

Contextual structures and interaction dynamics in the Brazilian Biogas Innovation System

Luiz Gustavo Silva De Oliveira^{a,b,*}, Simona O. Negro^a

^a Copernicus Institute of Sustainable Development, Innovation Studies Group, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands

^b ICIS, Maastricht University, Kapoenstraat 2, 6211 KP Maastricht, the Netherlands

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ABSTRACT

Although biogas technologies in Brazil have a huge potential and a long history few studies have examined biogas in Brazil as a technological field. Accordingly, this paper aims to understand which conditions enabled or constrained the diffusion of biogas technologies. More specifically, this research applies and adapts the Technological Innovation System (TIS) framework to examine biogas-specific and context-related conditions as well as their interplay. Data were collected by performing an event history analysis from 1979 to 2016 along with 24 in-depth expert interviews. Our findings indicate that the evolution of geographically embedded sectoral regulations and infrastructures as well as their interactions have been responsible for major changes in the biogas field in Brazil. By demonstrating how this occurred, this research has opened up new possibilities to promote biogas technologies in Brazil. This study also provides an important analytical method that focuses on exploring activities and their background conditions to consider contextual influences in TIS. Consequently, three major ways of contextual influences for TIS studies are suggested – evolution of contextual structures, interaction of contextual structures and translation of external events by these interactions.

1. Introduction

The energy transition towards more sustainable energy systems represents a relevant societal challenge [1,2]. This transition requires sharp increases on the share of modern forms of renewable energy technologies [1–3]. However, technological development and diffusion are far from being easy processes [4]. New renewable energy technological fields are subject to different conditions and determinants [5]. These conditions can be national policy frameworks, international energy prices, local conditions for entrepreneurship and availability of resources and technological characteristics [6–9]. This fact emphasises the need to investigate the broader contexts that enable or constrain new renewable energy technologies.

A good example of these different conditions and their interplay is the case of bioenergy technologies in Brazil. First, the fact of being a global south country indicates specific socioeconomic conditions and forms of access to the global knowledge networks and financing which directly affects technological development [10,11]. Second, Brazil

presents successful experiences of bioethanol and biodiesel technologies [12,13]. These technologies have a long history of experimentation and development in Brazil and achieved high shares on fuel consumption matrix and institutionalisation level. However, other bioenergy technologies such as biogas technologies could not reach the same success level.

Biogas in Brazil has a large potential and several possibilities for its production and use. Recent studies present the potential ranging from 23 [14] to 40 [15] million m³ per day based on agricultural, livestock, industrial and urban residues. Among their benefits in Brazil, biogas technologies reduce carbon emissions, mitigate local pollution and promote local development [16–20]. Moreover, experimentation with biogas technologies dates back from the late 1970s and comprises distinct technological schemes, e.g. for power generation and vehicle fuel and from manure and sugarcane residues. However, only few studies have taken a comprehensive perspective of the history of biogas projects [17,21] and the diffusion hurdles of biogas technologies [22]. Therefore, nonetheless the high potential and its successful

Abbreviations: ANEEL, Power sector national regulatory agency; ANP, Oil, Natural Gas and biofuel national regulatory agency; BBIS, Brazilian Biogas Innovation System; CDM, Clean Development Mechanism; CSTR, Continuous Stirred Tank Reactor; ICE, Internal Combustion Engine; EPE, National Energy Research Office; MSW, Municipal Solid Waste; ONS, National Power System Operator; STI, Science Technology and Innovation; UASB, Up-flow Anaerobic Sludge Blanket reactor

* Corresponding author at: Copernicus Institute of Sustainable Development, Innovation Studies Group, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands.

E-mail address: l.g.silvadeoliveira@uu.nl (L.G.S. De Oliveira).

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implementation in other countries, the reasons why biogas is not diffused and implemented on large-scale in Brazil needs to be investigated.

In order to understand the development of renewable energy technological fields, scholars have been applying the technological innovation system (TIS) framework [e.g. 23–27]. The TIS framework [28,29] recognises innovation as the outcome of interactions between innovators and supportive actors, infrastructures and the institutional environment. The innovation processes benefit from a well-functioning innovation system. Analysts apply the TIS framework and focus on revealing the systemic structural and dynamic conditions for developing and diffusing technologies [30]. These studies have provided valuable policy recommendations on how to foster renewable energy fields [4,23,31,32].

Nevertheless, criticisms say that TIS studies may be myopic and insufficient in accounting for exogenous or contextual influences [33]. In other words, TIS analyses may overestimate the innovation system functioning and underestimate external influences to the innovation system on the success or failure of innovations. For instance, competing innovation systems, generic political processes and sectoral dynamics and differences between global north and south countries are commonly pointed out as important factors. Recent studies have attempted to address this issue [33–36]; however, it remains a point of contention.

This paper combines this conceptual line of reasoning with the empirical analysis of the biogas technological field in Brazil and raises the following research question: *How did endogenous and exogenous influences affect the development of the Brazilian Biogas Innovation System between 1979 and 2016?* The primary goal of this paper is to explain how both endogenous (biogas-specific) and exogenous (contextual-related) influences have affected the development of biogas technological field in Brazil.¹ The secondary goal is to discuss how to examine contextual influences within TIS studies. For this, the methodology is based on event history analysis [37] supplemented with 24 in-depth interviews with key stakeholders in the Brazilian Biogas Innovation System (BBIS).

The paper yields two important outcomes. Firstly, it demonstrates how the interactions of sectoral and geographic institutions, actors and infrastructures defined the development of BBIS. Given the low level of institutionalisation, throughout the period biogas projects were subjected to the (mis)alignment of sectoral policies and regulations. Also, favourable regional conditions of feedstocks for biogas production were an advantage only when positive sectoral and macro influences occurred. Finally, broader macroeconomic conditions have determined sectoral contexts and indirectly influenced biogas activities. Thus, these findings improve the understanding of successful conditions for the Brazilian Biogas Innovation System.

Secondly, the adaptation of TIS framework (as developed by Wiczorek and Hekkert [30]) advances the debate on TIS contexts by proposing an analytical framework that systematically examines contextual influences. This framework understands technologies as ‘bundle’ of value chains [38], enabling the identification of interaction points between technologies and their context (as suggested by Bergek et al. [33]). Consequently, analysts can study how the engagement of actors towards specific activities under specific conditions posed by contexts influences TIS activities and processes. Lastly, the evolution of contextual structures, the interaction of contextual structures and the translation of external events by these structures are suggested as patterns of contextual influences.

2. Technological Innovation Systems and contexts

Innovation systems’ frameworks have evolved in response to the linear model of innovation and the dominance of neoclassical economics in policy arenas [39]. These frameworks consider innovation as

a result of interactions within networks of different actors embedded in institutional contexts [40]. The TIS framework focuses on explaining the emergence and dynamics of a particular technological field. The TIS approach combines a structural and a functional analysis of the innovation system [28].

The structural analysis aims to examine which different system components are present. These components are often classified into actors (private, public, research agents, universities, consumers, etc.), institutions (legislation, norms, standards, values, etc), interactions/networks (formal networks, social communities, social relationships, etc) and infrastructure/materials (physical systems, material artefacts, financial systems, etc.) [30]. The functional analysis [28,29], identifies key processes (functions) necessary for proper system functioning, i.e. to promote the development and diffusion of a focal technology.

Here, the key processes adopted follow [29,30] and comprise entrepreneurial activities (F1) – development of risky activities by entrepreneurs (new companies or incumbents) that are responsible for implementing new products and services; knowledge production (F2) – expansion of technological knowledge base through learning mechanisms; knowledge exchange (F3) – diffusion and exchange of new knowledge through different players and channels; guidance of search (F4) – alignment of visions, expectations, formal targets and goals to steer efforts of different players to common goals; market creation (F5) – need to create proper (protected) spaces for technological development due to incipient character of new technologies; resource allocation (F6) – allocation of adequate type and volume of resources for system activities; and creation of legitimacy (F7) – improvement of legitimacy and acceptance of new technologies and counteraction to possible resistance to changes. Several empirical studies have shown that the importance of these key processes differs across different phases of development [41–44]. These two concepts provide valuable information for theory development, the identification of problems and policy recommendations [28].

Moreover, an innovation system does not operate in a vacuum. Instead, a TIS is embedded and nested in other socio-technical systems or contextual structures [45,46]. The embeddedness of a TIS in other contextual structures calls for a better understanding of their influences on TIS development [33,38,46]. Recently, TIS scholars proposed a number of relevant contextual structures which TIS analyses should examine [33]: technological, sectoral, political and geographical. However, typical analyses[e.g. [24,47]] identify system evolution by focusing only on what happens within the TIS, which results in a superficial perspective on TIS contexts.² This lack of systematic analysis of TIS contexts is a common criticism of TIS studies [48]. Additionally, the application of the TIS framework in developing countries has demonstrated the amplified relevance of context for the development of technological fields [e.g. 49,50]. Examples of important contextual factors are the lack of a well-structured national innovation system [51], poor initial conditions [52], weak positions in global value chains [53] and a larger role of implicit policies [54,55].

2.1. Analytical framework to explore contextual influences on Technological Innovation Systems

For TIS scholars [33], contextual influences vary according to the degree of interdependence between contexts and TIS. In close

¹ It is important to explain that this paper does not intend to present an overview of biogas plants nor legislations.

² It is noteworthy to discuss that the conceptualisation of TIS as developed by Anna Bergek and her colleagues includes taking into consideration some exogenous factors. This fact is noted in two main points. First, her set of functions includes the process of *development of positive externalities*, which accounts for the interdependence of TIS development and external structures. Second, her consideration of inducement and blocking mechanisms provides room for analysing exogenous influences [28,32,97–100]. However, the understanding is that the identification of external structures and factors of influence are made in an ad hoc manner.

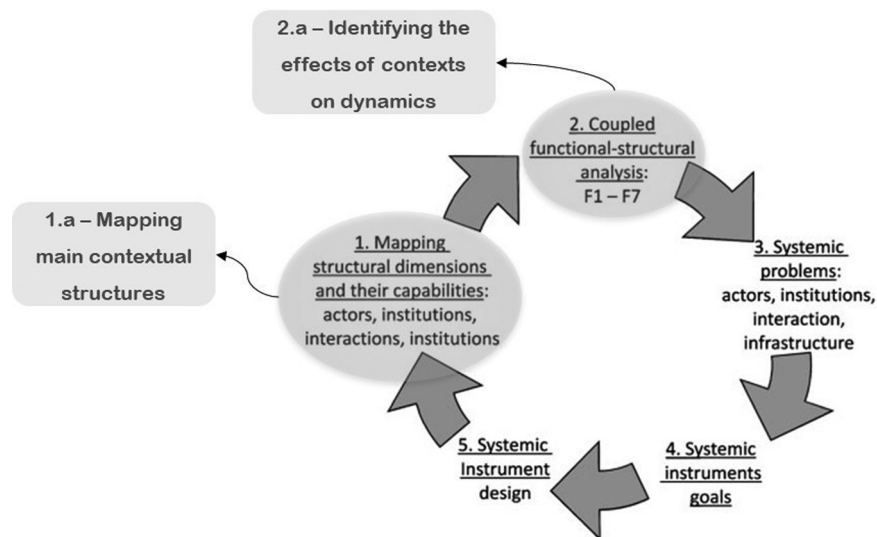


Fig. 1. Analytical framework—adapted from [30].

interactions, structural couplings – i.e. shared elements – are present. In distant interactions, external links – i.e. aspects that influence TIS but are not affected by it – are the main form of influence. For instance, the former can be a power utility that operates in several TISs (solar, wind biogas, etc.), while the latter can be an important event, such as a political crisis. Moreover, these influences must be investigated not only as static specific factors, but as factors possessing intrinsic dynamics that affect the focal TIS.

TIS scholars [33:54] have also suggested some “generic types of contextual structures”, namely other TISs, sectors, specific geographic and political contexts. Although these categories are useful, TIS analysts still struggle to define the range of what is a structural coupling and an external link for each of these contextual categories. These authors also admit that “the distinction between a focal TIS and different context structures is often “blurred” and, therefore, not a straightforward exercise” [33:54]. Therefore, “the focal TIS and its contexts are always constructs of a specific analytical choice” [33:54]. One suggestion used to untangle this analytical trap is to apply a theory-guided research strategy [56,57]. In this way, analysts must explore the possible theoretical explanations to have a better picture of “what aspects of a context are likely to be relevant to the process and outcome under study” [56:1153].

Following this recommendation, this paper adopts the understanding of technologies as a ‘bundle of value chains’ [38:405] to delineate how biogas technologies interact with and overlap distinct contextual dimensions. In this model, these interactions “emanate[s] from [structural] overlaps” [38:407]. Structural overlaps – structural couplings for Bergek et al. [33] – encompass material, organisational and institutional dimensions. Therefore, by explicitly describing the value chains of a specific TIS and examining their most relevant interactions with distinct structures of contextual categories as in Bergek et al. [33], it is possible to select the relevant contextual structures to analyse. This approach addresses the analytical challenges of the boundary definition for contexts as pointed out previously. Thus, the TIS analytical framework as developed by Wicczorek and Hekkert [30] is adapted (as in Fig. 1).³ The specific details of this adaptation are explained below.

2.1.1. Defining the boundaries of analysis by exploring the value chains

The adaptation 1.a in Fig. 1 refers to the definition of the boundaries of the analysis both for the focal TIS and for the contextual structures.

³ Because this research aims to explain the evolution of biogas history in Brazil, we focus on the structural and functional analysis rather than the full analytical cycle.

According to Sandén and Hillman [38:404–405], “[a]ny specific technology [...] is defined by a set of complementary and alternative value chains” and “is a combination of upstream and downstream hierarchies” of products and processes. Hence, analysts can delineate system boundaries in wider or narrower fashion. In the case of biogas, the analysis of innovation system may consider the biogas production for power generation, biogas production from swine manure for power generation or biogas production from different substrates for different uses. This choice is an analytical choice and depends on the particular research questions.

Nevertheless, this method of boundary definition is closely related to what is suggested in TIS literature [28,58]. It also refers to the TIS boundaries only and not to the contextual structures. However, the description of value chains made by specifying products and processes enables analysts to explore the exact activities and entities⁴ for the different levels of the different value chains. Put simply, the specific activities in value chains are performed by certain agents under certain conditions, in which the conditions may be institutional, infrastructural, political or geographic.

The identification of these agents and conditions enables to determine how these value chains relate to contexts. For instance, the collection and treatment of substrates for biogas production may be performed by sanitation utilities or farmers embedded in different institutional, geographic and infrastructural conditions. Therefore, by applying this framework to the different streams of the delineated value chains and taking into consideration the main categories of contexts as in [33], TIS analysts can map the boundaries of contexts.⁵ This is presented for our case in Section 4.

2.1.2. Exploring the contextual influence on Technological Innovation Systems dynamics

After defining the boundaries of contexts, it is necessary to examine how the contextual structures evolved. This means the analysis must investigate the dynamics of the elements of contexts and their influence

⁴ We understand entities and activities as in [101:35], in which entities are engaged in certain activities that are responsible to produce changes or transmit causal forces.

⁵ It is important to note that Sandén and Hillman [38] proposed this conceptualisation to explore the technological interactions. We do think that the presentation of a complete list of technological interactions across value chains is relevant. However, we do not present this list here because our main goal is to understand contextual influences and not the technological interactions.

on TIS [33] (2.a in Fig. 1). First, the analyst must consider the timeframe of the analysis. A good way to do this is to set the same timeframe as the TIS analysis.⁶ Second, the analysis may be more theory-guided or more grounded-developed. With the former, the analyst can account for different disciplinary and conceptual explanations. For example, it is possible to explain the evolution of sectoral contexts using Sectoral System of Innovation [59] or Industrial Dynamics [60] frameworks. On the other hand, grounded analyses, which are adopted for this research, requires extensive collection of data about the contextual elements mapped through the value chains.

The next step is to explain how this evolution of contexts affects TIS structure and dynamics. These effects are more evident in TIS structures. As the contextual structures are mapped through the couplings of entities, activities and conditions in value chains, changes in these entities, activities and conditions lead to changes in the couplings. For instance, if new important players appear in sectoral contexts, or if there is any significant institutional change through time in sectors that interact with a focal TIS, the changes will very likely affect the actors and institutions in the TIS. Therefore, it is possible to detect these effects by exploring the evolution of contextual structures and their interactions with TIS structural elements.

The contextual effects on TIS dynamics are less obvious. Analysis of TIS dynamics, or the functional analysis, is generally performed by examining indicators that would be proxies for several activities [23,31]. For example, one way of tracing the fulfilment of knowledge production in TIS is to analyse R&D indicators that are expected to represent knowledge production activities. Although this may be a reasonable strategy for gaining a broader understanding of TIS functioning, it is necessary to really check the activities, i.e. who is engaged and under what conditions, to analyse contextual influences. This is exactly the outcome of the value chain analysis and the mapping of contextual structures. For example, for R&D activities analysts must map the main actors, their sectoral embeddedness, region and stream of value chain, among other possible factors. By exploring these activities in TIS, analysts can trace the influence of contexts. In the following section, data collection is explained.

3. Methodology

The analyses of the biogas value chains and contextual influences (Section 4) and the structural–functional analysis (Section 5) were conducted with desk-based research and verified with interviews. The main sources used for the desk-based research were documents (scientific, professional and public reports). Scientific literature databases, such as Web of Knowledge, Periódicos Capes and selected Brazilian universities, were used to retrieve scientific papers on biogas experiences in Brazil. Electronic files of the Lexis-Nexis® database, selected newspapers⁷ and websites of sectoral media were the main type of media documents collected.

This research also comprised the collection of reports of activities, public consultations, research reports, technical reports and official government documents for selected organisations. For the structural–functional analysis, it was developed an event history analysis from 1979 to 2016 [37]. The event history analysis is a type of process method [61,62] for mapping the sequence of events⁸ that have taken place. This mapping aims to construct a narrative for a particular process [41] from data of events of the literature and of interviews [63:37–43,64:67–73]. The events are stored in a database and allocated to the

system functions.

However, to identify the contextual influences, it was necessary to go beyond the mapping of events and their sequences by collecting detailed data about the events. To construct a large database, data collection also comprised specific information about the events' main actors, place and sector, main activities and motivations and exchanged products. This information was used in the coding process to describe the functional pattern of BBIS. This method allowed us to make inferences about contextual influences because it could relate the system functions to specific details, such as engaged actors, their sectoral and geographic embeddedness, and their explicit motivations.

Subsequently, researchers conducted 24 semi-structured expert interviews to confirm the constructed narrative. The questions were grouped into the following categories: the identification of system elements, system functioning, sectoral contexts, regional aspects and the Brazilian national environment. The existing TIS literature, which presents main indicators and follow-up questions [28–30,63,65,66], was the main reference to define the questions. The interviews were recorded, transcribed and analysed. Among the interviewees listed in Table 1 were consultants and representatives of governmental bodies, private and state-owned companies, industry associations, intermediary organisations, universities, farmers and researchers of the BBIS.

The TIS dynamics and contextual influences are represented in figures (see Section 5). Grey boxes represent the most relevant functions for each period. These figures also indicate the most relevant events or clusters/groups of events from the BBIS and its contexts. The selection of events or clusters followed the coding process that comprised specific categories derived from TIS functions and from empirical data. These categories included the following: expectation, interaction/network, international context, knowledge, legitimacy, lobby, local context, market creation, national context, projects, research group, resource allocation, sectoral context, state-level context and technological context. These categories allowed us to identify which cluster of events was most relevant for each period.

Additionally, these figures included single events when they directly affected BBIS structures, or when they were crucial for the fulfilment of BBIS functions. These events or clusters of events could be from the BBIS or from its contexts. For the representation of the functions, as these functions can be fulfilled by different types of activities,⁹ boxes were named according to the most relevant activities for the period. The respective subsections present the explanations of these activities. Lastly, the arrows between events or cluster of events indicate which events preceded other events. The arrows linking events or cluster of events and boxes indicate the relevance of these events to the fulfilment of certain function, and the arrows connecting boxes and events indicate the effect of this function fulfilment to other events.

4. Biogas value chain and its contexts in Brazil

Biogas is generated by a biochemical reaction, in which organic matter is degraded by microorganisms in the absence of oxygen. The main products are methane, carbon dioxide and digestate, which is the residue of anaerobic digestion [67,68]. Like natural gas, biogas is a flexible fuel with several applications [69]. The set of technologies related to biogas ranges from biomass treatment to biogas logistics and use. However, the core of biogas technological innovation lies in the production and treatment technologies, which require specific biodigesters, yeast strains and technologies for removal of water, sulphur, siloxanes and carbon dioxide [70]. Therefore, the different combinations of feedstocks and technologies yield a plethora of possibilities in biogas value chains in Brazil.¹⁰

⁶ The timeframes of TIS and contextual analysis may not match because they may not be synchronised (e.g. see [56]).

⁷ We searched for 'biogás', 'biodigestor' and 'digestão anaeróbica' in the digital archives of *O Globo* and *Folha de São Paulo*.

⁸ Events are the basic analytical construction done by the analysts in order to relate the empirical fact and the theoretical [61].

⁹ See Section 2.

¹⁰ The study of Paraná state case [74] illustrates the possibilities of developing the biogas value chain.

Table 1
List of interviewees.

Category of players	Number of interviewees	Acronyms
Governmental bodies (G)	6	G1 to G6
Utilities (Ut)	5	Ut1 to Ut5
Private companies (P)	3	P1, P2 and P3
Intermediary organisations (I)	3	I1, I2 and I3
Research centre/company (R)	3	R1, R2 and R3
Financial organisation (Fin)	2	Fin1 and Fin2
University (Un)	1	Un1
Farmer (F)	1	F1

4.1. Biogas value chain, technological trajectories and Brazilian Biogas Innovation System boundaries

Biogas activities can be placed into three main categories: feedstock supply and logistics, biogas production and treatment and biogas uses and logistics. Given Brazil's large potential to produce biomass and the flexibility of biogas applications, biogas technologies involve a profusion of institutions, actors and materials. From the upstream side, this situation introduces several categories of actors, such as sanitation utilities, farmers and agroindustries; different type of rules, e.g. sanitation regulations, agricultural market rules and environmental legislations; and a variety of material aspects, such as sewage, organic fraction of Municipal Solid Waste (MSW), manure, vinasse, UASB¹¹ reactors, landfills and dunghill lagoons. The downstream side introduces energy utilities, engineering companies, power and natural gas sectors regulations, ICE¹² generators, compressors and power and natural gas systems to name some actors, institutions and materials [19,20,22,71–74]. Consequently, biogas technologies have evolved across different technological trajectories or technical routes.

A series of recent publications [75–79] have contextualised biogas technologies for Brazil. The choice of anaerobic reactor for biogas production (CSTR,¹³ UASB, anaerobic lagoons, plugflow and batch dry fermentation reactors) depends mostly on the geographic density, quantity, seasonality and characteristic feedstocks (livestock manure, agroindustrial residues, sewage and sludge and organic fraction of MSW) [77,79]. These factors influence the type of biogas treatment¹⁴ and the scale of biogas production. Therefore, the scale of biogas production varies according to regional and sectoral activities. For instance, livestock production tends to involve small or medium-scale biodigesters, whereas industrial residues, such as those from ethanol production, may be handled on larger scales.

Conversely, the scale of biogas production in urban areas depends on the population, the related waste and residue concentrations and infrastructural systems. Technical infrastructure plays an important role in urban biogas projects. Because urban sanitation and waste management projects are capital-intensive investments, the selection of technical schemes influences the availability of either the substrates or the biogas. The case of UASB reactors in sanitation systems and landfills illustrates this dependence on technical infrastructures.

Additionally, the selection of biogas-use technologies, mostly power generation, substitution of thermal or automotive fuels or injection into gas grids, is influenced by the scale of biogas production. The selection of biogas-use technologies has also a strong influence on the choice of biogas treatment technologies. For example, biomethane production requires a more intensive biogas treatment technology than power generation or cooking fuel use. These treatment technologies have distinct scales, placing technical or economic constraints on the choice

of other technologies in a biogas project.

With this set of conditions, it is possible to highlight four main technological trajectories for biogas related to the feedstock sector (see Fig. 2). The first (T1) is based on livestock manure comprised mostly of the residues from swine production. T1 leads to small or medium-scale projects in rural areas, primarily in the southern region. Biogas production occurs mainly in anaerobic lagoons; however, more modern biodigesters like CSTR are also used for production. Power generation and heating fuel are the predominant uses of biogas in this scheme. Consequently, biogas treatment technologies in T1 are simpler than those for other trajectories and involve mostly the removal of water and sulphur content.

The second trajectory (T2) is also based on residues; however, these come from industrial processes, mainly related to the food, beverage and sugarcane industries. The main difference between industrial and livestock residues is the concentration and quantity of residues that can be much higher. Therefore, the scale of biogas projects goes from small to very large. Projects in this trajectory tend to apply CSTR types of biodigesters and use biogas in different ways; however, power generation is still dominant. This use depends on local demand and infrastructure. These two trajectories require different types of technological development, such as the scaling-down of biogas production and treatment technologies and the adaptation of biogas production technologies for a very large scale, e.g. the sugarcane sector.

Residues from the sanitation sector (sewage and sludge) lead to the third trajectory (T3). Biogas production for this trajectory relies heavily on the type of infrastructure in the sewage systems. If these systems employ UASB type reactors for sewage treatment (anaerobic treatment), there is a possibility of capturing biogas produced during the treatment of waste water and use sludge (output of the treatment) in a different biodigester. If sanitation systems apply a chemical treatment procedure, then the only possibility is use of the sludge. In general, biogas projects for this trajectory are small and medium-scale projects that apply power generation schemes for self-consumption. Therefore, these biogas treatment technologies are similar to those in previous trajectories.

The fourth trajectory (T4) refers to biogas production in the waste management sector. The dominant technical route is based on the capture of landfill gas. This dominance entails the higher relevance of biogas treatment technologies as no digester is needed in this case. Power generation is the dominant use of biogas; however, biomethane projects have been proposed recently. The scale of such projects is a direct outcome of the size of landfills. Important technological development must be achieved for this trajectory, particularly the development of biogas treatment technologies that remove siloxanes and assure the quality of biomethane.

The investigation led to other projects in which these trajectories overlap with each other, e.g. co-digestion of residues, biomethane production from livestock manure and dry processes for MSW. However, the selection of these trajectories represents the majority of projects that have been developed during the period analysed. These trajectories also indicate where contextual influences may be expected in the biogas value chain. They highlight the relevance of feedstock sectors, of sectors that use the biogas produced and of most propitious regions and places for biogas projects. However, future development of biogas technologies in Brazil may encounter other trajectories.

4.2. Main contexts for Brazilian Biogas Innovation System analysis

This section aims to present the main contextual aspects to investigate so that TIS analysis can account for the influences of contexts on the dynamics of BBIS. From the description of technological trajectories, it was possible to detect contextual influences of the four categories presented in Bergek et al. [33]. However, the discussion in next sections grouped these influences into sectoral and geographic contexts. This is consequence of several interactions between contextual

¹¹ Up-flow Anaerobic Sludge Blanket Reactor.

¹² Internal combustion engines.

¹³ Continuous Stirred Tank Reactors.

¹⁴ For instance, biogas from vinasse has a much higher concentration of sulphur than biogas from livestock manure [102].

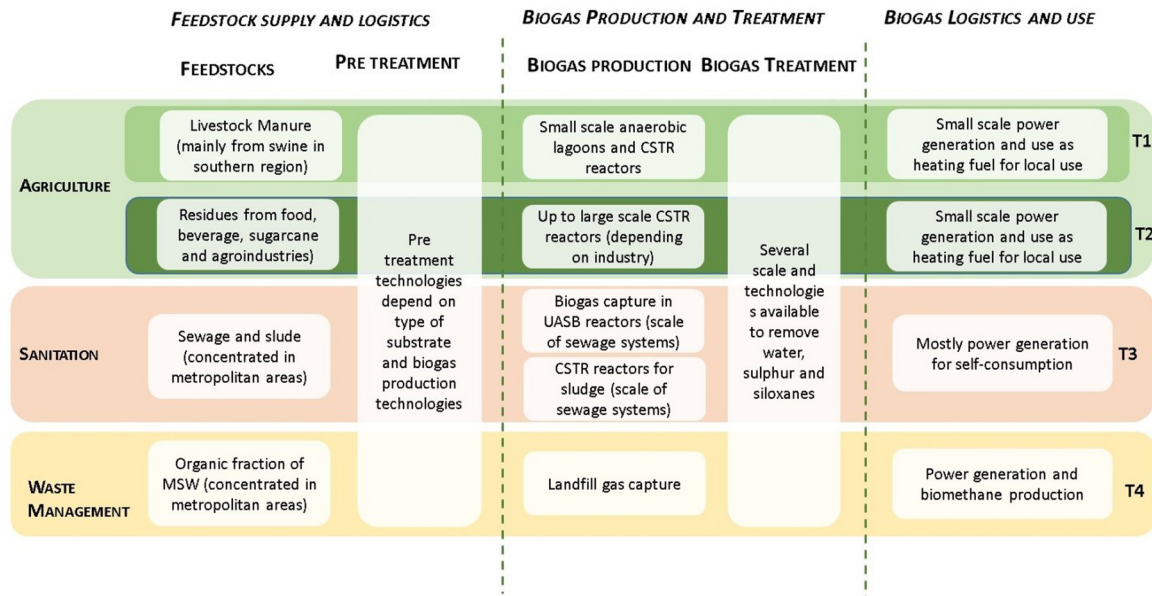


Fig. 2. Main technological trajectories of biogas production in Brazil.

structures. Therefore, technological and political factors and structures can be analysed through the lens of sectoral and geographic contexts. Moreover, for readers that are not familiar with the Brazilian conditions, some general aspects of sectoral and geographic contexts in Brazil are presented.

4.2.1. Sectoral contexts

Sectoral structures emerged as the most important contextual influences on biogas technological trajectories. Biogas projects are engaged mostly in activities within the *Agriculture* sector (including agriculture, livestock and agroindustry), the *Energy* sector (mainly power and natural gas) and the *Sanitation* sector (including water and sewage treatment and waste management sectors). The *Environmental* and *Climate Change* policy fields¹⁵ also influenced these trajectories. The strongest influences came from specific actors and institutional, physical and resource infrastructures.

For institutional structures, the first focus of investigation was how their evolution has influenced the BBIS. This was a crucial point because the research covered 37 years, and sectoral institutions have changed several times due to several institutional reforms. For example, the power sector has faced two large institutional reforms within the last 25 years. Our second focus was on how sectoral institutional overlaps, voids and interactions create both barriers and opportunities for biogas projects. For instance, agricultural activities must comply with environmental regulations and market structures, due to the commodity market feature, whereas the sanitation sector has specific regulatory frameworks in addition to environmental rules. Another example is the low-carbon agricultural plan (climate change field and agriculture sector) which has enabled several biogas projects.

Sectoral institutional structures also interact with the political system. The interactions with different governance levels, given by the Brazilian federative political system [80], provide distinct governance structures across sectors. For example, national environmental policies define the macro guidelines that regional and local bodies must follow and adapt to local conditions. The fields of climate change and the sanitation sectors follow the same shared governance structure,

national guidelines and targets and regional and local rules. In contrast, the agricultural sectors are less regulated and more market-oriented.¹⁶

On the downstream side, the power sector is regulated by national agencies¹⁷ (ANEEL,¹⁸ CCEE¹⁹ and ONS²⁰), including the definition of tariffs. In contrast, the natural gas sector is subjected to regulation shared by national (ANP) and state-level (regulatory and executive agencies) bodies. This situation involves not only diverse rules but also the need for vertical and horizontal coordination among these governance levels. Therefore, understanding how this interaction affects BBIS dynamics seems to be crucial.

These governance structures lead to a distinct set of actors, such as utilities, private companies and national and local governmental bodies according to sectors. It is essential to analyse what are the roles of these sectoral actors in the development of biogas projects and technologies since they bring different logics into BBIS. It is also essential to investigate how these actors interact with other actors in a cross-sectoral context. For instance, while environmental agencies may support and push biogas technologies by enacting regulations for waste and residues treatment, these regulations may also be too strict and constrain the development of biogas projects.

These governance structures may also hinder important interactions. As biogas projects deal with players and regulations of distinct sectors, horizontal and vertical knowledge exchange is vital. For example, if centralised energy regulatory agencies have to interact with agricultural players, it may be very difficult to find common solutions for biogas projects since they have few spaces for interactions.

Physical infrastructures represent other relevant sectoral influences. They have a strong impact on the development of biogas projects because each sector has distinct infrastructural conditions. Sanitation sectors have low numbers of adequate treatment systems. Sewage systems collect only 80% of effluents and treat 40% only, whereas MSW management collects 98% of solid waste but still has around 30% of

¹⁶ Although state players are also important, such as the national supply company, Embrapa and Banco do Brasil.

¹⁷ Although there are state-level agencies, the relevance of these for the power sector compared with natural sector is minimal.

¹⁸ Power sector regulatory agency.

¹⁹ Electricity National Chamber of Commercialisation.

²⁰ National Power System Operator.

¹⁵ Here, there is an implicit understanding of sectors as organisational fields [103] and as policy fields [94].

dumps.²¹ As discussed, the choice of anaerobic or chemical processes for sewage treatment and the choice of landfills or other schemes have direct impacts on biogas decisions for these sectors. In recent years, the agricultural sectors have been improving their residues management through tillage in agriculture and the expansion of livestock manure treatment. However, the expansion of confined livestock production systems increases the need for new rural sanitation systems.

On the downstream side the power sector is the most universal in Brazil in terms of physical infrastructure, while the natural gas grid is concentrated in a few cities only. Furthermore, physical infrastructures are territorially embedded, meaning that quality and accessibility vary among regions. For instance, there are differences in quality between urban and rural power networks and sanitation systems, and access to a natural gas grid is more limited in country cities.

Furthermore, the main driver for BBIS technological interactions is the interaction between institutional and physical infrastructure. While the formal rules influence the definition of business models, accessibility and quality of products, the types of infrastructure enable or constrain different technologies. Therefore, possible influences of other technologies can be investigated by focusing on these interactions. On the upstream side, the primary example comes from the sanitation sectors. The choice for landfills in waste management results in no development of biogas production technologies, but only biogas treatment and use technologies. In sanitation, the development of biogas projects is either planned with expansion of the system or has to rely on anaerobic systems.²²

On the downstream side, power sector regulations and grids define which and how distinct types of distributed generation technologies can access the grid and trade electricity. This creates an important type of competition between these technologies. Still, biogas projects that aim to use biogas as fuel must comply with fuel regulations and natural gas grid conditions.

Finally, as resources are crucial for any TIS development, it is crucial to examine how sectoral resource structures act upon BBIS resources. Despite having a successful agricultural innovation system, Brazil concentrates R&D&I in the public research company, Embrapa, and in universities with low private investment and no mandatory rules for private companies [81]. For the sanitation sectors, R&D&I resources are scarcer. Because there is no mandatory investment in R&D&I, and because there has been a long period without significant investments in infrastructure, research and innovation activities depend mostly on the inner motivation of single actors [82,83].

In contrast, the energy sector possesses abundant funds for R&D&I activities, which is a consequence of mandatory regulations that force investments in R&D. Moreover, combined R&D&I projects are not common across sectors, which would be crucial for the biogas field. Another important resource is human resources, i.e. skilled labour. The availability and quality of human resources is hugely disparate across sectors, because the qualifications of labour vary according to sectors.

4.2.2. Geographic aspects and influences

Recently, TIS studies tried to capture geographic influences beyond the national level [e.g. 34–36,49,84], even though most scholars still concentrate on national influences [85]. At the international level, TIS studies have focused on technology transfer activities and financial resource allocation [e.g. 35,49]. However, other factors, such as shocks in international prices and international crises, are important as well [46]. For BBIS, there are three main factors to be mapped. The international development of biogas technologies is the first relevant factor because of the possible technology and policy transfers. Then, it is necessary to investigate the interactions with and roles of international

players that facilitate these transfers. Third, changes in international prices of agricultural, mineral and energy commodities are relevant because they directly affect the Brazilian economy and biogas-related sectors.

At the national level, analyses must account for the interrelationships of BBIS and the Brazilian National Innovation System (BNIS) and political structures, more specifically understand how macro national conditions affect both sectoral and TIS dynamics. Since the broad definition of NIS [86] already accounts for some political issues, and because a detailed description of political factors goes far beyond the scope of this paper, this study borrows from two recent studies on BNIS [55,87]. These studies presented the historical development of BNIS, its current strengths and weaknesses as well as the role of macroeconomic policies by examining four macro groups: Education and Research, Production and Innovation, Finance and Funding and Government (regulations and policies).

Lastly, sectoral contexts have already discussed regional and local actors, institutional settings, resources and material aspects play important roles for biogas in Brazil. This fact is consequence of the interactions between regional features and sectoral conditions create specific situations that influence biogas activities. Therefore, the singular geographic factor to examine is the evolution of substrate availability. Availability of substrates is consistently distributed with regional edaphoclimatic characteristics and consequent agricultural production. It also results from the urban population concentration that determines the differentiation of urban from rural areas. This situation yields regions that are more suitable for certain feedstock, which leads to different sorts of technologies. For example, the concentration of sewage and sludge treatment systems is higher in big cities, swine manure is produced mainly in rural areas of southern states, as sugarcane and ethanol production take place mostly in São Paulo state.

5. Brazilian Biogas Innovation System

The historical analysis documents four main phases²³ of biogas development in Brazil (see Fig. 3 for temporal and geographical distribution of events in which the height of the bars represent the number of events per year, and the circles represent the total number of events per city. See also Fig. 4 for an overview of phases).

The first phase is the period of 1979–1986. The initial event of biogas promotion in Brazil usually is pointed out as the inauguration of the ‘*Granja do Torto*’²⁴ biodigester [17,21] in 1979, and the first incentives for biogas production in Brazil in the 1980s. These incentives were a direct consequence of the oil crises in 1973 and 1979 and public pressure for improved sanitation services. This phase achieved some success as about 3000 biodigesters were installed. Nevertheless, the oil prices drop in 1986 and the deterioration of Brazilian macroeconomic conditions discontinued the positive cycle of biogas activities.

The following phase (1987–2002) represents the recession of biogas experimentation and the decline of the BBIS. Meanwhile, several macro institutional changes happened to create a turbulent environment for the BBIS. During the third phase (2003–2011), CDM²⁵ projects stimulated biogas technologies. During this period, the BBIS was resurrected and experienced important structuration. Contextual events marked the end of this phase, such as the decline of CDM projects and the consequences of international economic crisis.

The last phase (2012–2016), started with the development of important milestones for biogas, such as state-level biogas policies, the creation of national associations and research networks. However, the current economic and political crises in Brazil may have a negative

²¹ SNIS (National Sanitation Information System) – www.snis.gov.br.

²² In general lines, chemical sanitation treatment makes biogas projects unfeasible.

²³ The end of each phase was chosen on the basis of change in activities or key events; therefore, not all periods are equal in length [37].

²⁴ One of the official residences of Brazilian president.

²⁵ Clean Development Mechanism of the Kyoto Protocol.

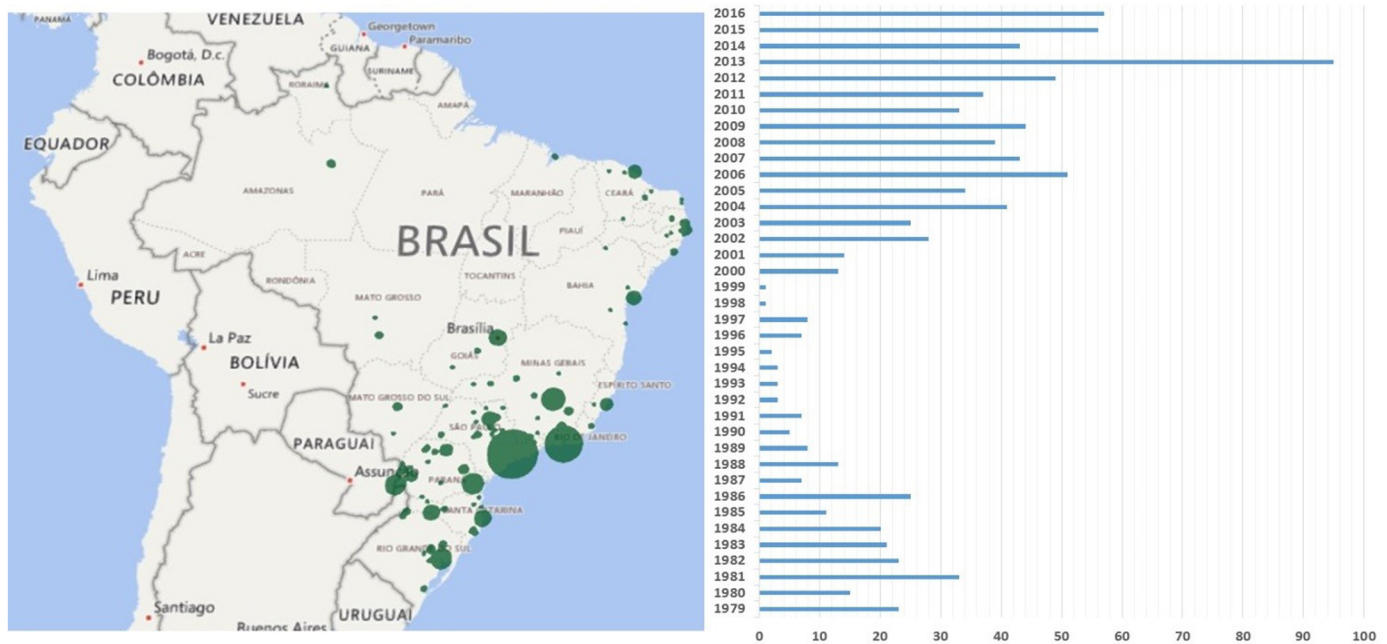


Fig. 3. Geographic and time overview of mapped events.

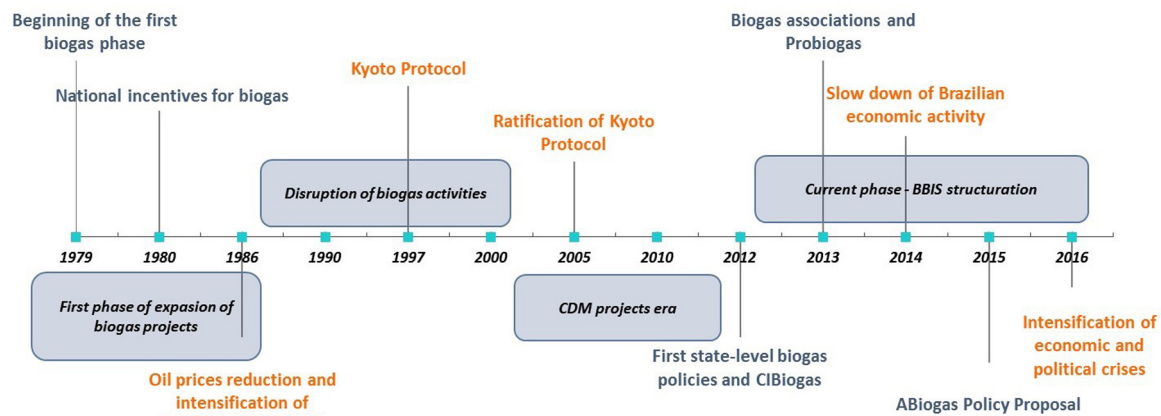


Fig. 4. Timeline of main phases of biogas activities in Brazil.

impact on the BBIS's future activities. In the following sections, the detailed description of these phase is presented, starting from the initial contextual conditions, development of BBIS activities, changes in contexts and impacts on BBIS activities.

5.1. Biogas kick-off (1979–1986)

This period started under the pressure of two global oil crises in 1973 and 1979, which led to the search for reducing oil dependence. Coinciding with these events was the growing concern for environmental issues, such as resource depletion and local pollution, and the diffusion of biogas technologies in other developing countries like China and India [88].

In Brazil, high oil prices were translated into macroeconomic pressures and consequent actions to reduce external oil dependency. During this period, the Brazilian government decided to intensify the promotion of alternative energy and several measures were implemented. For instance, the famous PROALCOOL programme to promote the expansion of ethanol production from sugarcane [12]. In addition, the initial effects of intensification of livestock production and the increasing

urbanisation started to pressure the environment and demand more sanitation services.

This situation set the contextual environment for BBIS development by enabling the *convergence of the visions of biogas* as one of the solutions for these contextual problems among different types of actors and promoting the initial fulfilment of guidance of the search and engagement of key players. This set of activities comprised the first relevant process that triggered the BBIS's development (see Fig. 6). First, the engagement of researchers, for instance the UNESP²⁶'s biogas research project funded by CNPq²⁷ in January 1979 and practitioners, for example from Embrater,²⁸ led to the *Granja do Torto* biogas project (trajectory T1), which was launched in November 1979. These initial events aligned the expectations of searching for alternative energies and the need for better sanitation in rural and urban areas around the biogas technologies as a convergent solution for these problems.

²⁶ University of the state of São Paulo.

²⁷ National Research Council.

²⁸ Brazilian technical enterprise of rural extension.

Then, a series of events started to shape the BBIS and led to the second important process based on the *resource allocation* by the incumbents, which intensified the engagement of other actors and the development of projects. Financial resources were provided by national and state-level bodies (including state-owned companies). Knowledge was provided by sectoral utilities and private companies established in Brazil. Feedstocks were dependent on regional and local players.

National government bodies created funding lines to biogas solutions through the development bank and research agencies. State-level bodies stimulated projects through state-level banks and state-owned companies. Energy and sanitation state-owned companies had fundamental roles on both the supply and demand sides of biogas technologies and actively participated in R&D projects. Rural development agencies and the Brazilian Agricultural Research Corporation (Embrapa) mobilised not only farmers and, consequently, the supply of substrates, but also provided important knowledge resources through operational and research activities. Universities and some private companies complemented the knowledge infrastructure of this period, with private companies participating later on and more on biogas treatment and use technologies.

The outcome of this resource allocation was the development of several projects. Initially, the majority of projects occurred in rural areas (trajectory T1), especially in the southern states of Paraná and Santa Catarina, where rural sanitation along with biofertiliser production were the main motivations, and biogas energy use was to be a by-product.²⁹ The most diffused biodigester technology was the Indian biodigester model since it was relatively cheap and easy to adapt [21]. Research projects concentrated in areas where there were already strong research groups on rural- and agriculture-related topics such as in São Paulo's universities (UNESP and Unicamp) and the southern region (with Embrapa and universities like UEL and UFSC).

The combination of convergence of visions around biogas as solution for oil dependence and local environmental problems, resource allocation by important incumbents and development of several projects brought about the increase of legitimacy of biogas technologies and experimentation with other technological trajectories. This *increasing of legitimacy* became the third relevant process of BBIS expansion, reinforcing the pressure for resource allocation.

The energy use of biogas from landfills was more relevant in São Paulo, Rio de Janeiro, Minas Gerais and Ceará states (trajectory T4). The necessary set of resources (knowledge and financial) was also mostly provided by sanitation and energy utilities that already experimented with digestion technologies. Besides, since the landfills produce gas without any additional technology needed, technological development concentrated on the biogas treatment and use technologies. Meanwhile, also because of the search for reducing oil dependence, the promotion of natural gas vehicles in some urban areas motivated experimentation with biogas from landfills in these vehicles.³⁰ For this, the engagement of car manufacturing companies was crucial in developing automotive technological solutions for specific projects.³¹

Other important experiences occurred as a consequence of ethanol

production expansion (trajectory T2). The increased legitimacy of biogas technologies fitted very well the problems of surplus of vinasse³² production and shortage of diesel supply in the sugarcane sector. Players were able to develop specific biodigestion and biogas treatment technologies targeting the treatment of vinasse and automotive uses of biogas. However, these experiences presented technological limitations.³³ Lastly, another avenue of biogas experimentation, less explored, was the combination with other energy technologies.³⁴

Nevertheless, after this positive cycle, and although BBIS underwent a noticeable development, changes in contexts along with technical problems negatively affected BBIS functioning. First, the intensification of the national macroeconomic crisis, which had already started in 1982 [55], and the plunge in international oil prices reduced the availability of resources extremely reduced the contextual pressure for searching for *alternative* energies. These changes, therefore, affected the convergence of problems and the resource allocation processes.

Key actors, such as national governmental bodies and state-owned companies, altered their strategies or lost their financial capacities, cutting off financial support for biogas projects. Second, technical problems of biogas projects triggered a vicious cycle for biogas activities. These technical problems, e.g. inadequate material specification and incorrect operation of biodigesters, were primarily due to a lack of knowledge related to operating and designing projects of both companies and users, particularly in rural areas.

Other important issues were the lack of regulations for biogas projects and the quality and accessibility of technical infrastructure. The former allowed the development of poorly designed projects. Although there was the engagement of incumbents, virtually no biogas-specific regulation or standard was enacted during this period. Infrastructures, such as the power and natural gas grids and sanitation systems, were less accessible, restricting the production and capture of biogas values.

These issues also entailed higher relevance of sectoral regulations. By that time, these regulations were too strict and hampered the development of important biogas activities. For instance, the role of distributed generation (DG) in the power sector and fuel use of biogas for either transportation or injection into the gas grid. Hence, several projects could not fulfil the high expectations they raised in terms of environmental solutions and cost reduction, which contributed to the downturn of legitimacy.

In sum, contextual influences were central for this phase in both positive and negative ways (see Fig. 5). International contexts provided pressure on the existing regimes (through the oil crises), which were translated by national and sectoral actors into several problems (e.g. the need to reduce oil dependence and improve energy efficiency) and solutions (e.g. the promotion of alternative energies, including biogas) according to regional and local conditions. After this initial alignment of contextual conditions, key incumbents allocated resources and the resulting development of projects increased legitimacy.

The vicious cycle of this first phase also started with changes in macroeconomic contexts and international oil prices, and then intensified through the internal problems of biogas activities. International and national factors affected mainly the alignment of contextual conditions and the resource allocation, whereas technical problems undermined the legitimacy of biogas technologies. Thus, the coupling of processes that promoted BBIS development was severely weakened.

²⁹ These projects created a huge cycle of positive expectations due to the possibility of cost reduction with biofertilizer mainly but also energy. For instance, the expansion of Liquefied Petroleum Gas in replacement of firewood raised the costs for farm production. However, the share of chemical fertilizer costs and the possibility of replacement with biofertilizer was more relevant for rural areas. Lastly, the compliance with better environmental manure treatment was also relevant.

³⁰ Landfill projects in Belo Horizonte, Rio de Janeiro and São Paulo for vehicles (1983–1986), as well as R&D projects in Londrina with biogas tests for tractors (1984) and the fuel station of UNESP and Mangels in Jaboticabal (1985), are relevant examples.

³¹ Projects for automotive biogas happened in different cities, such as Londrina for tractors (Sanepar, Mangels, MWM and Valmet) and for taxis and trucks in Rio de Janeiro (CEDAE, Comlurb, CEG and Marsh).

³² Liquid residue of ethanol production.

³³ Several players were involved, such as Dedini, IPT, Unesp, Comgás, UEL and PEM-Engenharia; however, there were persistent technical problems, mainly for controlling biodigestion reactions and biogas treatment technologies.

³⁴ For instance, projects like Pirai do Sul (PR) and Cedro (PE) attempted to create 'sustainable cities' models through the integration of different technological solutions, including biogas.

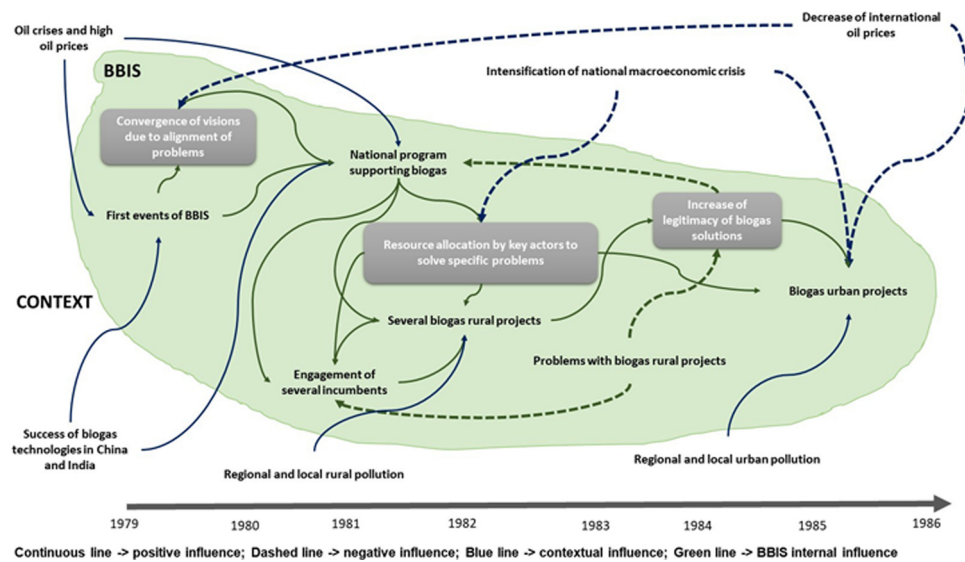


Fig. 5. Interaction of BBIS activities and their contexts for the first phase.

5.2. Biogas tumble (1986–2002)

This phase was marked by the great dismantling of basic BBIS structures due to the continuation of negative cycles present in the previous phase. At the international level, low oil prices continued. On the environmental front, during the whole period there was increasing legitimization of climate change problems. Important events, such as the Brundtland report (1987), the establishment of IPCC in 1988, the Rio de Janeiro Earth Summit in 1992 and to the Kyoto Protocol in 1997 strengthened the process of increasing legitimization for carbon emissions reduction. On the political economy front, the internationalisation of neoliberal policies converged to the standardisation of macro-economic policies.³⁵

Domestically, the period started with the continuation of macro-economic crises that lasted until the stabilisation of the Brazilian economy in 1994. Consequently, the main actors aborted most biogas activities. Only a few experiments were left, e.g. some urban biogas projects, particularly in landfills. However, by the beginning of 1990s these were also terminated. The only elements of the BBIS that remained were some isolated knowledge development projects.

With economic crises continuing throughout the period, by the end another economic crisis took place (1999); thus, the negative influence of macroeconomic conditions continued during this phase. Moreover, this phase also showed a very turbulent environment, when significant macro institutional changes occurred, namely changes from a dictatorship regime to a democracy (1985), the establishment of a new constitution (1988) and the opening of the economy (1990). Sectoral contexts also presented important institutional changes, following the liberalisation manual. The law of concessions (1995)³⁶ was an important policy for the institutional changes of several sectors, such as the liberalisation of the oil and power sectors and the creation of regulatory bodies (in 1996 for the power sector³⁷ and 1997 for the oil and natural gas sectors³⁸).

Industrial and innovation policies during this period were mostly based on a belief in liberalisation, leading to quick implementation of free-trade policy instruments and limited implementation of innovation

policy instruments such as coordination and support mechanisms [55]. Noteworthy events also occurred in the power sector: the deep crisis of the power sector in 2001, which was a consequence of the liberalisation processes and lack of planning [89]; the power sector R&D law enactment, which obliged power utilities to invest in energy efficiency and R&D projects (2000)³⁹; and the PROINFA programme (2002),⁴⁰ which is the main RES-E⁴¹ incentive program of Brazil [90].

In Brazil, other sectoral and geographic factors were also important. First, environmental laws and agricultural policies created the institutional contexts for the following phase.⁴² Second, by the end of the period, during a new economic crisis, the government acknowledged the need for further intervention and created important Science, Technology and Innovation (STI) policies such as the sectoral innovation funds (1999–2002) and a national programme to support incubators and technological parks (1998–2002) [55].

Third, there was continuous growth in population rates in the urban areas, from roughly 135 to 176 million, and urbanisation from 70% to 82% during that period.⁴³ In metropolitan areas, the huge concentration of population and resulting MSW led to conflicts between municipalities (e.g. in Rio de Janeiro state) as well as to important local and regional actions to improve waste management.⁴⁴ For sanitation systems, it also entailed the diffusion of UASB reactors. The expansion of Brazilian agriculture, in rural areas, entailed the need for better manure treatment and consequent local initiatives in which local and regional environmental bodies, together with rural development agencies and Embrapa, started to promote the use of dunghill lagoon schemes.

These factors combined provided the institutional environment, problematic situations and the availability of feedstocks for BBIS in the following phase. Therefore, the end of this phase brought to some extent the convergence of contextual problems similar to the beginning of the first phase: the Kyoto Protocol, with the possibility of using CDM resources, and the intensification of local and regional pollution problems, with consequent actions to mitigate them such as regional

³⁵ Particularly for Latin America, neoliberal policies were highly promoted by international organisations through the Washington Consensus [104] (for further discussion see [105]).

³⁶ http://www.planalto.gov.br/ccivil_03/leis/L8987cons.htm#art30.

³⁷ http://www.planalto.gov.br/ccivil_03/leis/L9427cons.htm.

³⁸ http://www.planalto.gov.br/ccivil_03/leis/L9433.htm.

³⁹ http://www.planalto.gov.br/ccivil_03/leis/L9991.htm.

⁴⁰ http://www.planalto.gov.br/ccivil_03/leis/2002/L10438.htm.

⁴¹ Renewable energy sources for electricity.

⁴² For example, http://www.planalto.gov.br/ccivil_03/leis/L7797.htm, http://www.planalto.gov.br/ccivil_03/leis/L7735.htm and http://www.planalto.gov.br/ccivil_03/leis/L9605.htm.

⁴³ http://seriesestatisticas.ibge.gov.br/lista_tema.aspx?op=0&no=10.

⁴⁴ The Bandeirantes Landfill initial actions and the promotion of dunghill lagoons for manure treatment date from the late 1990s.

environmental regulations and the diffusion of landfills and UASB reactors. Despite this, because there was no robust biogas activity within a turbulent macroeconomic environment, this phase could not produce a positive cycle of actions. In other words, projects were conducted as isolated actions and did not promote the engagement of actors during this period. Nonetheless, contextual events enabled the environment for another positive cycle of biogas activities.

5.3. The CDM era of biogas (2003–2011)

Once more, the convergence of contextual problems played out as the initial mechanism to activate the ‘dormant’ BBIS. Following the activities at the end of the previous phase, the increasing pressure for solving local and regional urban and rural pollution problems guided the actions of different actors towards better environmental management. Nationally, a series of CONAMA⁴⁵ resolutions provided the regulatory basis for water bodies and effluents, the use of sanitation sludge in agriculture, and the environmental licensing for sanitation facilities, as well as for small-scale agroindustries and landfills.⁴⁶ In urban areas, programmes of municipalities and states targeted the negative impact of waste dumps. In rural areas, the involvement of private companies, farmers and Embrapa aimed at the livestock manure problem.

Moreover, these local/regional problematic situations encountered a fertile environment in sectoral, national and international scenes. In 2003, the new Brazilian government initiated several sectoral institutional changes (presented in Table A1 in the Appendix). Important reforms were undertaken in STI, energy, bioenergy and sanitation policies. Later on in this phase, the promulgation of natural gas, climate change and waste management laws completed the large sectoral reforms during this period. Although one might assume this produced a turbulent environment, similar to what happened in the second phase, this was not the case.

New sectoral regulatory frameworks created a more propitious environment as they addressed important problems. For instance, in the new regulatory model of power sector introduced incentives for renewable and decentralised energy, and the sanitation policies provided important targets for system expansion. Additionally, the agricultural sectors in this period continued to show intense growth and expansion on international markets due to high commodities prices, the outcomes of intensive research and the diffusion of best practices. For sugarcane particularly, the introduction of flex-fuel cars boosted the ethanol market.

Two other factors made the environment more stable for biogas experimentation: the national macroeconomic and international contexts. During this period, macroeconomic conditions were relatively favourable⁴⁷ and constant economic growth was observed until the international crisis in 2008. After the slight recession in 2009, economic growth returned in 2010 and 2011. Internationally, validation of the Kyoto Protocol in 2005 boosted the market of CDM projects.⁴⁸ The latter became an interesting business model for biogas projects.⁴⁹ Thus, an increasing awareness for local/regional pollution problems, a relatively stable macroeconomic environment and the CDM instrument for mitigating GHG emissions characterised the process that reactivated the dormant BBIS by providing the *guidance of search*.

This process motivated the engagement of important players that foresaw financial return on investments with the trade of carbon

Table 2
Main Biogas Projects in Phase 3.

Project	Year	Trajectory	Main Business Model	Description
Ambev Project	2003	T2	Biogas with energy recovery	Biogas from industrial residues to promote energy efficiency
Nova Gerar landfill	2004	T4	Biogas burning	World's first registered CDM project
ETE Barueri	2004	T3	Biogas with energy recovery	Biogas recovery from sewage treatment
Sadia Sustainability Project	2004	T1	Biogas burning	Improvement of dunghill lagoons (mostly swine manure) to anaerobic lagoon with biogas recovery through CDM
Bandeirantes landfill	2006	T4	CDM	World's biggest CDM trade by the time
Start-up of Consórcio Verde project	2007	T2	Biogas with energy recovery	First activities of the project that would lead to important developments in the following phase
Itaipu biogas project	2008	T1	Biogas with energy recovery	Engaged small farmers and utilities for the swine manure treatment in the west of Paraná state
Geoenergética pilot projects	2004, 2008 and 2009	T2	Biogas with energy recovery	Aimed the biodigestion of residues of the sugarcane industry for large-scale power generation
Geoenergética commercial project	2011	T2	Biogas with energy recovery	Larger scale biogas project in the sugarcane sector

⁴⁵ National Environmental Council.

⁴⁶ Table A1, in the Appendix, presents these resolutions.

⁴⁷ However, Cassiolato [55] presented the appreciation of exchange rates, from 2006 onwards, as a negative effect.

⁴⁸ The relevance of Brazil for CDM projects is illustrated in [106].

⁴⁹ CDM allowed countries of Annex I (developed countries) investing in GHG mitigation projects in non-Annex I countries (developing countries) under specific conditions.

certificates and started to allocate resources to biogas CDM projects (see the main projects for this phase in Table 2). Municipalities led landfill projects while agroindustries promoted rural projects. Intermediary actors, such as consultancies, played important roles by providing knowledge on the business model and bureaucratic procedures. This model also attracted the interest of international players (technology suppliers and consultancies) for the Brazilian market, and they supported important learning processes by contributing with technological solutions (e.g. manure management systems and biogas treatment systems) and organisational and market solutions (how to develop CDM projects).⁵⁰

Projects that applied the CDM business model achieved high level of legitimacy at the beginning of the phase, mainly in trajectories T1 and T4. After the success of Nova Gerar and Bandeirantes landfills (capturing and burning landfill gas to mitigate methane emissions), several municipalities tried to set up similar projects to use the CDM resource to improve waste management conditions—trajectory T4. The Sadia Sustainability programme⁵¹ launched in 2004 promoted the improvement of dunghill lagoons (mostly swine manure) to anaerobic lagoons with biogas recovery through CDM—trajectory T1. This project influenced other food companies to take the same path, mainly in the states of Santa Catarina, Minas Gerais and Paraná.

In parallel, the biogas projects led by AMBEV (2003) were also important references to increase the legitimacy of biogas solutions—trajectory T2. They implemented biogas technologies into the industrial processes to increase energy and economic efficiency. Consequently, there was an increase in *entrepreneurial activities* with biogas solutions with two main business models: (i) anaerobic digestion mainly as an environmental treatment without energy recovery (biogas burning) and little technological development; and (ii) biogas recovery for power generation that required more efficient projects and technological adaptation.

In other words, the *resource allocation* at the beginning of the period resulted in successful projects, more knowledge about biogas solutions (important learning mechanism) and a *positive cycle for legitimacy*. For instance, the success of trajectory T4 projects led to the formation of an inter ministry committee to promote and diffuse this design. The same happened for projects in trajectory T1, which were supported by several state-level environmental bodies. This coupling of processes (alignment of contextual conditions, resource allocation, learning as consequence of projects and increased legitimacy) led to a second period within this phase where key players, such as the energy incumbents Itaipu, Copel, Sanepar, Sulgás and the new entrant Geoenergética, were responsible for carrying out other models of biogas projects (Fig. 6 presents the cycles and interactions for this phase).

The formalisation of the Itaipu biogas project led to the engagement of small farmers and utilities in swine manure treatment in the west of Paraná state. The presence of Itaipu, an important player of the power sector, and the creation of Itaipu Technological Park (2003) enabled the exploration of different types of innovations,⁵² promoted interaction with other agents and became one of the most known references of biogas projects in Brazil.⁵³ This project has achieved important institutional contributions as it was one of the first biogas DG projects to acquire authorisation from ANEEL (in 2008) for commercialisation. It

represented an improved type of project for trajectory T1.

Geoenergética's projects are directed at the sugarcane sector (trajectory T2). The projects focused on the biodigestion of residues of sugarcane industry for power generation in scales larger than the traditional international large-scale biogas projects. The company is also one of the few national players investing in technological development with its own R&D centre. Lastly, in this phase, the first activities of Consórcio Verde project started, which is a partnership of a cooperative of agriculture producers (Ecocitrus), a livestock industry (Naturóvos) company and a natural gas utility (Sulgás). In the following phase, this project would become the reference for biomethane production in the agricultural sector.

Once more, this engagement occurred because of sectoral contexts at local and regional levels. The Itaipu project promoted biogas technologies in alignment with state-level environmental regulation as a solution to the water pollution associated with swine production. The residues of swine production were deteriorating the water quality of the Itaipu hydropower reservoir. Reacting to the engagement of local players to improve manure treatment, Sulgás promoted the application of biogas technologies and producing biomethane. Besides, Geoenergética tried to couple with the development of the sugarcane industry. The commitment of these players entailed the development of new models for biogas projects other than the two mentioned above, and *knowledge production* about biogas solutions.

Meanwhile, a negative cycle of expectations also took place. First, the international crisis in 2008 changed the positive scenario of the international economy – particularly for Brazil due to the discontinuation of the boost on commodities prices – and deteriorated the international carbon market. Additionally, UNFCCC⁵⁴ changed the rules for CDM projects related to the treatment of swine manure (2006–2007). It discouraged projects purely based on burning of methane without energy recovery, which was the most diffused model by that time.

Other contextual factors, to a lesser extent, acted negatively. Although biogas technologies achieved certain legitimacy, this was restricted to upstream sectors. Even in these sectors, biogas technologies were not at the centre of high-level discussions. One important illustration is the set of measures to promote agroenergy. These measures deliberately focused on bioethanol and biodiesel and not on biogas. As interviewee R3 said: 'In 2004, 2005 what was understood as agroenergy was basically biodiesel, sugarcane was already important, and both got many incentives'. This situation explains the virtual absence of institutionalisation of the biogas sector during this period.

Along with these contextual issues, technical problems and unrealistic expectations with biogas projects undermined their legitimacy. For instance, Querol et al. [20], analysing the Sadia Sustainability Programme, pointed out that the different expectations through the different levels of biogas projects combined with the poor capability of farmers to operate and maintain biodigesters led to frustration of farmers and companies in rural areas. This situation was rather similar to what happened in the first phase, with the diffusion of inefficient projects combined with the lack of skills to design and operate biogas plants and low level of institutionalisation. Thus, the combination of contextual negative pressure and decreasing internal legitimacy negatively affected the resource allocation and development of new projects.

Nonetheless, differently from the first phase, the development of different models of biogas projects, exemplified by the projects of Itaipu, caused a second learning process. This learning process combined with the favourable national economic situation and sectoral institutional structures, along with the engagement of important players, maintained the BBIS structures. This would produce a positive cycle at the beginning of the next phase.

⁵⁰ See [107,108] for specific analyses of technology transfers.

⁵¹ See [109] for in-depth analysis.

⁵² Itaipu Technological Park has different technological projects, such as biogas, solar PV and electric vehicle technologies. It can be understood as a contextual influence as the technological park was a consequence of STI policies.

⁵³ With the same motivation, local water pollution by swine production, players in Paraná developed a different type of biogas solution for small farmers, the so-called 'agroenergy condominium' [110]. This scheme comprises small properties that produce biogas in a decentralised way and then transport it through low-pressure pipelines to a central point.

⁵⁴ United Nations Framework Convention on Climate Change.

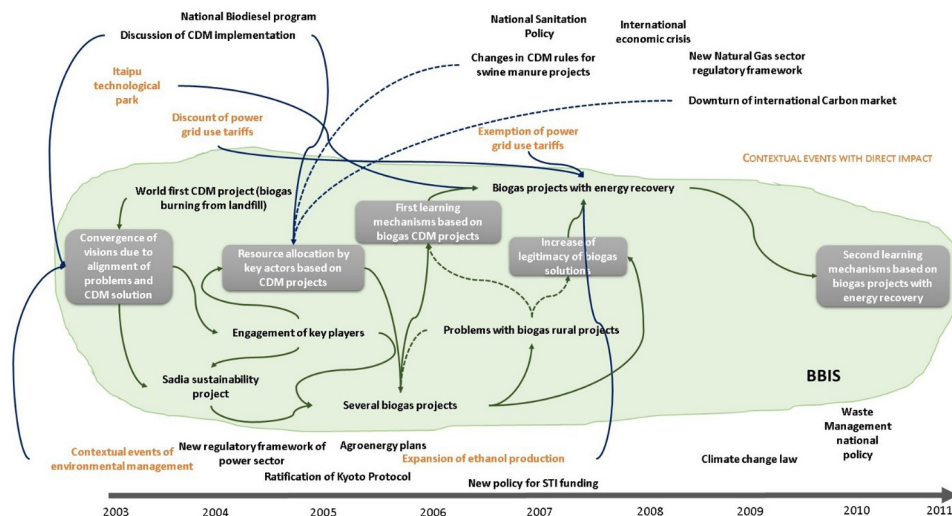


Fig. 6. Interaction of BBIS activities and their contexts for the third phase.

5.4. Structuring the biogas field (2012–2016)

The beginning of this phase once more started with important contextual events. In the power sector, ANEEL implemented, in 2012, the rules for micro- and mini-DG, establishing a net metering scheme.⁵⁵ Two revisions have occurred since 2012.⁵⁶ The first had limited schemes of virtual net metering⁵⁷ to avoid state-level taxation and the second expands the allowed installed capacity, enabling the virtual net metering schemes again in 2016.⁵⁸ Then, because of high dependence of hydropower,⁵⁹ the low rainfall led to a period of high electricity prices moderated only by the downturn of Brazilian economy by the end of 2015. Meanwhile, by the end of the period, a new national programme was established to promote DG in 2016, the PRO-GD programme.⁶⁰

The agricultural sectors continued to thrive mainly because agricultural commodities sustained their high price levels. Furthermore, the national climate change law led to significant events in the agricultural sector, mainly the low-carbon agriculture plan in 2012⁶¹ in which manure treatment was one of the seven main target actions. Particularly for the case of biogas, the international installed capacity of biogas plants experienced intense growth during this period, with Germany leading the world development of the technology,⁶² which would increase the relevance of German players.

In parallel, from the end of the previous phase, the learning processes yielded important structuration for the BBIS. This phase showed a more intense institutional evolution compared with previous periods. The states of São Paulo and Rio de Janeiro were the first two to settle biogas-specific policies, both in 2012. The policies were a consequence of distinct contexts and projects. Whereas in São Paulo the huge potential of biogas in sugarcane industry was the main driver, Rio de Janeiro focused on landfill potential. In the following year, the

partnership between the Brazilian and German governments, through the Brazilian ministry of the cities and the German international co-operation agency (GIZ), started the National Programme of Biogas (PROBIOGÁS). The main objectives were to promote interaction, diffusion of information and support best-case projects.

Meanwhile, as a consequence of the entrance of important biogas players who emerged at the end of the previous phase and developed important projects,⁶³ new intermediary actors and networks appeared. The creation of the international centre of biogas (CIBiogás) in 2012, located in the state of Paraná, was the result of many interactions that happened in the region and supported mainly by Itaipu. Its main goal is the professionalisation of the biogas sector through the diffusion of information and standardisation (laboratories, projects, etc.). Additionally, the creation of two biogas associations, ABiogás (December 2013) and ABBM (January 2014), represented an important step towards more integration and interaction in the sector.⁶⁴

Likewise, for networks, the Strategic R&D biogas project, promoted by ANEEL (2012) and supported by GIZ, intended to apply the R&D resources of the power sector to develop replicable commercial models of biogas projects. It promoted the interaction of different agents from different sectors, even though the results were somewhat lower than expected.⁶⁵ Then, the launching of BiogasFerti, research network for biofertiliser, led by Itaipu and Embrapa, aimed at developing knowledge and models to improve the value of the 'digestate'. The relevance of the digestate was evidenced by its inclusion in the discussions of a Ministry of Environment's task group (2016) that aimed to propose a new regulation on the usage of organic matter as fertilizer. In addition, the ABBM proposed the creation of NPDs (decentralised Research and Development centres) to promote an increase in university–industry interactions; however, it is still newly emerging and with few experiences.

⁵⁵ <http://www2.aneel.gov.br/cedoc/ren2012482.pdf>.

⁵⁶ <http://www2.aneel.gov.br/cedoc/ren2012517.pdf> and <http://www2.aneel.gov.br/cedoc/ren2015687.pdf>.

⁵⁷ Possibility to allocate energy credits to other power meters (see <http://www.cpuc.ca.gov/general.aspx?id=5408>).

⁵⁸ The second revision came up as consequence of many different lobbies and the waiver of added-value tax by many important states.

⁵⁹ Hydropower comprises 70% of power generation installed capacity in Brazil.

⁶⁰ <http://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?jornal=1&pagina=96&data=16/12/2015>.

⁶¹ <http://www.agricultura.gov.br/desenvolvimento-sustentavel/plano-abc>.

⁶² <http://european-biogas.eu/2015/12/16/biogasreport2015/>.

⁶³ Projects such as the large-scale biodigester of Geoenergética, Dois Arcos Landfill of Ecometano and Consórcio Verde project were cited many times during the interviews.

⁶⁴ ABiogás congregates the big players of the sector and aims at the creation of a national agenda for biogas, whereas ABBM is more locally oriented and gathers professionals and researchers with the aim to create a critical mass to spark innovation.

⁶⁵ While some interviewees were very critical of the programme (they said there was no strategic vision aligned to Brazilian reality), others realised the relevance for promoting interactions and allocating resources. However, the majority of the interviewees agreed that the outcomes are and will be lower than initial expectations.

These chains of events illustrate the structuration of the BBIS. The expansion of networks tried to influence high-level decision-makers, promoted institutional development and produced information about biogas potential, types of projects, technologies, services and policy advices. Consequently, these activities fulfilled the *guidance for search* and the *legitimacy* of biogas activities. Therefore, biogas players started to counterbalance contextual influences for the first time in Brazil. Pragmatically, the organisation of biogas players has led to several outcomes.

First, important institutional development for biogas at the national level in the natural gas sector. In 2015, because of interactions with different players,⁶⁶ the ANP established the regulation for the specification of biomethane fuel,⁶⁷ filling in an important gap for biomethane commercialisation. However, this regulation restricted the trade of biomethane from urban substrates due to the issue of measurement of siloxanes content.⁶⁸ In 2017, this controversy was solved through the publication of a specific regulation for biomethane from urban substrates.⁶⁹

Moreover, the biogas-specific policy proposal [14] and a series of technical publications by PROBIOGÁS can be also understood as the results of such a sectoral organisation of biogas players. This organisation has also influenced institutional development. Other states have recently established biogas policies, such as Rio Grande do Sul (2016),⁷⁰ or are in the process of establishing them, such as the case of Santa Catarina, whereas some relied on renewable energy promotion policies such as the states of Paraná, Minas Gerais and Pernambuco.

Thus, these new system elements (intermediary organisations, networks and institutions) stimulated *knowledge diffusion* processes. As said by one interviewee (Fin1), *'previously, biogas was only a word, without meaning. Nowadays, it is so much easier to talk to utilities and governmental bodies about biogas, they know minimally about the process, possibilities and benefits'*. Intermediary players and networks developed actions from knowledge diffusion of small rural biogas projects to the creation and presentation of policy proposals for national governmental bodies.

Besides, both *entrepreneurial* and *research activities* were more assertive for BBIS-specific problems; they addressed specific struggle points of biogas field and were the result of many interactions and important projects.⁷¹ It means that although new projects were not the main developments in this phase, important projects, such as the Caieras landfill that is the largest conversion plant, were relevant for the legitimacy of biogas field.

Nevertheless, this phase presented hurdles as well. First, although the international economy presented slight improvements in this period, the level of mineral commodities prices remained low. The great difference happened in the oil markets, which faced a huge decline in the prices from 2014 onwards. This situation, combined with the aggravation of economic and political crises in Brazil, created a very turbulent environment by the end of the period. The Brazilian economy

started to slow down until the severe recession in 2015 and 2016.

This macroeconomic situation negatively affected the sectoral contexts in two ways. It reduced the demand of energy sectors, restricting the markets and, consequently, diminished the resource allocation by important incumbent players, e.g. utilities. For instance, in the natural gas sector, the reduction of industrial activity slowed down the expansion of natural markets as well as the need for alternative gas supply. As one interviewee (Ut2) said: *'it is very challenging to justify new biogas projects to the board when the market is limited'*. A similar situation occurred in the power sector, leading to an important unbalance of financial conditions of the utilities.

Moreover, specific sectoral issues also played against investment in innovations. For the power sector, the success of wind energy in national auctions set a new low level for power generation prices, undermining competition from other sources. For the sanitation sectors, the possibility to invest in the expansion of infrastructure also decreased, reducing the level of investments for biogas projects. At last, this environment of crises affected regional governments,⁷² which experienced serious economic issues by the end of the period. These regional governments were responsible for the biogas-specific policies in the beginning of the period and for the few market creation mechanisms in place.

In addition, biogas-specific issues complemented these negative influences. Although this was a period of increasing legitimacy of biogas technologies and opening up of markets, as the power market with the net metering scheme, there were few new projects. This fact limited further knowledge production and cost reduction. Once more, an important exception was the launching of *Termoverde Caieras* project, which the biggest power landfill power plant in Brazil. The improvement of knowledge exchange over biogas solutions was not sufficient to solve important problems such as the lack of information by potential users of biogas technologies (including public decision-makers). Players continued to struggle to identify replicable business models and partnerships. This struggle led to the limited market creation mechanisms, negatively reinforcing the few numbers of new projects.

Here, financial and funding conditions were major issues. For rural projects, low-carbon agriculture funding lines have well attended the demand for small projects according to interviewees. Large-scale projects have the possibility of using existent funding lines, mainly from BNDES⁷³ and FINEP.⁷⁴ However, biogas players faced many difficulties to access them, specifically due to financial guarantees. In addition, the low level of technological development sustained the need for importation of technologies, which maintains the high project costs.

Another important issue was the lack of coordination of institutional development. The most representative case was the biomethane regulation that restricted the use of biomethane from urban substrates and impaired state-level policy of Rio de Janeiro.⁷⁵ This contest over the urban biomethane hindered resource allocation and the implementation of market creation mechanisms. What is more, although PROBIOGÁS promoted knowledge exchange among some organisations and high-level national governmental bodies, biogas-specific issues were still too restricted to state-level agendas. This was mostly a consequence of more difficult interactions among sectoral players at higher levels associated with the different frames they had to biogas issues. As PROBIOGÁS, which turned out to be an important development point,

⁶⁶ Particularly, because of the success of Consórcio Verde Project and discussions with Sulgás, Natural Gas utility of Rio Grande do Sul state.

⁶⁷ <http://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=02/02/2015&jornal=1&pagina=100&totalArquivos=156>.

⁶⁸ These projects could be developed only on an experimental basis or for self-consumption.

⁶⁹ <http://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=30/06/2017&jornal=1&pagina=69&totalArquivos=272>.

⁷⁰ http://www.al.rs.gov.br/legis/M010/M0100099.ASP?Hid_Tipo=TEXTO&Hid_TodasNormas=63057&hTexto=&Hid_IDNorma=63057 as a consequence of Consórcio Verde project and Sulgás participation.

⁷¹ PROBIOGÁS could bring the biogas discussion to the high level of ministries, even though the ministry of energy has still very little influence, whereas CIBiogás and associations could cultivate and promote new networks, new standardisation projects and more lobbying activities. In addition, intermediary players promoted many interactions with international players, from specific projects in Brazil to visits to biogas plants in European countries.

⁷² Important states for biogas projects, such as Rio de Janeiro, Rio Grande do Sul, Paraná and São Paulo.

⁷³ Brazilian Economic and Social Development Bank.

⁷⁴ Funding Agency for Research and Innovation.

⁷⁵ The renewable natural gas (RNG) policy of the state of Rio de Janeiro, which establishes that RNG should supply 10% of the natural gas market excluding thermal plants, could not deliver due to lack of regulation of biomethane from urban substrates by the ANP regulation.

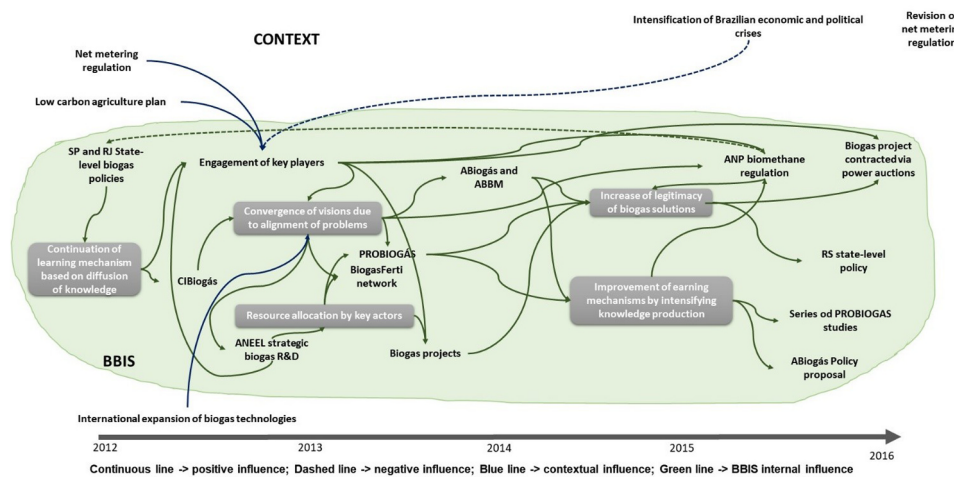


Fig. 7. Interaction of BBIS activities and their contexts for the fourth phase.

ended in 2017 other forms of interaction with high level national bodies must be implemented. The proposal of *RenovaBio* policy, with initial discussion from the end of 2016, is seen as one of the ways to provide important resource allocation and room for interactions.

In summary, this phase presented important structural development of the BBIS and, for the first time, biogas players had an important role in influencing the direction of BBIS development. However, the turn in contextual conditions, particularly in the macroeconomic arena, and the permanency of uncoordinated activities in the BBIS's activities pose important struggles for further development of the field. The picture below presents the cycle of processes discussed above. (Fig. 7).

6. Discussion and future perspectives

The findings indicated four phases of development for biogas technologies in Brazil which showed a tortuous trajectory due to both endogenous and exogenous conditions. The first three phases were influenced mostly by exogenous conditions, such as sectoral institutions, geographic availability of resources and key national and international events. Biogas players were mostly reactive to contextual pressures. This does not undermine the role of biogas-specific conditions (e.g. the development of inefficient projects in the third phase). It only emphasises the need for attention to contextual background conditions. The last phase, in contrast, showed a more substantial influence of BBIS players because of more assertive activities related to knowledge diffusion and production. The articulation of intermediary structures (e.g. biogas associations) and guided activities for production and diffusion of knowledge (e.g. the series of studies of PROBIOGÁS, CIBiogás, the policy proposal and biomethane regulation) led to a more intensive institutionalisation.

In the first phase, the initiation of biogas activities in Brazil occurred because of the oil crises and the resulting pressure to develop alternative energies. Additionally, the alignment of local sanitation problems with the successful international expansion of biogas projects triggered the promotion of biogas technologies as one of the alternative energies. Although important experimentation occurred, the absence of a regulatory framework for biogas projects and technological limitations to trade biogas energies resulted in difficulties to capture value with biogas energies and the development of inefficient projects respectively. The biogas field had virtually no formal institutionalisation and suffered from lack of trust due to inefficient projects. Consequently, changes in contextual conditions hardly affected it.

These adverse contextual conditions, deep economic crises and political reforms, lasted through most of the second phase, creating a very turbulent environment for any new experimentation. After a

period of very little activity, a convergence of contextual conditions similar to those in the first phase brought biogas activities back for the third phase. Sanitation systems to treat residues and waste continued to be a problem, but CDM provided a convenient and feasible business model that was an important source of financial resources. Other contextual influences were crucial, viz. the institutional reforms in key sectors like energy and the huge expansion of agricultural commodities and investments in sanitation.

The reforms enabled the trade of biogas energies, a downstream condition in the value chain that did not exist in the 1st phase. The expansion of agricultural production and sanitation systems provided the environment for investment expansion on the upstream side of the biogas value chain. For example, the expansion of UASB and landfill systems caused biogas technologies to be considered in the sanitation sector. The expansion of swine and ethanol production intensified the search for solutions to treat manure and vinasse, and the regulation of distributed generation in the power sector allowed new business models to emerge. Therefore, the biogas field started to develop its own critical mass of projects and actors. However, the international financial crisis and the drop of carbon prices questioned the main business model based in CDM projects.

The most relevant development of biogas field occurred in the latest phase. São Paulo and Rio de Janeiro states enacted biogas-specific policies. Important stakeholders created two industry associations, one research centre and one formal RD&I network. Moreover, national initiatives to promote biogas knowledge and projects (PROBIOGÁS and strategic R&D call ANEEL) were launched. This series of initiatives increased momentum, which spread to other important activities, such as the regulation of biomethane by ANP and the promotion of biogas projects in national power auctions.

However, the different visions and logics of contextual players created divergences. In the case of biomethane regulation, this was a temporal mismatch. The initial biomethane regulation allowed agricultural residues only. This fact counteracted the promotion initiatives that relied on MSW substrates, such as the Rio de Janeiro policy. For the power auctions, modelling biogas sources with the same criteria used for centralised sources led to little participation of biogas projects in these auctions due to modelling specifications.

These events occurred in a relatively calm environment. The upcoming political crisis of 2013 and the intensification of economic crisis from 2014 onward posed threats that were similar to those observed at the end of the first phase. Therefore, although it was observed as an important evolution of the biogas field in the last phase, the contextual background conditions had a strong negative effect on the development of biogas projects and new policies.

6.1. Insights for contextual influences on Technological Innovation Systems

The outcomes of our investigations provided important insights for understanding contextual influences on TIS studies because they demonstrated how the interaction of different types of contexts enabled or constrained activities in the BBIS. The study suggested distinct forms of contextual influences: (i) evolution of contexts affecting TIS; (ii) interaction of contexts providing certain conditions for TIS activities; and (iii) the interactions of contexts playing out as translators of external events to conditions of TIS activities.

First, sectoral institutional frameworks changed enormously during the period analysed. Since the biogas value chains are cross-sectoral, they brought into the BBIS important structural elements from sectors. This fact is illustrated in our study by the regulations for decentralised electricity and fuels trade, and the expansion of infrastructural and production systems in the agriculture and sanitation sectors. The evolution of institutional frameworks has also influenced conditions for project development, market creation and resource allocation activities. As discussed in Section 5, energy sectors have dedicated R&D resources and were responsible for the most significant market creation mechanisms for biogas technologies. Additionally, the role of utilities and agricultural companies in developing projects was crucial. This first type of contextual influence is aligned with the hypothesis of spatially sticky TIS [91], which states the higher relevance of local knowledge and markets.

Second, interactions of contexts yielded conditions for the development of BBIS activities. They provided positive background conditions when there was a convergence of contextual influences on downstream and upstream sides of the biogas value chains. For example, convergence of the increasing awareness of sanitation problems and high energy costs was an important driver for biogas activities. Put differently, contextual activities fulfilled the guidance of search process. Also, the convergence of the expansion of energy, sanitation and agricultural systems enabled the development of resource allocation for biogas projects. The evolution of environmental, climate and energy regulations created market opportunities for biogas projects and increased the legitimacy of biogas technologies.

However, these interactions also caused some difficulties. Actors possess distinct types of sectoral knowledge which affected how they dealt with different possibilities of biogas projects. Actors from different sectors had quite different visions and expectations about biogas technologies, which undermined development of common actions and knowledge exchange, maintaining these different visions on biogas. In addition, the contextual structures evolved at different rates. This led to a mismatch in timing and undermined project development, market creation and legitimacy of the technology, as observed in the last phase. These first two types of contextual influences relate more to what TIS literature names structural couplings.

Third, the last type of contextual influence relates to how interactions of contextual structures translated external links – events distant from TIS – to specific conditions that affected activities in the BBIS. Two main patterns were observed. Initially, there was a clear impact of negative macroeconomic conditions on resource allocation of key players. As consequence of several crises and adverse macroeconomic conditions, private actors retracted their investments and governmental agencies implemented budget cuts. These reductions of investments and budget cuts varied according to sectoral and regional embeddedness of actors. This movements occurred mainly at the end of first and last phases.

Moreover, findings demonstrated that external events intensified the perception of problems or solutions according to local realities affecting orientation of activities, resource allocation and legitimacy. The oil crises in the 1970s, the Kyoto Protocol and CDM discussions are good examples of such external events. The oil crises were responsible for the perceived intensification of the oil dependence problem and consequent triggered the search for solving it. The climate discussions

enabled biogas technologies to be viewed as a feasible solution for sanitation problems, and the CDM increased legitimacy and provided resources for biogas activities.

6.2. Practical implications of this study

Pragmatically this study proposes a framework for studying the contextual influences in TIS studies. This is done by applying the conceptualisation of technology as a bundle of value chains [38] into the TIS framework [30], taking into consideration the suggestions of including contextual aspects [33]. Hence, analysts can go beyond the ad-hoc definition of contextual influences and can explicitly identify and explain how activities and actors convey contextual influences into an emerging TIS. It improves the usage of TIS framework to inform the relationship between actors' behaviours, system conditions and external contexts. This framework enables to investigate the influences of different contexts such as geographic factors, sectoral infrastructures and national macroeconomic conditions.

For new renewable energy technological fields, this more detailed information can be particularly useful for both recommending strategic actions and for monitoring these actions. This is more visible for situations in which contexts play a more relevant role, such as conditions of developing countries [e.g. 35,36,49,92] and the case of renewable energy technologies that presents different types of contextual embeddedness [91]. The explanation of how actors engage in activities to bring in contextual influences into the development of new technologies provides knowledge of which actors are involved, for specific contexts and activity of field development. Moreover, after the description of these activities, it seems possible to use them to monitor and evaluate interventions. Therefore, analysts can discuss interventions not only for public policy but also or firm strategies. For example, the suggested patterns of contextual influences may lead to specific strategies depending on actors' positions.

Naturally, this research presents limitations that lead to future analyses. For tailor-made recommendations, it is still necessary to specify the main mechanisms that hamper continuity of positive cycles of TIS development. In other words, it is necessary to describe the exact activities by which a TIS problems, exogenous problems and interactions among them hamper the technological field. Additionally, for firms' strategy recommendations it seems necessary to deepen the understanding of organisational processes, while for policy recommendations seems necessary to understand the political structure and policy processes [93,94]. For instance, although this analysis improves the understanding about the conditions for successful development of biogas in Brazil, it is still necessary to examine how these conditions manifest themselves into specific problems and their interplay with policy mixes and organisational strategies.

Furthermore, our analysis is limited to understanding the conditions of our boundary definition: biogas technologies at national level. For specific regional policies or for interactions of regional and national policies, this analysis must be performed for local/regional conditions. Finally, the suggested types of contextual influences must be further researched. It is necessary to explore other cases with different conditions as well as to compare these cases. Distinct conditions to investigate can be defined according to the innovation and valuation modes as in [91] or/and conditions of countries in global south and north [11,95,96].

7. Conclusions

This study investigated the history of biogas technologies in Brazil by applying the TIS framework while accounting for biogas-specific and context-related influences. It is the first systematic historical investigation of biogas activities in Brazil, which comprehensively covered 37 years. It is also one of the first attempts to include systematic analysis of contextual influences in TIS framework. Thus, this research

explained the conditions in which biogas technologies thrived or dwindled, as well as proposed an analytical framework and patterns of contextual influences for TIS studies.

The explanation of how distinct set of sectoral and geographic conditions as well as specific events influenced the development of biogas field in Brazil goes beyond common analysis of barriers for renewable energies. It provides a comprehensive description of how Brazilian contextual conditions and actions of biogas players enabled or constrained biogas field development. Therefore, it opens a new avenue for private and policy actions for biogas in Brazil by shedding light on the need to recognise patterns of contextual influences. For instance, these findings may enlighten policy recommendations by focusing on contexts such as alignment and interaction of the macroeconomic and sectoral conditions, or by focusing on biogas-specific issues such as low number of new projects, lack of market creation mechanisms and few institutional developments.

For TIS studies, our research presented a framework for examining TIS structural–functional conditions subject to contextual influences. By employing the ‘bundle of value chains’ [38] perspective of technologies, instead of an ad hoc selection and description of contexts, the identification of the contexts that really mattered for the case was possible. Then, the specification of events, by including the search for agents, sectors, locality, motivations and resources, enabled to recognise the activities and their background conditions which explained contextual influences. Hence, this study went beyond a common structural–functional analysis focused only on endogenous conditions by incorporating

exogenous conditions in the mechanisms of structuration and functional fulfilment of the BBIS.

Moreover, the empirical findings suggest important insights for TIS studies by going back to the discussion of TIS embeddedness in other structures like innovation systems or socio-technical structures [28,29,45,46]. The contextual conditions were demonstrated through the evolution of contextual structures, the interaction of contextual structures, and by the translation of external conditions by these interactions. Therefore, the mapping of contextual influences through the identification of specific activities – accounting for conditions and entities – that fulfil system processes seems very suitable to explain the role of structural couplings as a promising way of improving TIS analyses.

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Declarations of interest

None.

Appendix

See Table A1 here.

Table A1
Sectoral institutional changes for the third phase.

Policy or program	Year	Description	Source
Innovation law	2004	It aimed to promote innovation by creating a propitious environment, by stimulating interactions and by stimulating innovation in companies	http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/110.973.htm
Power sector reform	2004	It introduced the scheme of national power auctions for expanding the generation and transmission capacity, new rules for trading electricity and new institutional actors	http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/110.848.htm
Incentives for renewable energy in power sector	2004	It enacted trade incentives for renewable electricity in 2004, under which renewable energy resources have partial exemption of grid-use tariffs according to the source	http://www2.aneel.gov.br/cedoc/ren2004077.pdf
Public-Private Partnerships law	2004	It regulated the Public-Private Partnerships.	http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/111079.htm
National agroenergy plans	2004–2005	Defined the main guidelines for agroenergy in Brazil (mainly focused on bioethanol and biodiesel).	https://docsagencia.cnptia.embrapa.br/cana/AGROENERGIA.pdf and http://www.agricultura.gov.br/arq_editor/file/Desenvolvimento_Sustentavel/Agroenergia/Programas/PNA%20-%202ed%20portugu%C3%AAs.pdf
National Biodiesel Program (PNPB)	2005	It defined the main guidelines for the promotion of biodiesel production and use	http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2005/Lei/L11097.htm
National law for federative consortiums	2005	It regulated the consortiums between federative entities.	http://www.planalto.gov.br/ccivil_03/_Ato2004-2006/2005/Lei/L11107.htm
Social label law	2005	It promotes via fiscal and financing incentives the purchase of biodiesel from small producers	http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/decreto/d5297.htm
"Law of Good"	2005	It regulated the fiscal incentives for investing in innovation	https://www.planalto.gov.br/ccivil_03/_Ato2004-2006/2005/Lei/L11196.htm
Embrapa Agroenergy creation	2006	It created a specific subsidiary of Embrapa to research agroenergy topics	https://www.embrapa.br/agroenergia/historia
CONAMA Resolution 357	2005	Rules for classifying water bodies and the conditions and standards for the discharge of effluents	http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=459

(continued on next page)

Table A1 (continued)

Policy or program	Year	Description	Source
CONAMA Resolution 375	2006	Rules for agricultural use of sludge from sanitation	http://www2.mma.gov.br/port/conama/res/res06/res37506.pdf
CONAMA Resolution 377	2006	Simplified environmental licensing for sanitation	http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=507
CONAMA Resolution 385	2006	Environmental licensing rules for small-scale agroindustries	http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=523
CONAMA Resolution 404	2008	Environmental licensing rules for small-scale landfills	http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=592
Expansion of power sector incentives for renewable energy	2007	It has expanded the 2004 regulation to total exemption of grid-use tariffs for renewable power from residues.	http://www2.aneel.gov.br/cedoc/ren2007271.pdf
National Policy of Basic Sanitation (PNSB)	2007	It has created the institutional framework for sanitation activities, including the main services and principles, obligations of service providers, the shared governance structure between all the federative entities. The universalization of services was included as main target for sanitation services planning.	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2007/lei/111445.htm
Restructuration of STI sectoral funds	2007	It changed the governance of STI sectoral funds	http://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2007/Lei/L11540.htm
National Policy of Climate Change (PNMC)	2009	It institutionalized the climate change field in Brazil, with voluntary targets for mitigation of greenhouse gases emissions and defining five sectoral mitigation plans, including energy and agriculture sectors	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/112187.htm
Natural gas sector law	2009	It has emulated power sector regulatory framework with free-markets environment and similar classification of players, attempting to stimulate the expansion of natural gas grids.	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/111909.htm
National Policy of Waste Management (PNRS)	2010	It has created the regulatory framework for waste management services, with two relevant modifications: the permission for landfills as last option and the obligation of dumps extinction by the year of 2014.	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/112305.htm

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