Linköping Studies in Science and Technology
Licentiate Thesis Nr. 1983

The diffusion of biogas systems in Brazil

Hanna Zanatta

LINKÖPING UNIVERSITY

Linköping Studies in Science and Technology

Licentiate Thesis Nr. 1983

The diffusion of biogas systems in Brazil

Hanna Zanatta

LINKÖPINGS UNIVERSITET

Environmental Technology and Management

Department of Management and Engineering

Linköping University, SE-581 83 Linköping, Sweden

www.liu.se

The diffusion of biogas systems in Brazil

ISBN 978-91-8075-482-8 (print)
ISBN 978-91-8075-483-5 (PDF)
https://doi.org/10.3384/9789180754835
ISSN 0280-7971
Printed in Sweden by LiU-tryck, 2024

Cover design: Hanna Zanatta

Abstract

Brazil is one of the largest economies in the Global South. Because of the country's strong agribusiness and large population, it has a huge potential for biogas production that has yet to be realized. Biogas systems could potentially address a broad range of social, environmental, and economic issues, such as improving accessibility to clean energy sources in rural areas, alternative cooking fuel, and providing proper treatment of organic waste. Hence, biogas systems can play an important role in sustainability transitions by improving the environmental performance of energy generation, waste management systems, and food production. However, despite the availability of substrate for biogas production and the multiple benefits that biogas systems could bring, there is still a large implementation gap.

Biogas systems go beyond technical components and involve a multitude of stakeholders, infrastructure, knowledge, and formal and informal institutions. Therefore, the diffusion of biogas systems cannot be explained only by analyzing the technical components of biogas systems. Previous studies have explored the influences of societal contexts on technological diffusion, but these explored countries in the Global North. However, social, economic, and political aspects differ significantly between Global North and Global South countries.

This thesis aims to explain how societal contexts influence the diffusion of biogas systems in Brazil. The thesis distinguishes between societal contexts, delineating them as societal environments and socio-economic structures. Societal environments refer to the circumstances and aspects surrounding the diffusion process where alignment processes between new socio-technical systems and society happen across five environments: user, business, regulatory, cultural, and trans-local. Socio-economic structures refer to societal arrangements that shape social and economic aspects of society. The Varieties of Capitalism framework provides a tool for comparison of the socio-economic structures of different countries in the Global North and South. The thesis relies on case studies based on quantitative and qualitative data from documents (scientific articles, news articles, technical reports, research reports, official documents by governmental agencies, and policies) and interviews.

Societal contexts appear to be more unstable and fragmented compared to counterparts in the Global North, influencing the diffusion of biogas systems. Hierarchical structures in Brazil lead to power disparities between administrative levels (municipal, state, and federal levels), impacting policymaking and hindering local-level biogas system configurations. The thesis highlights socio-economic diversity among Brazilian states and how it influences where and which biogas system configurations are formed. This thesis emphasizes that studies on biogas systems' potential should consider contextual aspects beyond substrate availability to comprehensively understand biogas systems diffusion in diverse settings.

Key words: anaerobic digestion, socio-technical interactions, sustainability transitions, Global South.

Sammanfattning

Brasilien är en av de största ekonomierna i den globala södern. Givet landets starka jordbruksindustri och stora befolkning finns goda förutsättningar för storskalig biogasproduktion. Men det är en potential som ännu inte har exploaterats i någon större utsträckning. Biogassystem har potential att bidra till lösningen på flertalet sociala, miljömässiga och ekonomiska frågor, såsom att förbättra tillgången till rena energikällor på landsbygden, erbjuda alternativa bränslen för matlagning och att tillhandahålla lämplig behandling av organiskt avfall. Därmed kan biogassystem spela en viktig roll i en hållbar omställning genom att förbättra miljöprestandan för energiproduktion, avfallshantering och livsmedelsproduktion. Trots de många fördelarna som biogassystem medför finns alltså fortfarande en stor klyfta mellan potentialen och vad som är realiserat.

Biogassystem sträcker sig bortom tekniska komponenter och inkluderar även en mångfald av intressenter, infrastruktur, kunskap samt formella och informella institutioner. Därför kan spridningen av biogassystem inte förstås enbart genom att analysera tekniska komponenter i biogassystemet. Tidigare studier som har studerat hur sådana bredare samhällsfaktorer påverkar spridningen av teknologi har huvudsakligen undersökt länder i västvärlden (det globala norr). Men sociala, ekonomiska och politiska aspekter skiljer sig betydligt mellan länder i det globala norr och det globala söder.

Denna avhandling syftar därför till att förklara hur olika samhällsfaktorer påverkar spridningen av biogassystem i Brasilien. Avhandlingen skiljer mellan olika sorters samhällsfaktorer och delar in dem i samhälleliga miljöer och socioekonomiska strukturer. Samhälleliga miljöer avser de omständigheter och aspekter som omger spridningsprocessen där anpassningsprocesser mellan nya sociotekniska system och samhället sker över fem miljöer: användarmiljön, affärsmiljön, den reglerande miljön, den kulturella miljön och den translokala miljön. Socioekonomiska strukturer avser samhälleliga arrangemang som formar sociala och ekonomiska aspekter av samhället. För att jämföra socioekonomiska strukturer i olika länder i det globala norr och globala söder används även ramverket ”Varieties of Capitalsim” som beskriver olika former av kapitalism. Avhandlingen baseras på fallstudier och använder kvantitativa och kvalitativa data från dokument (vetenskapliga artiklar, nyhetsartiklar, tekniska rapporter, forskningsrapporter, officiella dokument från statliga organ och policys) samt intervjuer.

Resultaten visar att de studerade samhällsfaktorerna i Brasilien verkar vara mer instabila och fragmenterade jämfört med motsvarigheter i det globala norr, vilket påverkar spridningen av biogassystem negativt. Hierarkiska strukturer i Brasilien leder till maktobalans mellan administrativa nivåer (kommunal, delstatlig och federal nivå), vilket påverkar politiskt beslutsfattande och hindrar utvecklingen av biogassystem på lokal nivå. Avhandlingen lyfter fram betydelsen av socioekonomisk mångfald bland Brasiliens delstater och hur dessa påverkar var och vilka biogassystem som utvecklas. Avhandlingen understryker att studier om biogassystems potential bör överväga kontextuella aspekter bortom tillgång på substrat för att bättre förstå spridningen av biogassystem i olika sammanhang.

Acknowledgements

This licentiate thesis represents the outcome of the initial years of my PhD studies. I would like to acknowledge the Biogas Solutions Research Center (BSRC) for funding this research and for creating a conducive and stimulating research environment.

I am deeply grateful to my supervisor, Wisdom Kanda, and co-supervisors, Olof Hjelm and Thomas Magnusson, for their invaluable guidance, support, and constructive feedback throughout the entire process that led to this licentiate thesis. This research would not be possible without their expertise, patience, and encouragement.

I extend my gratitude to the interviewees in Brazil for their willingness to share insights that significantly contributed to this work.

I extend my appreciation to Hans Andersson for meticulously reviewing the early version of this thesis.

My sincere appreciation goes to my colleagues at the Division of Environmental Technology and Management for their insightful discussions, assistance, and encouragement during this research endeavor.

I would like to express my gratitude to my family for their support and understanding throughout this academic pursuit.

Hanna Zanatta

List of appended papers

I. Kanda, W., Zanatta, H., Magnusson, T., Hjelm, O., & Larsson, M. (2022). Policy coherence in a fragmented context: the case of biogas systems in Brazil. Energy Research & Social Science 87, 102454. https://doi.org/10.1016/j.erss.2021.102454

The article was conceptualized in a collaborative manner. Specifically, the author of this thesis contributed to the theoretical framing, data collection, methodology, analysis, writing of the original draft, and revisions.

II. Magnusson, T., Zanatta, H., Larsson, M., Kanda, W., & Hjelm, O., (2022). Circular economy, varieties of capitalism and technology diffusion: anaerobic digestion in Sweden and Paraná. Journal of Cleaner Production 335, 130300. https://doi.org/10.1016/j.jclepro.2021.130300

The article was conceptualized in a collaborative manner. Specifically, the author of this thesis contributed to the theoretical framing, data collection, methodology, analysis, writing of the original draft, and revisions.

III. Zanatta, H. (2023). To conform or to transform? A comparative case analysis of the societal embedding of biogas systems. Biofuels, 2257960. http://doi.org/10.1080/17597269.2023.2257960

The author of this thesis conducted the full process, from the conceptualization to the final revisions of the article.

Table of Contents

List of figures

List of tables

1. Introduction

This chapter elaborates on the central issue addressed in this thesis and highlights its importance from a societal and research standpoint. This chapter also presents the thesis's aim, research questions, and thesis outline.

Brazil generates substantial amounts of organic waste because of its strong agribusiness sector and large population. When left untreated, organic waste poses significant risks, including water contamination, greenhouse gas emissions, health problems, and loss of resources, leading to critical social, environmental, and economic problems. Biogas systems offer a suitable means for the treatment of organic waste through anaerobic digestion while simultaneously supporting sustainability transitions by substituting fossil fuels and recirculating nutrients. Biogas systems include several technologies across multiple stages of the biogas value chain, from the pre-treatment of organic matter to the use of the main products (biogas, digestate, and carbon dioxide). When combined, these different technologies form different configurations of biogas systems. Biogas systems can bring multiple benefits by improving the environmental performance of energy generation, waste management, and food production (Börjesson and Berglund, 2007). Obaideen et al. (2022) suggest that biogas systems could contribute to 12 of the 17 Sustainable Development Goals (SDGs)[1]. However, the benefits of biogas systems depend on local conditions and which configurations of biogas systems are established since different benefits are associated with different biogas technologies and products (Feiz et al., 2022). For example, the substitution of fossil fuels requires the use of biogas as an energy carrier, and the recirculation of nutrients depends on the use of the digestate as a fertilizer.

The diffusion of biogas systems in Brazil has accelerated in the past decade, yet only a small fraction of the technical potential[2] has been realized. In addition, the diffusion of biogas systems in Brazil remains restricted to only a few states. Out of the total estimated technical potential of around 80 billion Nm^3 of biogas annually, residues from the sugarcane energy industry represent the greatest technical potential for biogas production (50%), followed by agribusiness

---

[1] The Sustainable Development Goals (SDGs) are part of the 2030 Agenda for Sustainable Development, which was adopted by United Nations Member States in 2015. Together, the SDGs offer a blueprint for sustainable development and advocate for an integrated approach to address global challenges.

[2] Technical potential for biogas production refers to the maximum amount of biogas that could be produced using the available substrate and best available technology.

residues (45%), and lastly, municipal solid waste and sewage sludge (5%) (ABiogás, 2020). Despite representing a smaller fraction of technical potential for biogas production, most of the biogas produced in Brazil comes from the capture of landfill gas derived from municipal solid waste. As an end-of-pipe technology, landfill gas capture has a limited capacity to address a broader range of sustainability issues in comparison to other biogas technologies. These discrepancies in the diffusion of biogas systems across the country have been previously attributed to differences in substrate availability and technical aspects (De Oliveira and Negro, 2019). Although substrate availability, access to technology, and infrastructure (e.g., gas pipes, sewage network, electricity grid) are important factors in producing and utilizing biogas, these factors alone do not explain the contrast in biogas systems diffusion across Brazil. Biogas systems are multifunctional systems that emerge at the interface of different sectors (e.g., agriculture, waste management, energy). To successfully establish biogas systems, a multitude of stakeholders, knowledge, and formal and informal institutions need to come together in addition to technical components (Geels and Raven, 2006; Ottosson et al., 2020). These aspects are influenced by societal contexts which, in turn, can influence the diffusion of biogas systems by enabling specific paths for the adoption of certain technologies while blocking others, ultimately affecting the possible configurations.

The importance of societal contexts to the diffusion of biogas systems has been previously explored in the Global North[3], for example, by looking at how professional cultures influenced the diffusion of biogas systems in Austria (Wirth et al., 2013) and how the rise and fall of biogas systems' legitimacy influenced diffusion in Germany (Markard et al., 2016). However, historical and contemporary societal contexts in Global North countries differ significantly from Global South countries (Wieczorek, 2018). Societal contexts in Global South countries often exhibit heterogeneity in public services, limited accessibility to infrastructure, and large inequalities in contrast to Global North countries (van Welie et al., 2018). Diffusion of biogas systems in Global South countries could potentially address a broader range of challenges, such as an alternative to cooking fuel (Yasmin and Grundmann, 2019), proper treatment of

[3] The terms Global North and Global South are used to distinguish between societal contexts that present significantly different social, political, and economic settings (Pagel et al., 2014; van Welie et al., 2018). Global South countries refer to low to middle-income countries that were colonized in the past, such as Brazil and other countries in Latin America. Although countries in these categories have related characteristics, they are not entirely homogenous, and thus labeling countries as Global North or Global South are concepts used to describe different complex realities.

organic waste, increased accessibility to an energy source in rural areas, and decreased dependency on fossil fuels (Amigun et al., 2012).

Despite the large availability of substrates for biogas production in Brazil and the multiple benefits biogas systems could bring, biogas systems diffusion in the Brazil has thus far been limited. Previous studies on the diffusion of biogas systems in Brazil predominantly concentrate on the internal dynamics of biogas systems, exploring how endogenous aspects of biogas systems influence diffusion, or when societal contexts are included, these are simplified to drivers and barriers to diffusion (Borges et al., 2023; De Oliveira and Negro, 2019). However, inward-oriented perspectives provide limited explanations about how these different complex realities may influence systems' diffusion while treating societal contexts as merely drivers and barriers to diffusion overlook that these are dynamic entities.

The aim of the thesis is to explain how societal contexts influence the diffusion of biogas systems in Brazil. The thesis differentiates between societal contexts in the form of societal environments and socio-economic structures. These analytical terms conceptualize societal context at different levels that differ in terms of stability and longevity. Diffusion processes as dynamic alignments between new socio-technical systems and society happen across multiple societal environments, such as user, business, regulatory, cultural, and trans-local environments. These societal environments refer to dynamic dimensions where interactions between new socio-technical systems and society happen. As interactions between new socio-technical systems and societal environments occur, both can exert influence over each other, which can lead to change. Socio-economic structures on the other hand, consist of deeper structural trends that form social and economic arrangements of society. In relation to societal environments, socio-economic structures are harder to change and more stable. Because of the stability of socio-economic structures, biogas systems have weak or limited influence over these structures. Hence, the term "shape" is used to describe this unidirectional influence of socio-economic structures over the diffusion of biogas systems. To operationalize the presented aim, the following research questions are addressed:

I. How do interactions with societal environments influence the diffusion of biogas systems in Brazil?
II. How do socio-economic structures shape the diffusion of biogas systems in Brazil?

This thesis comprises a cover essay and three appended papers. The ambition of the cover essay is to complement the appended papers by describing how the appended papers are interrelated and combining the research findings within the wider context of biogas systems diffusion in Brazil. Following the introductory chapter, *Chapter 2. Biogas systems: technologies, configurations, and the Brazilian context* introduces biogas systems and provides an overview of biogas systems in Brazil. *Chapter 3. Theoretical perspectives on biogas systems and societal contexts* then elaborates on socio-technical systems, societal embedding, and varieties of capitalism frameworks and presents a theoretical synthesis that guides this research. Next, *Chapter 4. Methodology* introduces the research journey, data sources, analysis and discusses research quality and research ethics. *Chapter 5. Summaries of appended papers* continues and presents each paper's aim, specific methods, main findings, and conclusions of the three appended papers separately, while *Chapter 6. Answering the research questions* elaborates on how the appended papers contribute to answering the research questions together. Lastly, *Chapter 7. Conclusions* summarizes key findings and explores future research paths.

2. Biogas systems: technologies, configurations, and the Brazilian context

This chapter introduces biogas systems by explaining what biogas systems are, the possible origins of organic substrate, stages of production, different applications of biogas and other by-products, and environmental benefits, among other aspects of biogas systems. Subsequently, the chapter presents an overview of the diffusion of biogas systems in Brazil and reports on the different biogas system configurations present in Brazil.

Biogas comes from the degradation of organic matter of biogenic origin in the absence of oxygen in a process called anaerobic digestion. Different types of substrates are suitable for anaerobic digestion, such as manure, organic household waste, sewage sludge, wastewater from the food and beverage industry, and stillage from ethanol production, among other agricultural residues. The effluent or digested substrate of anaerobic digestion, called digestate, is rich in macronutrients, including nitrogen, phosphorus, potassium, and sulfur, micronutrients, and organic matter, thus making it an excellent fertilizer. Landfilling of organic matter also produces biogas, but because it is in landfills, the organic waste is mixed with other fractions of household waste, and the effluent cannot be used as fertilizer. When biogas comes from landfills, it is commonly referred to as landfill gas.

Biogas consists mostly of methane (CH_4) and carbon dioxide (CO_2) and smaller amounts of water (H_2O), nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), and other trace gases. Biogas is an energy carrier that can substitute fossil fuels in electricity generation, heat generation, or as transportation fuel. However, the use of biogas as a transportation fuel requires further refinement of biogas to biomethane, which means increasing the methane content to above 95% of the volume and removing most of the carbon dioxide and other impurities. As the carbon dioxide fraction from biogas is biogenic, the carbon dioxide removed during the upgrading of biogas is usually released into the atmosphere. However, carbon dioxide can also be captured and utilized after further processing to cover the needs of, for example, food industries, cooling systems, and greenhouses. After upgrading, biomethane is compressed to increase energy density and facilitate transportation or injection into the gas grid. The energy density can be further increased by liquefying the biomethane. During the liquefaction process, the compressed gas is cooled to temperatures around and below minus 162 degrees Celsius. Both compressed biogas (bio-CNG) and liquified biogas (bio-LNG) can be used as transportation fuels and directly substitute compressed natural gas (CNG) or liquified natural gas (LNG) since, chemically, these products are the same. Different combinations of organic matter for anaerobic digestion, applications of the biogas produced, and use of the digestate and carbon dioxide form distinct configurations of biogas systems.

Because of the variety of substrates and applications of biogas, digestate, and carbon dioxide, biogas systems can cut across several sectors and have multiple functions. Biogas systems can fulfill several roles as they can be adopted for the hygienization and treatment of organic waste, the production of renewable fuel, and the production of biofertilizers. When it comes to the treatment of organic waste, competing technologies rarely combine the benefits of energy recovery (i.e., incineration) and recirculation of nutrients (i.e., composting) but usually provide one of them (Börjesson and Berglund, 2007). The use of biogas as an energy carrier allows for energy recovery from organic waste, the substitution of fossil fuels, and carbon capture, storage, and use. The use of the digestate as a fertilizer allows the recirculation of nutrients back into the food value chain and can replace mineral fertilizers. The introduction of a biogas system usually improves the overall environmental performance of the systems they replace (Börjesson and Berglund, 2007). Biogas systems' environmental benefits originate from the substitution of fossil fuels by biogas as an energy carrier, recirculation of nutrients by using the digestate as a fertilizer, treatment of organic waste, reduction of greenhouse gas emissions, and capture and utilization of carbon dioxide. Different combinations of technologies form different configurations of biogas systems, and these different systems' configurations will have drastically different levels of greenhouse gas emissions, which are affected by the type of substrate and energy efficiency, among other technical parameters (Börjesson and Berglund, 2006).

2.1. Configurations of biogas systems in Brazil

Biogas systems have experienced rapid diffusion in Brazil in the past decade (Figure 1). Biogas production from solid waste and sewage treatment has been particularly prominent. Within this group, landfill gas capture technologies represent the majority of biogas technologies adopted. According to the Brazilian Biogas Association (Abiogás), the maximum technical potential for biogas production is around 80 billion Nm^3 of biogas annually, with half of this technical potential in the sugarcane energy sector, followed by the farm-based residues (e.g., manure, straw, bark) with 35%, other industries (excluding sugarcane energy industry) representing around 10%, and solid waste and sewage treatment representing 5% of this technical potential (ABiogás, 2020).

Despite the increased diffusion of biogas systems in Brazil, only a small fraction of the technical potential for biogas production has been realized. Even when considering only the easily available and concentrated substrates for biogas production, less than 3% of the technical potential has been realized. Furthermore, most of the biogas produced in Brazil comes from solid waste and sewage treatment, which have a smaller technical potential for biogas production than the other sectors.

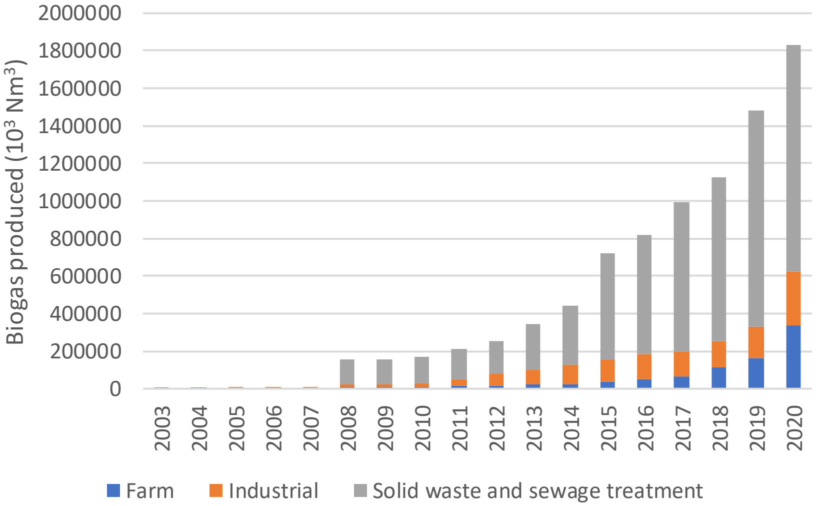

Figure 1. Volume of biogas produced in Brazil according to the origin of organic substrate (based on CIBiogás, 2021[4])

When contrasting Figure 1 and Figure 2, it is possible to see that although the volume of biogas production is higher from solid waste and sewage treatment sources, farm-based biogas facilities diffuse faster. It is important to mention that these categories represent significantly different configurations of biogas systems regarding, for instance, the type of biogas technologies, scale of production, and use of products. For example, farm-based biogas facilities are usually small-scale[5], while landfill gas capture facilities are classified as large-

[4] The dataset only includes biogas used for energy purposes; thus, the flaring of biogas is not included. Consequently, the figures do not include biogas technologies that were adopted with the sole purpose of treating organic waste.

[5] In this thesis, biogas facilities are classified as small-scale when biogas production is below 1 million Nm^3 annually, medium-scale when biogas production is between 1 million and 5 million Nm^3 annually, and large-scale when biogas production is above 5 million Nm^3 annually.

scale. Another contrast between these distinct system configurations is the use of the digestate. In landfill gas capture facilities, the remaining effluent cannot be repurposed since the organic fraction was mixed with other materials. In comparison, farm-based biogas facilities use the digestate as fertilizer. Most of these farm-based facilities can use the digestate within the same area, thus enabling the recirculation of nutrients.

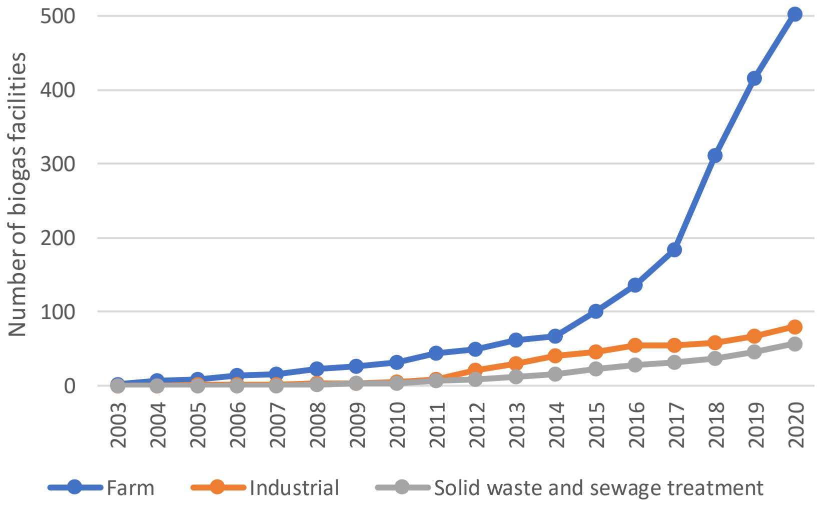

Figure 2.Number of biogas facilities in Brazil according to origin of organic substrate (based on CIBiogás, 2021).

In Brazil, biogas is mainly used for electricity generation (Figure 3). Electricity generation has diffused faster than other applications of biogas. How the electricity generated is used may vary depending on the sector. Large-scale biogas facilities usually generate electricity and sell the electricity at national auctions or through contracts with the final user (open market). In contrast, small and medium-scale biogas facilities use the electricity generated for internal processes. Sewage treatment plants, for example, use the electricity generated for internal processes because of the high demand for electricity by sanitation companies. Similarly, farm and industrial biogas facilities generate electricity and heat to supply internal processes. Although there has been a threefold increase in biomethane production in Brazil between 2018 and 2020, biogas upgrading remains uncommon. When biogas is upgraded, the biomethane is compressed (bio-CNG) and utilized for industrial purposes or transportation.

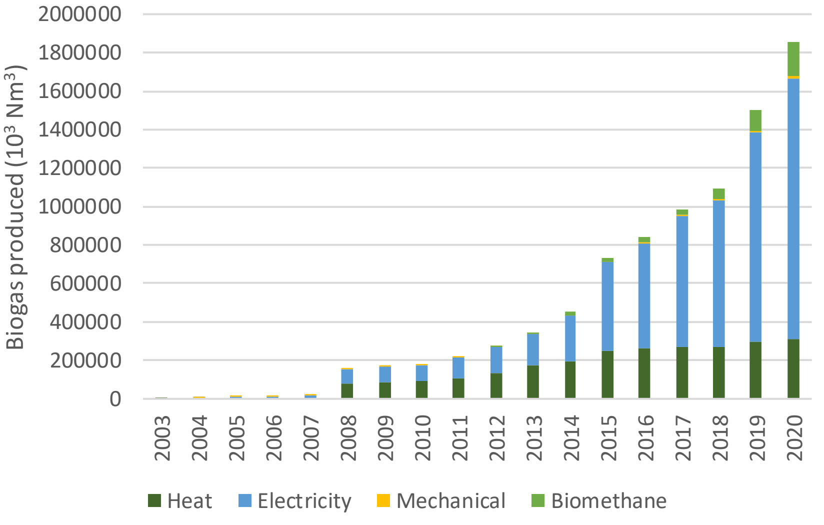

Figure 3. Use of biogas in Brazil (based on CIBiogás, 2021).

2.2. Biogas systems in the Brazilian context

As a consequence of the oil crisis in the 1970s, the Brazilian federal government supported several research projects that focused on alternative energy sources and aimed at increasing energy security and reducing dependency on fossil fuels. Among these research projects was the installation of an anaerobic digestion reactor in Brazil at Granja do Torto, Brasilia, which marked the beginning of the development of biogas systems in Brazil (Palhares, 2008). At the same time, ethanol also received extensive support from key actors at the federal and state levels. In 1975, the federal government introduced the National Fuel Alcohol Program (ProÁlcool), aiming at stimulating ethanol production from sugarcane. The Energy Mobilization Program (Programa de Mobilização Energética – PME) implemented by the federal government in 1982 aimed at substituting fossil fuels and increasing energy efficiency. The PME financed farmers' adoption of small-scale anaerobic digestion reactors, especially in the South and Southeast regions. Although thousands of anaerobic digestion reactors were installed at the time, operational problems combined with the lack of specialized professionals led to the discontinuation of these anaerobic digestion reactors shortly after (Reis, 2020). Additionally, when oil prices declined, the PME became economically unfeasible, culminating in the stagnation of biogas systems development in the 1990s.

A new cycle of biogas technology diffusion in Brazil started at the beginning of the 21st century, powered by a favorable economic scenario and incentives based on the Kyoto Protocol (De Oliveira and Negro, 2019). Created to assist countries in achieving their emission reduction goals, the Clean Development Mechanism (CDM) supported the adoption of environmental technologies in Brazil, including biogas technologies. Many firms financed the purchase of anaerobic digestion reactors by farmers, especially swine farmers, in return for the carbon credits generated by the project. Using the biogas produced was not a requirement to obtain the carbon credits from the anaerobic digestion of manure. Therefore, many of these projects neglected energy efficiency and biogas production. Although the number of biogas plants increased during this period, most of these plants only flared the biogas produced. Consequently, many of these biogas plants had low production efficiency and high biogas leakages.

Other governmental programs implemented in the early 2000s also supported the uptake of biogas systems in Brazil. Aiming to democratize access to electricity in rural areas, the Light for All program (Programa Luz para Todos) favored local and renewable energy sources for electricity generation. The program financed up to 85% of investment costs to install anaerobic digestion reactors and power generators. The program also helped existing CDM projects producing and flaring biogas to install electricity generators. In parallel, the shale gas revolution in the United States boosted the offer of gas-powered electrical generators and pushed prices down, thus making these technologies accessible to biogas producers. Large municipalities took advantage of CDM schemes to implement landfill gas capture technologies and flared the biogas to reduce emissions and obtain carbon credits.

In 2010, the federal government approved the National Policy of Solid Waste (Política Nacional de Resíduos Sólidos – PNRS). The policy aimed at ending improper waste disposal, such as dumpsites, by 2014 and presented a waste hierarchy to support the development of municipal waste management systems. According to PNRS's waste hierarchy, anaerobic digestion was a preferable choice for the treatment of organic household waste. The responsibility for the development and implementation of suitable waste management systems fell upon the municipalities. However, most municipal governments did not have the human and financial resources to successfully implement the requirements of the PNRS. Most municipalities deemed anaerobic digestions of organic household waste unsuitable as they required waste segregation and larger investments than other competing technologies.

Whereas in the early 2000s, the diffusion of biogas systems was driven by environmental concerns and incentives to environmental technologies, by the end of that decade, the use of biogas as an alternative energy source pushed the diffusion of biogas systems. Because of the increasing diffusion of biogas systems in Brazil, federal and state governments took measures to regulate the sector and promote markets for biogas. The first biogas-specific policies appeared in 2012 when the states of São Paulo and Rio de Janeiro implemented a biogas state policy to mitigate emissions and promote biogas production in the waste management sector, respectively. In parallel, biogas actors began to organize themselves and formed two biogas associations: the Brazilian Association of Biogas and Methane (Associação Brasileira de Biogás e Metano-ABBM) and the Brazilian Biogas Associations (Associação Brasileira do Biogás – Abiogás). ABBM gathers practitioners and researchers interested in biogas systems to share knowledge among individuals. On the other hand, Abiogás is an industrial association that provides institutional representation for public and private organizations across the biogas value chain. Although these associations serve different functions, the existence of two associations resulted in conflicts and portrayed the biogas sector as divided.

Only a few years after the first state policies, the federal government provided specifications regarding biomethane quality. In 2015, the National Agency of Petroleum, Natural Gas, and Biofuels (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis – ANP) standardized the quality requirements of biomethane produced from agricultural residues. The resolution facilitates the commercialization of biomethane as it defines minimum quality standards and methane content for fuel intended for vehicle, residential, and commercial use, thus enabling the injection of biomethane into gas grids. However, biomethane specifications from solid waste and sewage treatment plants were only established in 2017 after a long negotiation between biogas actors and the regulatory agency.

In Brazil, gas markets have been regulated and controlled by state governments. Historically, state companies held the monopoly over piped gas commercialization and infrastructure. Hence, biogas producers were often unable to commercialize biomethane or develop infrastructure for the distribution of biomethane. Efforts to open gas markets in Brazil and the recent stimulus of biofuels helped to promote biogas upgrading and opened new possibilities for biogas systems. Since 2016, a series of policies implemented at the federal level aimed at breaking Petrobras' (energy company whose largest shareholder is the Brazilian federal government) monopoly over gas markets, increasing competition, attracting new actors, and consequently reducing gas prices. The National Biofuels Policy (Política Nacional de Biocombustíveis – RenovaBio) is an example of policies aiming at promoting biofuels. RenovaBio sets annual decarbonization targets for fuel distributors according to their share of the Brazilian fuel market. To reach their decarbonization targets, fuel distributors must acquire decarbonization credits (CBIOs) emitted by biofuel producers. Biofuel producers receive the CBIOs equivalent to the emissions avoided in comparison to a fossil fuel reference. Biogas systems based on organic residues can benefit from this policy since they have substantially lower emissions in relation to fossil fuel reference. Yet, upfront costs to biofuel producers are high as they must be certified, thus favoring large-scale production and existing biofuel plants. Because of the COVID-19 pandemic, the program was delayed, and initial targets were reduced.

3. Theoretical perspectives on biogas systems and societal contexts

This chapter elaborates on the concepts and theoretical foundations that form the basis for this thesis.

Diffusion of systems is a social process that leads to change in the structure of social and technical systems. Because diffusion processes happen within the context of social systems, the structure of these systems influences the individual's decision to adopt or reject an innovation, as well as the norms of diffusion processes (Rogers, 2003). Early studies on diffusion processes focused on individual decision-making to adopt or reject innovations, which led to a bias towards individual adopters where they are to blame or praise for diffusion processes without much attention to the role of other actors (Lyytinen and Damsgaard, 2001). Although diffusion of innovation theory acknowledges the influence of social systems, these are rarely explored. When addressed, they are treated as just a consequence of individual decision-making, while the context is described as static and homogenous. In addition, diffusion of innovation theory struggles to incorporate complex interactions between context and technologies that have the potential to transform entire systems. The diffusion of multi-functional technologies is a complex process that involves interactions between multiple actors and socio-technical systems beyond the adopters. When the analysis is restricted to technologies and adopters, the influence of societal contexts is underdeveloped (Rip and Kemp, 1998), which can be misleading when analyzing the diffusion of systems.

Coenen and Díaz López (2010) identify three highly influential systems approaches to innovation and systems change for sustainability, namely, sectoral systems of innovation (SSI), technological innovation systems (TIS), and socio-technical systems. SSI sets analytical boundaries around products and puts the firms at the center of the analysis (Coenen and Díaz López, 2010). Technological change is often an incremental and path-dependent process, driven by firms and markets. As a result, SSI analysis is quite static. However, TIS suggests that new systems emerge from the interactions between TIS's structural components – actors, networks, and institutions that contribute to the development and diffusion of innovation – and how well they fulfill the system's functions (Bergek et al., 2008). Socio-technical systems approach the emergence and diffusion of technological systems in society and how they fulfill societal functions. New systems emerge from the interactions between three analytical levels: niche, regime, and landscape (Geels, 2011). Socio-technical systems address systems that have the fulfillment of societal functions as their primary goal and are dependent on technology to achieve their primary goal in society. The socio-technical systems approach widens the analytical focus in relation to the SSI approach to include the user, the use of technologies, and functionality (Geels, 2004). As technological systems leave protected spaces to enter more diverse markets, the TIS approach has limited analytical power to explain entire diffusion processes because it focuses on the performance of emerging technological systems (Mignon, 2016). Regarding the TIS approach, the socio-technical systems approach offers a better understanding of contextual factors and how they influence systems' diffusion. Therefore, this research uses socio-technical systems approaches to explore the diffusion of biogas systems in Brazil.

3.1. Socio-technical systems

The socio-technical systems perspective is concerned with interdependencies between society and technology, exploring how societal change encourages technological development and stimulates societal development (Trist, 1981). Technologies are always introduced against the background of societal contexts and their settings, and thus, diffusion is as much a social process as a technological one (Geels and Schot, 2007). The socio-technical systems perspective differentiates between pre-existing societal contexts in which technologies are introduced and the systems in focus. This differentiation particularly suits this thesis's aim and helps distinguish societal contexts from biogas systems.

Technology is an essential component of biogas systems since these depend on technologies to fulfill biogas systems' functions (e.g., organic waste treatment technology, energy provider, recycling of nutrients). However, biogas systems go beyond the technology to incorporate formal and informal institutions as well as the interactions between the different components. Biogas systems also rely on human actions as the production, use, and diffusion of biogas systems require interaction between several actors. In contrast to other approaches that analyze technological change, the socio-technical systems perspective considers other types of actors beyond the adopter of the technology and includes other actors. Instead of looking at single organizations, socio-technical systems analyze the inter-organization community. Therefore, socio-technical systems offer a holistic perspective to explore the interactions between social and technical elements central to biogas systems and their societal contexts. Socio-technical systems approaches cover other elements beyond the adopter and technology but also include, for example, knowledge, values, norms, and human and financial resources (Coenen and Díaz López, 2010).

3.2. Societal embedding

New socio-technical systems are always introduced against the backdrop of existing social groups, economic structures, political systems, exogenous environments, and their settings (Geels and Schot, 2007) and require that society is rearranged to a certain extent for the diffusion of new systems (Rip and Kemp, 1998). Diffusion, as a process of societal embedding, is the alignment process between technology and society where both are transformed in a co-evolutionary manner (Geels and Johnson, 2018; Kanger et al., 2019; Rip and Kemp, 1998). Societal embedding suggests that successful diffusion goes beyond the technology itself in a process influenced by contextual characteristics. The societal embedding framework distinguishes between different environments where the interactions between the new socio-technical systems (biogas systems) and their context happen. Because societal embedding conceptualizes societal environments as dynamic dimensions, it allows a deeper examination of how diffusion processes unfold and explains what influences societal environments may exert over diffusion processes.

Interactions between the new socio-technical systems and societal contexts are contested processes full of choices and struggles that can lead to different diffusion patterns (Geels et al., 2007) and result in regional differences in socio-technical systems over time (Hughes, 1983). Societal and technological change occurs because of these interactions (Geels and Schot, 2007), which happen across key societal environments and include the regulatory, user, business, cultural, and trans-local environments (Kanger et al., 2019). These interactions may be of two kinds: fit and conform or stretch and transform (Smith and Raven, 2012). External pressure may force the new systems to fit and conform to pre-existing societal environments. On the other hand, new systems may stretch and transform pre-existing societal environments, thus changing the terms and structures of pre-existing societal environments in favor of new systems. Furthermore, transform and conform patterns may be hybrid; that is to say, interactions can follow a conform pattern in one societal environment but transform another (Mylan et al., 2019).

3.2.1. Societal environments

Building upon previous contributions, it is possible to distinguish between five key societal environments for the societal embedding of biogas systems: user environments, business environments, regulatory environments, cultural environments, and trans-local environments.

User environments include the adopters of new technologies. It goes beyond the adoption of new technologies and involves integrating them into user's practices and routines (Geels and Johnson, 2018). When new technologies are domesticated and embedded into user's behavior and day-to-day life, user-technology linkages become strong connections between socio-technical systems and society that are hard to undo (Rip and Kemp, 1998). Biogas systems can emerge in the interface between vastly different sectors, such as agriculture and transportation, and can vary significantly from one local biogas system to another. Therefore, the user environment will also change between cases. Biogas technologies require constant attention to function properly and must be integrated into the user's daily routines (Wirth et al., 2013). Hence, the user environment plays an important role in the embedding of biogas systems.

Business environments refer to business practices, business models, strategies, development of value chains, and markets. The introduction of new technologies may require changes in the way businesses and markets function, whereas the diffusion of new technologies may lead to the downfall of established industries and technologies (Kanger et al., 2019). Because biogas systems cut across different sectors, integrating these systems into the relevant industries and markets faces extra challenges requiring that actors adjust to a variety of conditions and systems arrangements.

Regulatory environments concern multiple policies and policy instruments that can influence the adoption, production, distribution, and use of new technologies, markets, and the overall development of new socio-technical systems. The regulatory environment can be particularly hard for actors to navigate as, in the early stages of technology diffusion, appropriate policies may not exist (Deuten et al., 1997). Biogas systems present a complex policy landscape, including policies from various sectors and policies not explicitly designed for biogas systems but that influence them (Gustafsson and Anderberg, 2021). To describe the complexity of the biogas systems policy landscape, Gustafsson and Anderberg (2021) characterize five dimensions of biogas policies: type of policy instrument, administrative area where the policy is valid, administrative level from local to global, part of the value chain that is targeted, and temporal change and continuity. Multi-sectoral policy mixes risk becoming ineffective when combined with inconsistent policies, policy instruments, and incompatible implementation practices (Huttunen et al., 2014). Policy mixes can be evaluated in terms of their coherence, namely, the attribute of policy mixes to reduce conflict within and between single policies while stimulating synergies to achieve policy goals (Nilsson et al., 2012). Policy coherence can be analyzed within and between a single policy domain (Nilsson et al., 2012), between policy areas at the same administrative level, and between administrative levels.

Cultural environments encompass the articulation of pros and cons, debates, and narratives that can increase legitimacy and public acceptance of the new socio-technical systems. Narratives are public discourses transmitted by the system's actors to promote the new socio-technical system and perhaps to disqualify competing systems. The cultural environment is important for the diffusion of biogas systems because it can influence expectations and user preferences, mobilize political support, and provide access to resources. By constructing narratives that promote multiple environmental and societal benefits, biogas actors are able to mobilize support and push for the transformation of societal environments (Ottosson et al., 2020). Conversely, the lack of acceptance of the new biogas systems by wider society may result in counterattacks and resistance to the diffusion process (Markard et al., 2016). In the case of urban-based biogas systems, adopting anaerobic digestion as a waste treatment technology may require entire populations to change their behavior and sort the organic waste at home, for example.

Trans-local environments refer to the influence of external environments and the interaction between actors across different scales. Kanger et al. (2019) describe transnational communities as external environments "shaping the evolution of national socio-technical systems" (Kanger et al., 2019, p. 50). Although Kanger et al. (2019) delimited the socio-technical systems to national boundaries, similar ideas can be extended to socio-technical systems within national boundaries – for example, local and regional. Trans-local environments encompass the shared understanding among biogas experts, creating an arena for knowledge exchange at multiple scales. Even though biogas systems are dependent on local contexts, development at other scales will still influence the diffusion of biogas systems.

3.3. Socio-economic structures

Socio-economic structures refer to societal arrangements that shape societies' social and economic aspects, therefore impacting the interactions and flow of resources and knowledge. The varieties of capitalism literature explores how economies are built on institutions and offers a usable framework to analyze how socio-economic structures may shape diffusion processes. The varieties of capitalism (VofC) framework distinguishes between market economies based on how firms solve strategic issues across five spheres: industrial relations, vocational education and training, corporate governance, inter-firm relations, and employee relations (Hall and Soskice, 2001). VofC puts firms at the center of the analysis as these are essential actors in market economies. Firms are seen as rational actors that make strategic decisions to improve competencies and develop capabilities. The original framework classifies capitalist countries as liberal market economies (LMEs) or coordinated market economies (CMEs) according to how firms solve coordination issues. In LMEs, firms' relations are based on competitive relations and market-based mechanisms, which dictate how firms form, develop, and expand capabilities. In CMEs, trust-based relations, networks, and collaboration determine how firms coordinate relations and develop capabilities. LMEs and CMEs are extreme poles of the VofC framework. Later, studies added other sub-varieties of market economies, such as Western European mixed-market economies, the Nordic version of coordinated market economies (Eriksson et al., 2020), and hierarchical market economies (HMEs) (Schneider, 2009). The latter classifies Latin American countries such as Brazil, where the governments have strong agency and influence over markets. Contrary to CMEs, where formal institutions provide the ground for coordination, in HMEs, social coordination is based on similar social backgrounds (Nölke, 2010; Schneider, 2009).

Socio-economic structures support a particular set of coordination mechanisms; that is, how firms in different countries coordinate relations and develop capabilities is influenced by the country's socio-economic structures. Although the original VofC framework places the analytical boundaries at the national level, institutions at different geographical scales, from local to global, also affect firms' strategies and relations (Eriksson et al., 2020). Furthermore, the importance of these institutions and different governance levels may vary depending on the firm's size, sector, and location (Ebner, 2016). Thus, exploring diversity within and across national settings is crucial to understanding how these socio-economic structures influence diffusion.

3.4. Synthesis

Societal embedding describes diffusion as dynamic and multidimensional, where socio-technical systems are co-constructed through interactions between society and technology. These interactions happen across a set of societal environments: user, business, regulatory, cultural, and trans-local. Figure 4 shows a representation of the frame of reference applied in this thesis, where actors and technologies that form socio-technical systems are at the center of the analysis. The dashed circle separates the societal environments from the socio-technical system; however, the socio-technical system is an open system and is in constant interaction with the societal environments, as depicted with the dashed lines. Arrow A (Figure 4) represents the interactions between socio-technical systems and societal environments, and these interactions can strive to fit and conform or stretch and transform. Interactions are bidirectional because societal environments can influence the diffusion of socio-technical systems, and socio-technical systems influence societal environments. Additionally, interactions are hybrids because the type of interaction can change between societal environments; for example, the socio-technical system may conform with the user environment but transform their business environments.

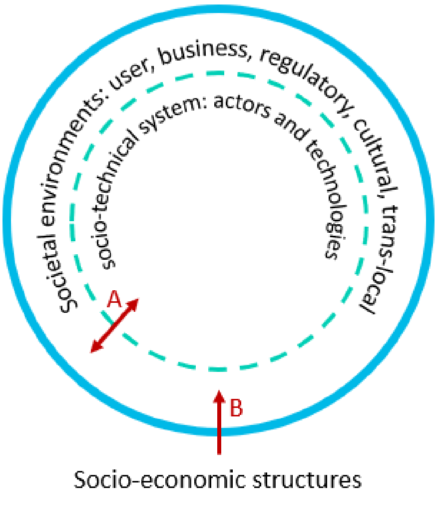

Figure 4. Representation of frame of reference. Arrow A represents the interactions between societal environments and socio-technical systems. Arrow B represents socio-economic structures' influence on socio-technical systems and societal environments.

The societal embedding framework suggests that diffusion processes are shaped by socio-economic structures. Biogas systems in Brazil are in the early stages of diffusion; therefore, the interactions between socio-technical systems and socio-economic structure are depicted as unilateral, meaning that new socio-technical systems have a limited influence on the socio-economic structures. Hence, socio-economic structures are placed outside the borders of societal environments and socio-technical systems in Figure 4. These socio-economic structures shape the diffusion of new socio-technical systems (arrow B).

4. Methodology

This chapter introduces the research context and journey and explains the motivation for the selection of case studies, followed by the specific methods for data collection and analysis. Lastly, it presents a short reflection on research ethics and research quality.

4.1. Research context and journey

My research journey started in 2020 as a master's student in Sustainability Engineering and Management at Linköping University (LiU). My master's thesis explored the conditions that enable or restrain the adoption of biogas technologies across Brazilian states. Data collected during the development of my master's thesis provided a basis for the development of Paper I, and the interviews were used in Papers II and III. Later that same year, in November 2020, I started working as a research assistant in the Division of Environmental Technology and Management at LiU. The first two papers were developed when I was working as a research assistant. Data collection from the different sources proceeded in parallel, as did the analysis for Papers I and II. During these initial phases of my research journey, all my contact with actors in Brazil was online because of the COVID-19 pandemic and mobility restrictions that followed the pandemic.

These first stages of my studies, both as a master's student and a research assistant, were connected to the previous phase of the Biogas Solution Research Center (BSRC), formerly named Biogas Research Center. I started as a PhD student in March 2022, with the start of the second phase of the BSRC. The BSRC is a transdisciplinary competence center funded by the Swedish Energy Agency (Energimyndigheten). The BSRC gathers partners from businesses, the public sector, and academia with the aim of advancing knowledge on sustainable biogas systems. The research within the competence center covers different areas relevant to the development of biogas systems, from processes and production systems to the societal conditions and sustainability aspects of biogas solutions. The BSRC is divided into five main research areas: conditions and strategies, production systems, digestion processes, market and use, and sustainability effects, and five innovation projects, each connected to one of the main research areas. My PhD studies are connected to the market and use research area at BSRC. The development of Paper III happened during the first years of my PhD studies, but the data was collected previously as a research assistant and during the development of my master's thesis.

Figure 5. On the left is a co-digestion biogas facility in Curitiba, Paraná; on the right, a farm-based biogas facility in Castro, Paraná.

Between July and August 2023, I went on a field trip to Brazil with the purpose of confirming previous findings, personally collecting the perspectives of different actors, and identifying empirical areas for further research. Although this research covers an extensive geographical area in Brazil, the field trip was limited to only three states because of time restrictions. The field studies lasted three weeks and covered three metropolitan areas in Brazil: the cities of Curitiba, Rio de Janeiro, and São Paulo. The locations for the field studies were selected based on the diversity of biogas projects and their potential for further development. However, the choice of location influenced which actors and type of biogas systems configurations I was able to see in person during this field trip; that is, several of the actors were involved with waste management and sanitation systems. Table 1 presents a list of organizations, and their locations, visited during the field trip to Brazil.

Table 1. List of organizations visited during field studies in Brazil.

Location	Type of organization	Organization's name
Curitiba (PR)	Biogas producer / Co-digestion of urban waste	CS Bioenergy
	Biogas producer / Farm	Chacará Marujo
	Biogas producer/ Sanitation company	Sanitation Company of Paraná (Sanepar)
Rio de Janeiro (RJ)	Biomethane producer	Gás Verde
	University	Fluminense Federal University (UFF)

	University	Federal University of Rio de Janeiro (UFRJ)
	State government	Sustainability state secretary
	Waste management company	Municipal Urban Cleaning Company (Comlurb)
São Paulo (SP)	Biogas association	Brazilian Biogas Association (Abiogás)
	Industrial association	Federation of Industries of the State of São Paulo (FIESP)
	Municipal civil society representative	-
	University	Federal University of ABC (UFABC)
	University	University of São Paulo (USP)

4.2. Research design

Each appended paper focuses on a specific part of the overarching research questions and employs different methodological approaches. Figure 6 presents the scope of each paper in relation to the theoretical synthesis presented in Subchapter 3.4. Figure 6 presents all the main components of the analysis, socio-technical systems, societal environments, and socio-economic structures across all three papers. However, it highlights the components that are present in each appended paper while hiding the components that are not.

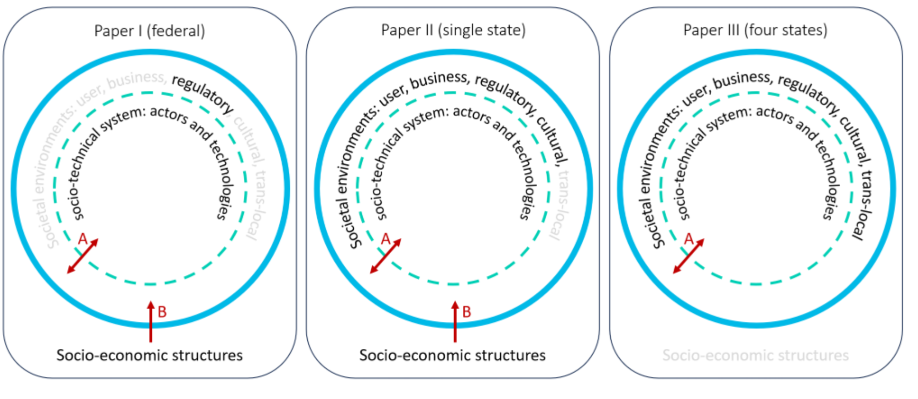

Figure 6. Representation of scope of appended papers. Arrow A represents the interactions between societal environments and socio-technical systems. Arrow B represents socio-economic structures' influence on socio-technical systems and societal environments.

Paper I focuses on the regulatory environment and how socio-economic structures can explain (in)-coherence in biogas-related policies in Brazil, thus influencing the formation and establishment of biogas systems. Paper II employs a comparative analysis between Sweden and the Brazilian state of Paraná, examining four dimensions of societal embedding: user, business, regulatory, and cultural environments. The comparison between Sweden and Paraná highlights the differences in socio-economic structures between both cases and helps in understanding how these structures influence the diffusion of biogas systems. The analysis of the diffusion of anaerobic digestion in Sweden highlights the influence of socio-economic structures on diffusion processes and serves as a support to better explain the diffusion of biogas systems in Brazil. Paper III also employs a comparative analysis but across four Brazilian states (São Paulo, Rio de Janeiro, Paraná and Goiás) and adds a fifth societal environment, the trans-local environment, to better understand the involvement of transnational organizations in the diffusion of biogas systems in these states.

4.3. Case studies

The case study is an empirical research method that allows us to investigate a phenomenon in-depth within its real-world context (Yin, 2018). Interactions between the socio-technical systems and societal contexts are at the core of this thesis. Thus, case studies are suitable research methods for this thesis as they consider the surroundings of the phenomenon in focus. Whereas other research methods, such as surveys, have a limited ability to investigate the context, the attention given to interconnections between phenomenon and context separates case studies from other research methods. Case studies accept a full range of evidence, from observation of events of interest as they occur and interviews with the involved actors to quantitative data sources (Yin, 2018). This thesis gathered a wide range of data from interviews, documents, and statistics on the production and use of biogas. To define the pertinent contextual conditions, the five societal embedding environments provided the dimensions of contextual aspects relevant to understanding the phenomenon of interest.

This thesis relies on a case study research design. However, each appended paper uses a different logic to select the cases. Paper I applies a single case design, while Papers II and III follow comparative case designs. The selected cases start from a broader perspective in Paper I, taking Brazil as a country and become more granular in Papers II and III, zooming into specific states. Paper I investigates policy coherence in the context of a hierarchical market economy and how this shapes the diffusion of biogas systems, taking Brazil as the single case study. The single-case design allowed for an in-depth analysis of policy mixes related to biogas systems. Although Paper I uses a single-case design, attention is also given to sub-levels of the case, that is, the Brazilian states. Paper II uses a comparative case study research design between Sweden and the

Brazilian state of Paraná to explain how socio-economic structures shape the diffusion of biogas systems. In this paper, the comparative case-study design highlights the differences in socio-economic structures between hierarchical market economies (Paraná/Brazil) and coordinated market economies (Sweden). Paper III also uses a comparative case-study design to outline the different biogas systems configurations across Brazil and investigate the alignment between socio-technical systems and societal environments across four Brazilian states. The four cases present different trajectories of biogas systems diffusion and different patterns of interactions between societal environments and biogas systems.

4.4. Data collection

The case studies drew upon diverse data sources, including interviews and documents, encompassing both qualitative and quantitative data. Given that each case study within this thesis employed a unique research design, the significance of each data source varied across the papers. Table 2 clarifies the role played by each data source in the respective appended papers. Subsequently, Sections 4.4.1 and 4.4.2 explain the data collection process in detail according to interviews and document sources, respectively.

Table 2. Use of data sources according to interviews and document sources in each appended paper.

	Paper I	Paper II	Paper III
Interviews	As a secondary source, interviews provided the context of policy developments.	Interviews provided a broader contextual understanding.	Interviews were the main source of data, providing an in-deep understanding of the actor's actions and strategies.
Documents	Policy documents from both federal and state levels were the main source of data.	Annual statistics provided quantitative data on the production and use of biogas in the Brazilian state of Paraná.	Documents from several sources strengthen the findings from the interviews, playing a supporting role.

4.4.1. Interviews

Interviews provided an in-depth understanding of actors' strategies and motives behind actor's actions as well as an in-depth understating of the context. Because this study addresses actors' reasoning, semi-structured interviews are preferable, allowing for flexibility in follow-up questions and fluidity in discussions. Semi-structured interviews allow a more fluid stream of questions while maintaining consistency through the interview guide and alignment with the study's aim (Bryman, 2012).

The interview guide, prepared according to the five societal environments previously presented (see 3.2.1), included relevant questions regarding each of these environments. The interview guide steered the interviews conducted with key actors at different administrative levels and across several sectors. These questions were classified according to the type of actors interviewed, such as adopters, governmental agencies, researchers, and technology providers. Therefore, not all questions were pertinent to all actors, and the interview guide was adjusted accordingly. Using semi-structured interviews allowed for the interview guide to be adapted depending on the organization and its role in the diffusion of biogas systems.

The interviews were carried out in two stages, the first in 2020 and the second round in 2021, to validate the findings. Table 3 presents a list of interviews. Key actors for the interviews were selected according to the organization's role in the diffusion of biogas systems in Brazil, relevance for the diffusion process, and overall involvement with biogas sectors or relevant administrative areas. Because the socio-technical systems approach focuses on the inter-organizational community instead of single actors, participants with an overall understanding of their areas of activity were prioritized. In total, 19 semi-structured interviews were conducted online with 22 professionals. The interviews were conducted in Portuguese or English, recorded with the interviewees' consent, and then transcribed word for word in the original language of the interview.

Table 3. List of interviews.

Date	Type of organization	Main area of activity	Interviewee's position
2020-04-24	Association	Biogas and biomethane	Technical support
2020-05-01	Governmental agency	Energy	Technical consultant
2020-05-11	Research group	Gas, biogas, biomethane, innovation	Deputy Director
2020-05-15	Science and technology institution	Renewable energy, biogas, biomethane	Biogas Analyst Technological Development Director
2020-05-21	Technology provider	Biogas, biomethane, sugarcane energy	Director
2020-05-22	Gas distributor	Natural gas, biomethane	Planning and Environment Manager

2020-05-27	Academia	Biogas	Researcher/ Senior Lecturer/ Former executive director of biogas association
2020-05-29	Intergovernmental organization	Energy	Researcher/ Coordinator
2020-06-03	Intergovernmental organization	Industrial development	Project Management Expert
2020-06-03	Innovation support organization	Industrial sectors, small and medium companies	National coordinator of energy
2020-06-04	Governmental agency	Energy	Head of Special Advisory on Regulatory Affairs Public policy specialist Secretary for energy planning and development
2020-06-05	Association	Biogas, biomethane	Executive Manager
2020-06-11	Sanitation company	Sanitation	Research and Development Manager
2020-06-30	Association	Biogas, biomethane	Director of International Affairs
2020-07-01	Gas Distributor	Natural gas, biomethane	President and Chief Executive Director
2020-07-07	Technology provider	Transportation	Director of Public Affairs
2021-09-13	Governmental agriculture research	Agriculture	Senior researcher
2021-09-15	Technology provider	Waste management	Business development director
2021-09-20	Food producer	Agriculture	Farmer

4.4.2. Documents

All appended papers rely to a certain extent on documents as a data source. The set of documents includes scientific articles, news articles, technical reports, research reports, official documents by governmental agencies, and policies. Most of the documents were in Portuguese (my mother tongue) except for scientific articles and a few technical reports. The set of documents helped to identify initiatives involving biogas; actors involved in the development, implementation, and use of biogas technologies; and relevant policies on biogas-related administrative areas and their goals, strategies, and instruments.

Keywords such as biogas, biomethane, and anaerobic digestion (in Portuguese: *biogás, biometano, and digestão anaeróbica*, respectively) were employed to uncover news articles from news outlets at the state and national levels related to biogas systems. Technical reports provided quantitative data on the estimated potential for biogas production, current biogas production, and use of biogas produced. Annual statistics on biogas production refer to the total volume of biogas produced in Nm^3 per biogas facility. Because the source of the substrate and the technology employed changes between biogas facilities, it is not possible to estimate the energy content since it depends on the methane content. Therefore, the application of biogas produced also refers to the total volume of biogas in Nm^3. The dataset aggregates several types of substrates for biogas production under three categories of biogas facilities: agriculture, industrial, and waste and sewage. Annual statistics on biogas production do not account for biogas facilities that do not use the biogas produced; that is, flared biogas is not included in the dataset. Landfill gas capture and wastewater facilities are grouped under the same category. However, most of the biogas in this category comes from landfill gas capture, as just a handful of sewage treatment plants are in the dataset.

Brazil is a federative country; thus, different competences, mandates, and duties are organized according to administrative areas at three levels of governance: federal, state, and municipal. To investigate policy mixes in Brazil, biogas-related policies were retrieved from two of these levels, the federal and state. The data collection did not include municipal policies because there are more than five thousand municipalities in Brazil, and the federal and state governments have either more agency over biogas-related projects as the main financier of basic social services or have the mandate over the biogas-related administrative areas in Brazil. Furthermore, the pre-assessment studies showed that even in municipalities with a higher rate of biogas systems diffusion, biogas-related policies were still unusual at the municipal level.

In Brazil, all levels of public administration disclose their activities daily in official gazettes. The official gazettes inform citizens of every public decision, meeting, project, and other activity in which the government is involved. They are available online and are open access. Through these documents, it is possible to identify any discussions happening related to biogas systems, proposed and approved policies, and any biogas-related projects in which the government may be involved. These official gazettes were used as a starting point to find relevant biogas policies at the state and federal levels. The search used the terms biogas, biomethane, and anaerobic digestion (in Portuguese: *biogás, biometano, and digestão anaeróbica,* respectively), which allowed us to find policies directly connected to biogas systems. To identify the indirect policies that could influence the diffusion of biogas systems, a second search was conducted in each of the administrative areas (energy, environment, waste, water, agriculture, transport, economy, construction) relevant to biogas, but it was restricted to the federal level.

4.5. Analysis

The analysis of the empirical data from interviews and documents focused on the interactions between biogas systems and their societal environments and on how socio-economic structures shape diffusion processes. Reports on the theoretical, technical, and economic potential of biogas together with annual statistics on biogas production and use, contributed to the interpretation of the current state of biogas systems diffusion in Brazil and across Brazilian states. Biogas development trajectories were constructed by aggregating quantitative data on biogas production and utilization at individual facilities across Brazil. Documents provide specific information, corroborate information, and reflect the perspective and purpose of actors (Yin, 2018). Thus, these reports provide evidence beyond the quantitative data that they aim to present and reflect the strategic position of the actors. Many of these reports include discussions on what is needed to increase biogas production and use, thus portraying the perspective of the actors involved. The interviews helped to corroborate these perspectives and to get a deeper understanding of actors' actions and strategies. News articles from news outlets at state and national levels helped to construct the narrative of the diffusion of biogas systems in Brazil by defining a timeline of events and identifying actors involved in the development of biogas projects. Technical reports, research reports, and annual statistics played a supporting role in the analysis and enriched the contextual understanding of the biogas system in Brazil.

In Paper I, policy documents were the main source of data. The relevant biogas policies in Brazil were classified according to Gustafsson and Anderberg's five categories of biogas-related policies (2021). Policies that presented more than one type of policy instrument influenced more than one stage at the value chain, or several administrative areas were classified according to the instrument, stage, or area that had the greatest impact on biogas systems. The time dimension refers to the year the policy was first implemented, time-based goals, and any modifications to these policies that may influence biogas systems. Paper I analyzes internal, external, and temporal policy (in)-coherence within and between administrative areas and how it changes over time. The varieties of capitalism framework provides insights to analyze the sources of (in)-coherence in the regulatory environment and explain how socio-economic structures shape the diffusion of biogas systems.

Societal embedding environments were used in the analysis of empirical data in Papers II and III and helped distinguish between different dimensions of the Brazilian context. Interviews were the main data source for Paper III and provided a broader contextual understanding of Papers I and II. The interviews were transcribed word for word in the language in which the interview was conducted (Portuguese or English). The transcribed interviews were analyzed following the five societal embedding environments: The user environment looks at the reasoning behind the adoption of biogas technologies; the business environment refers to the development of value chains, markets, and business models; the regulatory environment investigates biogas-related policies; and the cultural environment addresses public acceptance. Paper III also refers to the trans-local environment that explores the interactions between actors across different scales. The analysis in Paper III defined the direction of alignment between biogas systems and societal environments as either conformative or transformative (Smith and Raven, 2012) according to actors' actions and strategies. Conformative actions and strategies aimed at portraying biogas systems as competitive and conventional according to pre-existing societal environments, while transformative actions and strategies argued for change and antagonized pre-existing societal environments.

4.6. Research ethics

Studying a contemporary phenomenon in its real-world context calls attention to specific ethical considerations involving human participation and their protection (Yin, 2018). Informed consent, privacy, and confidentiality were central to conducting the interviews and managing data. The interviews were conducted with special care and sensitivity, informing participants about the nature of the study and asking for consent to conduct and record the interviews. The interviewees were first informed about the purpose of the study when invited to participate and again before the interviews. Additionally, before the interviews, all participants gave informed consent to the interviews and the interviews being recorded. All interviews were audio recorded and transcribed word for word. Some interviews included a video record mainly because of the online tools used, but only the audio records were used in this study. The personal data collected (name, contact information, records, employment) was not disclosed, nor were individual statements that could be used to identify individuals. To protect the privacy of participants, the names of the organizations they work for were not included in the papers, and their positions were only described in general terms.

4.7. Research quality

Reliability and validity are common criteria used to judge research quality (Bryman, 2012; Yin, 2018). Reliability assesses if the operational methods of a study can be repeated. Validity evaluates the overall integrity of the research and can be assessed in detail by examining how the operational measures reflect the phenomenon studied (construct validity), how causal relationships are defined (internal validity), or if the findings are generalizable beyond a study (external validity). Because reliability and validity were originally designed to assess the quality of quantitative research, these criteria have raised questions among some researchers about their applicability in evaluating qualitative research. Some researchers have adapted the meaning of these criteria to fit qualitative research, thus softening the importance of measurement issues (Bryman, 2012). Likewise, Yin (2018) suggests that reliability and validity can be adapted for judging the quality of case studies because case studies are part of the larger body of empirical social research. Hence, in this section, I reflect on the quality of my research based on reliability and validity criteria adapted to case studies, as discussed by Bryman (2012) and Yin (2018).

To assess the reliability of case studies, the researcher should provide a complete trail of operational methods and subject the research to peer scrutiny (Bryman, 2012). In this regard, I kept a case study database that contained the documents (policies, reports, new articles, scientific articles), notes, records from the interviews, and pictures from study visits. Additionally, all the appended papers were assessed externally on different occasions. First, early versions of the appended papers were presented in seminars at the Division of Environmental Technology and Management. Paper III was further developed during a PhD Course in Academic Writing at Halmstad University, where it was subject to scrutiny by colleagues. Additionally, Paper III was submitted and accepted to a Paper Development Workshop, where I received constructive feedback from other researchers in the field of technological diffusion. Finally, all three papers were submitted and accepted to scientific journals, where the papers went through at least one round of peer reviews.

Triangulation involves using more than one method or multiple sources of evidence to study a social phenomenon, and it is an important tool to support the internal validity of research (Bryman, 2012). To deal with internal validity, I used documents from several sources (policies, scientific articles, news articles, technical reports, research reports) and multiple interviews and compared the findings from different documents with the findings from the interviews. In all appended papers, information from different sources corroborated the findings, and jointly, they helped describe the context. External validity is concerned with the generalizability of results beyond the case study (Yin, 2018). Case studies seek analytic generalization and use theory to support the generalizations of findings at a conceptual level higher than the case study itself (Yin, 2018). Rather than statistical generalization, case study research sheds light on theoretical concepts and aims at analytic generalization; that is, case studies seek to uncover lessons learned that go beyond the setting of a specific case. As my research is based on case studies, the appended papers target analytic generalization. The appended papers provide insights into under which conditions the findings are valid, making it possible to articulate when and where the findings could be applicable to other cases. Furthermore, because societal contexts are in focus, the appended paper accounts for the contextual aspects and characteristics that influence the diffusion of biogas systems.

5. Summaries of appended papers

This chapter presents the summaries of the appended papers. Each summary introduces the background and aim of the paper and the paper's methods, followed by the main findings and conclusions. The purpose of this chapter is to facilitate the reader's understanding of how the thesis builds upon the appended papers and how each paper contributed to answering the thesis' aim and research questions.

5.1. Paper I – Policy coherence in a fragmented context: the case of biogas systems in Brazil

Several policies are required to address the multiple challenges faced by the diffusion of sustainable systems. Policy mixes refer to the set of policies, interactions between them, and how they influence certain challenges. As new policies are often introduced against the background of existing policies and adopted at different times, policy mixes may present different, and sometimes competing, rationales. This paper aims to "analyze policy mixes related to biogas systems in Brazil." It addresses the following research question: "What are the coherence and incoherences within and between biogas-related policies in Brazil, and how do they influence the development and diffusion of biogas systems?"

Methods

Relevant biogas-related policies were retrieved from both the federal and state levels. The focus on federal and state-level policies is justified, as these have stronger agency over biogas matters in Brazil. A policy was considered relevant for this study if it directly mentions biogas, biomethane, digestate, or anaerobic digestion or if the policy could influence any part of the biogas value chain, for example, production, distribution, and use within the related administrative areas. The policy documents were classified according to five dimensions of biogas-related policies, namely: type of policy instrument, administrative area where the policies are valid, administrative level, targeted part of the biogas value chain, and temporal change and continuity.

The documentation study was supplemented by semi-structured interviews that helped to understand the context in which the policies were implemented and how these impacted the diffusion of biogas systems. The paper analyzes internal, external, and temporal policy (in)coherence within and between biogas-related policies across administrative areas, such as energy, waste, transport, agriculture, and the environment. Varieties of capitalism supported the analysis of policy coherence based on how institutional structures influence the sources of policy of policy (in)coherence.

Main findings and conclusion

The paper highlights the importance of policy coherence between federal and state administrative levels to support the transformation of energy systems towards more sustainable practices. In Brazil, biogas technologies are usually regarded as waste treatment technologies. Thus, the use of biogas and other byproducts of anaerobic digestion suffers from inconsistencies and conflicts between waste management policies and other areas such as transportation and energy. Because of the multi-sector characteristics of biogas systems, several incoherences appear between policies in different administrative areas, which hinder the adoption of biogas systems; in particular, the development of complex biogas systems that require alignment between multiple actors is constrained by the default means of coordination. To overcome these issues, centralized control over operations allows firms to deal with high political and economic volatility.

The administrative level of policy implementation can also influence the replicability of similar biogas system configurations since some administrative areas are regulated at different administrative levels. Therefore, Brazilian biogas actors prioritize the implementation of a biogas policy at the federal level and the harmonization of state policies. Because governments have a high level of influence over markets in hierarchical market economies, actors expect governmental intervention to support technological diffusion and resolve conflicts through policies instead of other modes of coordination. The analysis shows that biogas systems could benefit from a decentralized policy approach since the pre-conditions for the development of biogas systems can change significantly between states. However, Brazil is characterized by centralized power and agency by the federal government in policy processes, which imposes some extra challenges to the adoption and diffusion of biogas systems.

5.2. Paper II - Circular economy, varieties of capitalism and technology diffusion: anaerobic digestion in Sweden and Paraná

Anaerobic digestion of organic matter is a key enabling technology for the circular bioeconomy as it allows for the recirculation of nutrients while addressing multiple environmental problems (e.g., organic waste treatment, greenhouse gas emissions, nutrient recirculation). This paper aims to "explain how socio-economic structures influence the diffusion of key enabling technologies for circular economies." It does so by comparing the diffusion of anaerobic digestion technologies in Sweden and the state of Paraná in Brazil. The paper compares the societal embedding of anaerobic digestion across four societal environments and refers to varieties of capitalism frameworks to distinguish between socio-economic structures in the different cases.

Methods

According to varieties of capitalism, the cases present different socio-economic structures, which are used to explain the differences in societal embedding processes. Paraná, as a Brazilian state, is classified as a hierarchical market economy, whereas Sweden represents a Nordic variety of coordinated market economies. The comparative analysis uses four societal embedding environments: user, business, culture, and regulatory.

The cases rely on both quantitative and qualitative data. The Swedish case is based on quantitative data from vehicle statistics, gas supply statistics, and reports on the production and use of biogas. Additionally, qualitative data from conferences, workshops, study visits, and seminars was also used for this study. The qualitative data for the Swedish case was gathered in connection to the Biogas Research Center activities, such as research area meetings and annual conferences. Paraná's case relied on quantitative data from statistics and reports on biogas production and use. In addition, qualitative data from semi-structured interviews with biogas actors relevant to Paraná and the document study complemented the data set for the Paraná case.

Main findings and conclusion

The analysis highlights trade-offs between socio-technical systems' complexity and speed of diffusion. In Sweden, anaerobic digestion developed with the support of municipalities and evolved from a waste management tool to local circular systems involving multiple specialized actors. In contrast, Paraná biogas production remained a secondary process performed mostly by single actors across the food value chain.

Anaerobic digestion appears as a solution to several problems; however, which problems get prioritized will influence the diffusion trajectory. The adoption of anaerobic digestion technologies was triggered by environmental problems in both cases. Whereas in Sweden, anaerobic digestion was coupled with public transport to reduce air pollution in urban areas, in Paraná, the adoption of anaerobic digestion was triggered by the eutrophication of water bodies created by the indiscriminate expansion of agriculture. Socio-economic structures influenced the identification of problems, who are the problem owners, and the agency of problem owners.

The Swedish regulatory environment supported the diffusion of anaerobic digestion by offering financial support for the implementation of biogas facilities, but also through restrictions on organic waste disposal. In Paraná, the regulatory environment is quite fragmented as different sectors, such as electricity and sanitation, must follow regulations at different administrative levels. Lastly, the integration of waste management and public transportation in Swedish municipalities created a tangible connection for citizens and stimulated public engagement, while in Paraná, similar projects were not as successful, experiencing problems with the proper sorting of waste.

5.3. Paper III - To conform or to transform? A comparative case analysis of the societal embedding of biogas systems

Biogas systems are multifunctional and multi-actor systems that can appear across several societal domains. Therefore, biogas systems can present different configurations and possibly develop through different types of socio-technical interactions. For new socio-technical systems, such as biogas systems, to emerge and diffuse, it requires alignment between technology and multiple societal environments. The paper explores the interactions between societal contexts and biogas systems across four Brazilian states with the aim of explaining how these influence systems' diffusion and which systems' configurations are adopted. The paper addresses the following research question: "How does alignment between technology and societal environments shape the diffusion of biogas systems?"

Methods

The research followed a comparative case study design and relied on qualitative data from semi-structured interviews, grey literature, and quantitative data on the potential, production, and use of biogas. A total of 19 semi-structured interviews with 22 individuals were conducted. The interviewees were selected based on their involvement with biogas systems across the biogas value chains; that is, individuals with an overall perspective of their field were prioritized. The analysis of the interviews followed the five dimensions of societal embedding. The analysis focuses on how the alignments between societal environments and biogas systems either aim to fit and conform to unchanged societal environments or aim to stretch and transform societal environments to benefit certain configurations of biogas systems. The actions and statements of actors indicate the direction of alignments.

The case selection was based on a pre-study that explored the diffusion of biogas systems across the country. To select four states as case studies, the pre-study considered substrate availability (type and amount), the number and scale of biogas plants, the application of the biogas produced, and estimated realized potential. Based on these conditions, São Paulo state, Rio de Janeiro state, Paraná, and Goiás were selected.

Main findings and conclusion

The paper demonstrates how different regional contexts have a strong influence on which biogas system configurations diffuse. The comparative analysis shows how patterns of alignments between technology and societal environments vary across administrative levels (scale), across multiple sectors, and across states (space). Relevant policies for the diffusion of biogas systems vary across the state and federal levels, which affected the feasibility of certain biogas system configurations, thus influencing the actions of biogas actors in the different states. Alignments also varied across sectors as different user groups responded in diverse ways when facing challenges presented by pre-existing societal environments. Furthermore, local assets such as infrastructure, formal and informal institutions, and industrial base change between the four states, thus influencing the patterns of alignments across the space.

Interactions between societal environments appear since actors' actions to either conform or transform a certain societal environment can restrict possible alignments with other societal environments. Therefore, biogas systems that easily conform to several pre-existing societal environments can diffuse faster than other system configurations. This highlights possible trade-offs between conforming to a pre-existing societal environment, which allows for faster diffusion, and the environmental benefits of biogas systems.

The paper expands the empirical base of societal embedding studies to underexplored contexts in the Global South, thus highlighting some issues of institutional instability that have received limited attention. The fit and conform stretch and transform dichotomy becomes harder to operationalize in the studied context of Brazil. The lack of clear institutions hinders the directionality of diffusion since it creates fragmentation within biogas systems and biogas actors' efforts.

6. Answering the research questions

This chapter investigates the connections between the main findings of each appended paper and the research questions. The first subchapter explores diffusion dynamics and how societal environments influenced the diffusion of biogas systems in Brazil. The following subchapter examines how socio-economic structures shape diffusion biogas systems.

6.1. Societal environments and the diffusion of biogas systems

Technological diffusion as a societal embedding process involves a variety of actors, such as users, policymakers, technology providers, and industrial associations, among others (Kanger et al., 2019). Biogas systems actors are the organizations that actively support and are involved in the diffusion of biogas systems from both the supply and demand sides. On the demand side are the adopters of biogas technologies, which are at the core of user environments. Embedding into the user environment involves the integration of new technologies into the adopter's daily practices and articulation of competencies (Geels and Johnson, 2018). Paper III identifies five main groups of adopters of biogas technologies: farms, food and beverage industries, sugarcane energy industries, sewage treatment plants, and landfills, which represent different user environments. These user environments present different motivations for adoption and exhibit different characteristics related to capacity and capabilities.

Although the diffusion of biogas systems has accelerated in the past decade, biogas production plays a secondary role in these actors' economic activities. Only a handful of actors have biogas or biomethane as their core business, and these focus on landfill gas, residues from ethanol production, and sewage sludge. For food producers such as farms and food and beverage industries, biogas production is a secondary activity as their core business and competences lie in the food sector. Farmers and food industries did not have previous knowledge of the treatment of organic waste or energy production prior to the adoption of biogas technologies. On the other hand, sugarcane energy industries, although related to the food sector through sugar production, have their internal competencies and knowledge of the biofuel sector. The adoption of biogas technologies may still be technologically challenging to ethanol producers, yet these user groups are able to redeploy their internal resources and knowledge to biogas production.

The user environment also influences which biogas technologies are adopted. Paper II explores the reasons for the adoption of biogas technologies and how the perceived problems influenced the type of technologies adopted. In Paraná, concerns with water quality prompted the search for technologies that could be used for handling the manure. The eutrophication of the Paraná basin caused by the indiscriminate expansion of animal husbandry motivated farmers' adoption of biogas technologies. Biogas production from manure offered a viable solution to reduce environmental impact. However, because biogas technologies were initially adopted to solve environmental issues such as eutrophication and greenhouse gas emissions, many biogas projects neglected the use of biogas. The adoption of biogas technologies by food and beverage industries aims to correct the disposal of organic waste and reduce operational costs since the biogas produced is usually used for heat generation to supply internal processes. Early adoption of biogas technologies in the waste management sectors focuses on emission reduction and implementation of Clean Mechanism Development (CDM)[6], in which end-of-pipe technologies such as landfill gas capture and biogas flaring could already ensure participation. In contrast, the adoption of biogas technologies by the sugarcane energy sectors focused on resource efficiency and improving overall environmental performance, which considers both the use of byproducts and biogas application.

Business practices, value chain development, and markets are aspects of business environments (Kanger et al., 2019). The user groups identified in Paper III belong to different sectors, which influence the business practices of each user group and the assimilation of biogas technologies into these business environments. In Paraná, the food and beverage industries have strong relationships with farmers and close connections to local issues. These industries offer support to the implementation of new technologies, such as biogas technologies, that can improve their production and environmental performance. In South Brazil, agricultural cooperatives are widespread, and food industries have a strong regional presence. The integration of biogas systems into cooperatives helps to strengthen the diffusion of biogas systems in this region because they can offer technical support to farmers who may not have the capacity to operate biogas facilities on their own. Paper II further explores the integration of biogas systems into the agribusiness sector and adds that the

[6] The Clean Development Mechanism (CDM) aims to reduce greenhouse gas emissions and stimulate the adoption of environmental technologies by transferring resources from the Global North to the Global South.

accessibility to technology providers in rural areas of Paraná helps overcome operational problems and reduce uncertainties for users.

However, biogas systems integration into the agribusiness sector does not come without contestation because it challenges the legal and cultural identity of farmers as food producers. Farmers, as food producers, have access to special financial support and other services, but the production of biogas, even as a secondary process from agricultural residues, challenges this identity. As shown in Paper III, the cultural environment influences the adoption of biogas technologies by farms. Investments in technologies that can reduce environmental impact from agriculture activities, such as biogas technologies, compete with other investments in their core business. In contrast, the adoption of biogas technologies by sugarcane energy industries reinforces their identity as biofuel producers and as part of the energy sector.

The cultural environment influenced not only which actors adopted biogas, but also which biogas technologies were adopted. Some configurations of biogas systems require a larger interaction with the community than others, such as biogas production from urban solid waste, because it requires citizens to adapt to new ways of sorting their waste. In Brazil, segregation of waste at the source is uncommon, and just a small percentage of municipalities provide the collection of segregated waste. Paper II shows how the adoption of anaerobic digestion in local waste management systems to treat organic waste was unsuccessful because of inadequate sorting of urban solid waste. Paper III further elaborates on adopting landfill gas capture technologies in waste management systems, especially in large, populated areas such as São Paulo and Rio de Janeiro. Landfill gas capture technologies add another layer of complexity to landfill operations; nevertheless, they do not require citizens to engage with them or change their practices. Therefore, public acceptance is not required to the same extent as more pro-active biogas technologies.

Most of the biogas produced in Brazil comes from landfill gas capture, and in most cases, the biogas is used for electricity generation. These landfills generate large volumes of biogas daily and have low demand for electricity. Thus, these actors usually sell the electricity in national auctions for renewable energy or through direct contracts with the final consumers. Electricity markets in Brazil are organized at the federal level and favor large-scale generation. Paper I presents several policies that benefited electricity generation from landfill gas capture by providing tax exemptions. On the other hand, small-scale biogas power plants, like farm-based facilities, are restricted to compensation schemes for prosumers, which limits income possibilities. Compensation schemes aim to boost distributed generation across the country and provide small-scale power generation access to electrical grids. However, they do not pay the producer for the electricity supplied to the electrical power grid; instead, the producer receives discounts on their own electricity bill equivalent to the electricity supplied. Yet, small-scale biogas plants are usually on farms, and their primary purpose is to treat the residues from agricultural activities. These actors have the potential to generate more energy than they usually need but are discouraged from participating in decentralized electricity generation. The regulatory environment influences which technological options are available to adopters and intermediate actors' access to different markets.

Supply-side actors include technology providers and other actors that support biogas systems establishment, such as policymakers, technical services providers, industrial organizations, and research organizations. The constellations of actors involved in the diffusion of biogas systems change considerably across Brazilian states and among different user groups. In some states, such as Goiás, biogas projects were largely disconnected and mostly managed by single actors with control over whole operations, from ownership of substrate to the use of biogas and other by-products. Paper II presents a different picture of biogas systems in Paraná, where state actors highlight the benefits of biogas systems in rural areas and together push forward the establishment of biogas systems as a tool for regional development.

Trans-local environments refer to connections between different actors across administrative levels and the development of communities of experts. These have influenced the prioritization of certain biogas technologies and user groups as leading adopters. Paper III shows that in the states of São Paulo and Rio de Janeiro, the support of well-established industrial sectors, state and federal governmental agencies, and transnational actors supported the development of biogas projects. This allowed large firms in these regions to direct the agenda for advocacy groups for biogas systems nationally, thus reflecting their views on desirable pathways for the diffusion of biogas systems. Transnational companies in the food and beverage sectors were among the early adopters of biogas technologies. Many multinational food industries adopted biogas technologies as an organic waste treatment solution to comply with strategies from overseas headquarters. Several research projects to test the feasibility of biogas systems in Brazil were formed by both Brazilian and transnational organizations; these projects included research institutes, financial organizations, and technological providers, especially from the Netherlands and Germany.

6.2. Socio-economic structures and the diffusion of biogas systems

According to the varieties of capitalism framework, Brazil is classified as a hierarchical market economy (HME) (Schneider, 2009). Core characteristics of HMEs in Latin America are centralized corporate governance and the strong influence of the state in markets and employment strategic relationships (Schneider, 2009). These characteristics have influenced the diffusion of biogas systems in Brazil in different ways.

Corporate groups in HMEs are usually spread across several sectors, and corporate governance is hierarchical, as most firms are controlled directly by their owner and maintain centralized control over subsidiaries (Schneider, 2009). These subsidiaries may have little resemblance to each other in terms of the sectors and markets. In Brazil, most of the biogas facilities are controlled by single actors. In most cases, the same actors own the substrate for biogas production and use the biogas produced internally. Paper I suggests that single-actor configurations are preferable in HMEs because they reduce the need for negotiations with stakeholders and allow flexibility and rapid responses to changes since only one actor oversees the whole operation. Global South countries, like Brazil, experience high political and economic volatility (Wieczorek, 2018). Hence, strategies that allow flexibility and rapidly respond to changes from actors are usually preferable (Morgan et al., 2020). This also explains why small-scale biogas facilities have diffused faster than large-scale ones. To invest in large-scale biogas facilities, actors require political and economic stability (Ammenberg et al., 2018). Furthermore, single-actor configurations reduce the need for negotiation with stakeholders, which suits the main means of coordination in Brazil. Paper II shows that in Sweden, as a coordinated market economy (CME), multi-actor configurations of biogas systems that require cooperation among several actors prospered as they aligned with the means of coordination of CMEs.

HMEs are characterized by the strong interference of government in markets and a top-down approach to policymaking (Schneider, 2009). Paper I shows that federal and state governments maintained their positions as central actors for the diffusion of biogas either through policymaking or as the main financier of social projects across important administrative areas to establish biogas systems. Paper III further reinforces the role of government agencies in the diffusion of biogas systems by showing the influence of regulatory environments over business environments through the regulation of energy markets. In Brazil, important markets for the diffusion of biogas systems, such as energy markets, are controlled by governments, electricity markets at the federal level, and gas markets at the state level. This top-down approach typical of HMEs is explored in Paper II, which shows that governmental agencies were central actors in the diffusion of biogas systems as several of the early initiatives were coordinated by the government at different administrative levels.

Government control over markets also influences inter-firm relationships since it incentivizes actors to pursue their interests politically rather than negotiate with each other, as happens in CMEs (Schneider, 2009). Because of governments' influence over markets in HMEs, intermediaries either do not exist or have limited influence (Nölke, 2010; Schneider, 2015). Consequently, biogas actors expect governments to fill the gaps left by the lack of intermediaries (Paper I). Indeed, governmental interference is expected in Global South countries (Wieczorek, 2018). This becomes evident when investigating the work done by the advocacy groups and industrial associations related to biogas systems. The development of biogas-specific regulations and legal representation of the biogas sector are priorities for these groups. Paper II shows that Paraná's government implemented a biogas-specific state policy clarifying the rights and duties of actors across the biogas value chain and left biogas out of the state-piped gas monopoly. In Sweden, similar policies do not exist, and matters of rights and duties of different actors across the value chain are resolved through coordination between the different actors.

7. Conclusion

In this chapter, I reflect on the primary aim of this thesis, explaining how societal contexts have influenced the diffusion of biogas systems in Brazil.

The aim of the thesis is to explain how societal contexts influence the diffusion of biogas systems in Brazil. To operationalize the aim, societal contexts are explored from two perspectives: societal environments and socio-economic structures. Through the lens of the societal embedding framework, the thesis explores the influence of societal environments on the diffusion of biogas systems across the user, business, regulatory, cultural, and trans-local societal environments. The Varieties of Capitalism framework provides a categorization of socio-economic structures in the Brazilian context, and it is used to explain how socio-economic structures shape the diffusion of biogas systems.

Societal contexts in Brazil appear to be more unstable, fluid, and fragmented in comparison to their counterparts in countries in the Global North. Institutional instability appears in the lack of long-term governmental commitment, large public or private investments, and the instability of government agencies themselves, which influenced the development of biogas projects and the establishment of biogas systems. A certain degree of institutional stability is necessary for the actors to have confidence in the long-term development of biogas systems. Hence, an unstable societal context can constrain systems' diffusion since actors may lack the security to invest in new technologies. Among the different configurations of biogas systems present in Brazil, landfill gas capture has been the most successful in terms of the volume of biogas produced. In contrast to other more proactive biogas technologies, landfill gas capture has enjoyed relatively stable support in regulatory, business, and cultural environments. In the regulatory environment, most policies on waste management consider landfills as an adequate solution. Also, some states offer subsidies for electricity produced from landfill gas capture. Both in the business and cultural environments, practices have remained relatively stable, and landfill gas capture does not require changes in business practices or logistics or for citizens to adapt their daily practices when it comes to waste management.

Brazil is structured around three administrative levels (municipal, state, and federal), which causes a fragmentation of Brazilian societal contexts. This fragmentation is particularly prominent in the regulatory environment. Because biogas systems are multi-functional, relevant policies for biogas systems appear across all administrative areas (especially at the state and federal levels) and multiple administrative areas (e.g., water, environment, energy, and waste). Thus, incoherence and a lack of vertical (across administrative levels) and horizontal (across different sectors) coordination appear, influencing the diffusion of biogas systems. To address these issues, decentralization, differentiation, and coordination of policy mixes for biogas systems are necessary conditions to support the diffusion of biogas systems but also other locally bounded and multi-functional technologies. As a hierarchical market economy (HME), higher administrative levels (state and federal levels) have power and agency over policymaking, mobilization, and allocation of resources in Brazil. However, biogas systems usually have strong local connections to, for example, industry, farms, and waste management. The lack of power and agency of local administrative levels restrains the diffusion of biogas systems as it hinders certain types of biogas systems configurations. It also leads to actors directing their efforts to advocate for their perspectives with the higher governmental levels (federal and state) instead of solving coordination issues among themselves as in coordinated market economies (CME) such as Sweden. Although most basic social services are borne by municipalities, the federal government retains agency and power over local projects either as the main financier or as a regulator. Subsequently, many municipalities do not have the financial resources to invest in systems developments, such as campaigns to improve waste segregation at source, collection, and treatment of waste.

The thesis highlights socio-economic diversity and regional variety in societal environments across different Brazilian states. The different characteristics of societal contexts at the state level influenced the formation of biogas system configurations because pre-conditions for the implementation of biogas systems change across states, thus influencing where and which system configurations were formed. This becomes clearer when investigating the diffusion of farm-based biogas systems in Brazil. While agriculture residues for biogas production are available across the country, over 60% of farm-based biogas facilities are concentrated in just two specific states. This can be attributed to the specific societal contexts within these states, nurturing specific configurations of biogas systems over other locations that might initially seem to have higher potential for biogas production. Societal contexts influenced several aspects of biogas systems diffusion. This suggests that potential studies should incorporate measures beyond substrate availability to include contextual aspects such as the ones explored in this thesis.

References

ABiogás, 2020. O Potencial Brasileiro do Biogás. ABiogás.

Amigun, B., Parawira, W., Musango, J.K., Aboyade, A.O., Badmos, A.S., 2012. Anaerobic Biogas Generation for Rural Area Energy Provision in Africa, in: Biogas. IntechOpen. https://doi.org/10.5772/32630

Ammenberg, J., Anderberg, S., Lönnqvist, T., Grönkvist, S., Sandberg, T., 2018. Biogas in the transport sector—actor and policy analysis focusing on the demand side in the Stockholm region. Resources, Conservation and Recycling 129, 70–80. https://doi.org/10.1016/j.resconrec.2017.10.010

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37, 407–429. https://doi.org/10.1016/j.respol.2007.12.003

Borges, C.P., Silberg, T.R., Uriona-Maldonado, M., Vaz, C.R., 2023. Scaling actors' perspectives about innovation system functions: Diffusion of biogas in Brazil. Technological Forecasting and Social Change 190, 122359. https://doi.org/10.1016/j.techfore.2023.122359

Börjesson, P., Berglund, M., 2007. Environmental systems analysis of biogas systems—Part II: The environmental impact of replacing various reference systems. Biomass and Bioenergy 31, 326–344. https://doi.org/10.1016/j.biombioe.2007.01.004

Börjesson, P., Berglund, M., 2006. Environmental systems analysis of biogas systems—Part I: Fuel-cycle emissions. Biomass and Bioenergy 30, 469–485. https://doi.org/10.1016/j.biombioe.2005.11.014

Bryman, A., 2012. Social research methods, Fourth. ed. Oxford University Press.

CIBiogás, 2021. BiogasMap. URL https://mapbiogas.cibiogas.org/ (accessed 1.29.21).

Coenen, L., Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. Journal of Cleaner Production 18, 1149–1160. https://doi.org/10.1016/j.jclepro.2010.04.003

De Oliveira, L.G.S., Negro, S.O., 2019. Contextual structures and interaction dynamics in the Brazilian Biogas Innovation System. Renewable and Sustainable Energy Reviews 107, 462–481. https://doi.org/10.1016/j.rser.2019.02.030

Deuten, J., Rip, A., Jelsma, J., 1997. Societal embedding and product creation management. Technology Analysis & Strategic Management 9, 131–148. https://doi.org/10.1080/09537329708524275

Ebner, A., 2016. Editorial: Exploring Regional Varieties of Capitalism. Regional Studies 50, 3–6. https://doi.org/10.1080/00343404.2015.1039227

Eriksson, M., Andersson-Skog, L., Sabo, J., 2020. National institutions, regional outcomes. The political economy of post-war Swedish regional policy. Business History 1–14. https://doi.org/10.1080/00076791.2020.1796974

Feiz, R., Johansson, M., Lindkvist, E., Moestedt, J., Påledal, S.N., Ometto, F., 2022. The biogas yield, climate impact, energy balance, nutrient recovery, and resource cost of biogas production from household food waste—A comparison of multiple cases from Sweden. Journal of Cleaner Production 378, 134536. https://doi.org/10.1016/j.jclepro.2022.134536

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions 1, 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Geels, F.W., Johnson, V., 2018. Towards a modular and temporal understanding of system diffusion: Adoption models and socio-technical theories applied to Austrian biomass district-heating (1979–2013). Energy Research & Social Science 38, 138–153. https://doi.org/10.1016/j.erss.2018.02.010

Geels, F.W., Pieters, T., Snelders, S., 2007. Cultural Enthusiasm, Resistance and the Societal Embedding of New Technologies: Psychotropic Drugs in the 20th Century. Technology Analysis & Strategic Management 19, 145–165. https://doi.org/10.1080/09537320601168052

Geels, F.W., Raven, R., 2006. Non-linearity and Expectations in Niche-Development Trajectories: Ups and Downs in Dutch Biogas Development (1973–2003). Technology Analysis & Strategic Management 18, 375–392. https://doi.org/10.1080/09537320600777143

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy 36, 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Gustafsson, M., Anderberg, S., 2021. Dimensions and characteristics of biogas policies – Modelling the European policy landscape. Renewable and Sustainable Energy Reviews 135, 110200. https://doi.org/10.1016/j.rser.2020.110200

Hall, P.A., Soskice, D., 2001. Varieties of Capitalism. Oxford University Press. https://doi.org/10.1093/0199247757.001.0001

Hughes, T.P., 1983. Networks of power : electrification in Western society, 1880-1930. Johns Hopkins University Press.

Huttunen, S., Kivimaa, P., Virkamäki, V., 2014. The need for policy coherence to trigger a transition to biogas production. Environmental Innovation and Societal Transitions 12, 14–30. https://doi.org/10.1016/j.eist.2014.04.002

Kanger, L., Geels, F.W., Sovacool, B., Schot, J., 2019. Technological diffusion as a process of societal embedding: Lessons from historical automobile transitions for future electric mobility. Transportation Research Part D: Transport and Environment 71, 47–66. https://doi.org/10.1016/j.trd.2018.11.012

Lyytinen, K., Damsgaard, J., 2001. What's Wrong with the Diffusion of Innovation Theory?, in: Ardis, M.A., Marcolin, B.L. (Eds.), Diffusing Software Product and Process Innovations, IFIP — The International Federation for Information Processing. Springer US, Boston, MA, pp. 173–190. https://doi.org/10.1007/978-0-387-35404-0_11

Markard, J., Wirth, S., Truffer, B., 2016. Institutional dynamics and technology legitimacy – A framework and a case study on biogas technology. Research Policy 45, 330–344. https://doi.org/10.1016/j.respol.2015.10.009

Mignon, I., 2016. Inducing large-scale diffusion of innovation: An integrated actor- and system-level approach. Linköping University, Linköping.

Morgan, G., Doering, H., Gomes, M., 2020. Extending Varieties of Capitalism to Emerging Economies: What can We Learn from Brazil? New Political Economy 0, 1–14. https://doi.org/10.1080/13563467.2020.1807485

Mylan, J., Morris, C., Beech, E., Geels, F.W., 2019. Rage against the regime: Niche-regime interactions in the societal embedding of plant-based milk. Environmental Innovation and Societal Transitions 31, 233–247. https://doi.org/10.1016/j.eist.2018.11.001

Nilsson, M., Zamparutti, T., Petersen, J.E., Nykvist, B., Rudberg, P., McGuinn, J., 2012. Understanding Policy Coherence: Analytical Framework and Examples of Sector–Environment Policy Interactions in the EU. Environmental Policy and Governance 22, 395–423. https://doi.org/10.1002/eet.1589

Nölke, A., 2010. A "BRIC"-variety of capitalism and social inequality: The case of Brazil. Rev Est. e Pes sobre as Américas 4, 1. https://doi.org/10.21057/repam.v4i1.3441

Obaideen, K., Abdelkareem, M.A., Wilberforce, T., Elsaid, K., Sayed, E.T., Maghrabie, H.M., Olabi, A.G., 2022. Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines. Journal of the Taiwan Institute of Chemical Engineers 131, 104207. https://doi.org/10.1016/j.jtice.2022.104207

Ottosson, M., Magnusson, T., Andersson, H., 2020. Shaping sustainable markets—A conceptual framework illustrated by the case of biogas in Sweden. Environmental Innovation and Societal Transitions 36, 303–320. https://doi.org/10.1016/j.eist.2019.10.008

Pagel, H., Ranke, K., Hempel, F., Köhler, J., 2014. The Use of the Concept „Global South“. Presented at the Globaler Süden / Global South: Kritische Perspektiven, Humboldt-Universität zu Berlin.

Palhares, J.C.P., 2008. Biodigestão anaeróbia de dejetos de suínos: aprendendo com o passado para entender o futuro. URL http://www.infobibos.com/Artigos/2008_1/Biodigestao/index.htm (accessed 5.31.19).

Reis, L., 2020. Biogás no Brasil, história e perspectiva de futuro. CiBiogas. URL https://cibiogas.org/blog/biogas-no-brasil-historia-e-perspectiva-de-futuro/ (accessed 11.19.23).

Rip, A., Kemp, R., 1998. Technological change. Human choice and climate change. Vol. II, Resources and Technology 327–399.

Rogers, E.M., 2003. Diffusion of innovations, Fifth. ed. Free press.

Schneider, B.R., 2015. The developmental state in Brazil: comparative and historical perspectives. Rev. Econ. Polit. 35, 114–132. https://doi.org/10.1590/0101-31572015v35n01a07

Schneider, B.R., 2009. Hierarchical Market Economies and Varieties of Capitalism in Latin America. Journal of Latin American Studies 41, 553–575. https://doi.org/10.1017/S0022216X09990186

Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Research Policy, Special Section on Sustainability Transitions 41, 1025–1036. https://doi.org/10.1016/j.respol.2011.12.012

Trist, E., 1981. The Evolution of Sociotechnical Systems as a Conceptual Framework and as an Action Research Program, in: Van de Ven, A.H., Joyce, W.G. (Eds.), Perspectives on Organization Design & Behavior. John Wiley & Sons, New York.

van Welie, M.J., Cherunya, P.C., Truffer, B., Murphy, J.T., 2018. Analysing transition pathways in developing cities: The case of Nairobi’s splintered sanitation regime. Technological Forecasting and Social Change 137, 259–271. https://doi.org/10.1016/j.techfore.2018.07.059

Wieczorek, A.J., 2018. Sustainability transitions in developing countries: Major insights and their implications for research and policy. Environmental Science & Policy 84, 204–216. https://doi.org/10.1016/j.envsci.2017.08.008

Wirth, S., Markard, J., Truffer, B., Rohracher, H., 2013. Informal institutions matter: Professional culture and the development of biogas technology. Environmental Innovation and Societal Transitions 8, 20–41. https://doi.org/10.1016/j.eist.2013.06.002

Yasmin, N., Grundmann, P., 2019. Adoption and diffusion of renewable energy – The case of biogas as alternative fuel for cooking in Pakistan. Renewable and Sustainable Energy Reviews 101, 255–264. https://doi.org/10.1016/j.rser.2018.10.011

Yin, R.K., 2018. Case Study Research and Applications, Sixth. ed. SAGE, Thousand Oaks, California.

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789180754835

FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology, Licentiate Thesis Nr. 1983, 2024
Department of Management and Engineering

Linköping University
SE-581 83 Linköping, Sweden

www.liu.se

LINKÖPING UNIVERSITY