. (2022). Distributed photovoltaic generation in Argentina: An analysis based on the technical innovation system framework. Technology in Society, 68, 101839. https://doi.org/10.1016/J.TECHSOC.2021.101839
- Schaube, P. (2024). The influence of context-specific factors on the diffusion dynamics of onshore wind energy in Argentina. Wuppertal Paper (Vol. 203). Wuppertal Institut für Klima, Umwelt, Energie. https://doi.org/https://dx.doi.org/10.48506/opus-8612

The articles are not included in the digital publication, but can be accessed externally based on the sources provided above.