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Explaining the diffusion of biogas in India: a new functional approach considering national borders and technology transfer

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Abstract Renewable energy technologies have been identified as one important lever for mitigating environmental problems such as climate change. However, several obstacles stand in the way of their ample diffusion in both industrialized as well as developing countries. Besides the pure analyses of barriers to the diffusion of these technologies, the functions of innovation systems approach promises insights on how to augment their diffusion via policy measures. We extend these approaches by introducing a spatial dimension into the functions literature. Thereby, we allow transfer of technology, know-how and financial resources to be an integral part of the innovation system literature. By applying our new framework to the case of biogas in India, we do not only demonstrate its suitability and added value for researchers, but also derive policy recommendations for both, national and international policy makers on how to remove existing barriers by strengthening the functions of the innovation system.

Keywords Technological innovation system · Functions · Technology transfer · Biogas · India

JEL Classification B52 · O33 · O38 · Q42 · Q48 · Q55 · Q56

1 Introduction

Climate change represents a challenge to mankind which has large parts to be addressed by technological change (Pizer and Popp 2008). As the majority of anthropogenic greenhouse gas (GHG) emissions stems from the furnace of fuel

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(IPCC 2007a), renewable energy technologies (RET) are identified as one lever to decarbonise the economy (IEA 2010). Their ample diffusion is particularly instrumental in developing countries for three reasons. First, these countries have highly growing energy demands (IEA 2008); second, their untapped potentials of renewables are often higher than those of OECD countries (Peters et al. 2011; Schmidt et al. 2012); and third, RET often provide higher development dividends on the social and economic dimension than conventional energy technologies (Sutter and Parreño 2007).

Biogas is a technology which yields higher climate change mitigation potential than most other RET as it is based on the destruction of methane[1] (for an overview of different biogas technologies, see e.g. Kossmann et al. 2000; Singh and Pandey 2009). Therefore, this technology also profits more from international climate policy mechanisms such as the Kyoto protocol's clean development mechanism (CDM) than other RET (Schneider et al. 2010). Yet, also for biogas high untapped potential remains due to barriers which are not adequately addressed by current (climate) policy. A good example is provided by India.

India has a national program on household biogas since 1982. More than four million family size plants have been installed by 2010 (Tripathi 2010); however, India has woken up rather late to the potential other uses of biogas through the use of large-size plants (>100 m^3 digester size). Family-size biogas plants (2–4 m^3 digester size) allow for use of biogas only as a heat source at the household level. On the other hand, large-size biogas plants allow for upgrading of biogas to natural gas quality levels, which can replace natural gas from almost all its uses like powering gas engines for generating electricity, or for running motor vehicles. The slurry produced after digestion can be used directly as valuable fertilizer (Ravindranath and Balachandra 2009). Only a fraction of the country's potential has been tapped in spite of several governmental efforts to accelerate the development of waste-to-energy (WTE) projects using biomethanation.[2] Furthermore, no study has been done on the biogas potential from agricultural waste (including cattle-dung). To put into perspective India has the largest cattle population in the world (Ministry of Agriculture 2003). In contrast, e.g. Germany has had good success in the diffusion of biomass digestion. The biogas plants in Germany, with a total installed capacity of approximately 1400 MWe, produced 10 TWh of electricity in 2008, which accounted for about 1.6 % of the total demand (Poeschl et al. 2010).

Barriers to the diffusion of renewable energy technologies have been studied on various levels, ranging from a general discussion (Painuly 2001; Reddy and Painuly 2004) to a discussion specific to diffusion of bioenergy in India (Balachandra et al. 2010; Bhatia 1990; Jagadeesh 2000; Ravindranath and Balachandra 2009). However, there is no specific literature on diffusion of large-size biogas plants in India. While the literature on barriers is definitely helpful to explain the diffusion of

[1] The global warming potential of methane is 21 times higher than that of carbon dioxide (IPCC 2007b).

[2] Against an estimated biogas potential of 2448 MWe (in 2007) from urban wastes and 1276 MWe (in 2007) from industrial wastes (MWH 2006a), only 43 MWe have been harnessed (MNRE 2006) by the end of 2006.

a technology—or rather its absence—it has only a limited potential for deriving more systemic policy recommendations and hence, represents the first step only. Authors argue that to understand the successful or unsuccessful process of technology diffusion, more systemic approaches have to be applied (Edquist et al. 2005).

To this end, the "innovation system" approach can deliver important contributions (ibid.). Since our case study focuses on one specific technology, analyzing the innovation system along the 'technological dimension' is most suited. The analysis of the technological innovation system (TIS) has generally tended to focus on perceived weaknesses in the structural composition of the system, making it difficult to evaluate the "goodness" or "badness" of the TIS elements without referring to its effects on the innovation process (Bergek et al. 2008a). Contrarily, the functions of innovation system (FIS) approach is "very helpful in tracing the performance of a TIS" (Musiolik and Markard 2011, p. 1910) as it describes the well- and malfunctioning of the system. By analyzing weaknesses in the functional pattern of the TIS, i.e. "what is actually going on in the TIS" (Bergek et al. 2008a, p. 410), we can identify the key blocking mechanisms that, in turn, lead us to a specification of the relevant policy issues (Wieczorek and Hekkert 2012).

However, current studies based on the FIS approach have a shortcoming. While FIS scholars base their approach on the 'knowledge dimension' for the innovation system, their empirical cases till now have focused on specific geographies, mainly one single country (e.g. Musiolik and Markard 2011; Suurs et al. 2009). The spatial dimension is, however, not reflected in their theoretical frameworks, neglecting the role of national boarders and international technology transfer. Very recently, other authors also have criticized this neglect of the spatial dimension. Coenen et al. (2012) argue that the neglect of geographical factors in sustainability transition analyses has resulted in the undesirable effect of reducing comparability between places and emphasizing the particular rather than the general features of each case. Though innovation systems have become more international, the importance of the national institutions remains (Carlsson 2006). Hence, we develop a framework which explicitly distinguishes the national and international components of the TIS and takes into account the role of technology transfer. This framework is applied to the diffusion of large-size biogas plants in India to address the overarching question, how well does the national and international technological innovation system for large-size biogas function in India. Answering this research question allows for deriving policy recommendations on how to improve the functioning of the TIS and thereby increase the rate of diffusion of the concerned technology.

To this end, we proceed in three steps. First, we identify the major barriers to the diffusion of large-size biogas plants in India. Second, we analyze to what extent and how the functioning of the technological innovation system was able to remove these barriers. And third, we focus on the functions provided by the international part of the TIS and its role in the barrier removal.

The paper is structured as follows: we develop our theoretical framework in Sect. 2. While Sect. 3 explains the methodologies applied, Sect. 4 presents the results. In Sect. 5 we discuss our results and their policy implications before we conclude our study in Sect. 6.

2 Theory

Innovation systems have been identified as a well-suited approach to explain the diffusion or non-diffusion of technologies (Edquist et al. 2005). Innovation systems that are assigned to a specific technology or product are referred to as TIS in the literature (Markard and Truffer 2008). Bergek et al. (2007) define TIS as the socio-technical systems focused on the development, diffusion and use of a particular technology (in terms of knowledge, products or both). A well-functioning TIS is contingent to the status of its various[3] 'functions' (Suurs and Hekkert 2009). These 'functions' (see Table 1) are the processes which have a direct and immediate impact on the diffusion of a new technology (Bergek et al. 2008a). It is in these processes where policy makers may need to intervene, not necessarily the set-up of the structural components (actors, networks, institutions). Thus, the functions approach to innovation systems implies a focus on the dynamics of what is actually "achieved" in the system rather than on the dynamics in terms of structural components only. This ability to separate structure from content and to formulate both policy goals and policy problems in functional terms is the main benefit of functions approach (Bergek et al. 2008a).

This approach is well suited to map the key events in innovation systems, and to describe and explain shifts in technology-specific innovation systems (Suurs and Hekkert 2009). Each 'function' is associated with many event types (see Fig. 1) occurring under it and each event type leads to the partial removal of a specific barrier to that technology's diffusion. Hence, a well-functioning TIS leads to the removal of barriers and ultimately to the diffusion of the respective technology. Note that the functions can be interrelated and mutually reinforce each other (Bergek et al. 2008a; Suurs and Hekkert 2009).

The functions are provided by the structural elements of the TIS and their interaction, i.e. the actors, institutions, technological artefacts[4] and the networks (see Fig. 1). Since the TIS is defined as a knowledge-based approach for analyzing innovation systems, it should not be limited to a single spatial domain. Bergek et al. (2008a) state that an analysis of TIS always needs to have a strong international component, simply because a spatially limited part of global TIS can neither be understood, nor assessed, without a thorough understanding of the global context. Markard and Truffer (2008) stress the need to delineate the system in spatial terms. Despite these propositions, so far scholars have always empirically tested the FIS approach in a confined space, mainly one specific country, without considering it adequately in their theoretical framework (Coenen et al. 2012). Consequently, the transfer of technological, knowledge-based, financial and human resources across borders (from here on simply called technology transfer) is left out.

[3] The number of functions varies by source: some authors argue for seven (Bergek et al. 2008a; Hekkert and Negro 2009; Hekkert et al. 2007; Wieczorek and Hekkert 2012), others for eight functions (Bergek et al. 2008b; Musiolik and Markard 2011). We follow the seven functions approach as it has been applied in more papers empirically.

[4] Technological artefacts refer to the technological components involved in a TIS and also includes relevant infrastructure technologies. By taking into account actors, network and institutions, the TIS analysis goes beyond a technological system and applies a socio-technical perspective.

Table 1 Functions of technological innovation systems (Hekkert and Negro 2009; Hekkert et al. 2007)

Functions		Explanation	Event types associated (brackets indicate specific barrier(s) removed, refer to Table 3)
F1	Entrepreneurial activities	At the core of any innovation system are the entrepreneurs. These risk takers perform the innovative commercial experiments, seeing and exploiting business opportunities	Improved coordination between entrepreneurs and research institutions via joint projects, conferences, workshops, etc. helps in increasing technology access (M3) (Painuly 2001)
			Industrial associations formed by entrepreneurs are the information dissemination sources (I1). Such associations can also act as lobby group and vouch for better legal frameworks for their industrial sector (I4), and work with the govt. for forming standards related to system components and technical standards that lead to strengthening of the overall reliability of the system (T1) (Jagadeesh 2000)
F2	Knowledge development	Technology research and development (R&D) are prerequisites for innovation. R&D activities are often performed by researchers, but contributions from other actors are also possible	Indigenous development of technology and joint projects by private and state actors help in increasing technology access (M3) (T2) (T3) (T4) (Painuly 2001) and also help in lowering the capital expenditure (M6)
			Capacity building programmes may be undertaken by the govt. to enhance technical knowledge such as developing and demonstrating selected technologies to enhance competitiveness, replicability and assimilations (T2) (Balachandra et al. 2010). These programmes can be undertaken by govt. in partnership with ESCOs and other intermediaries
F3	Knowledge diffusion	The typical organizational structure of an emergent innovation system is the knowledge network, primarily facilitating information exchange	Information providers such as UN agencies, national and state government agencies/departments, and market intermediaries like consultants, NGOs, consumer groups, Energy Service Companies and trade associations are responsible for spreading awareness (M2). Improved awareness about RET projects among financers increase the access to capital for entrepreneurs (M5) (Balachandra et al. 2010). Prevalent practice of 'payback period' being the accepted criterion of taking decision on the project needs to be replaced with NPV criterion, especially in view of the long payback periods of biomethanation projects (B2)
			Better information access to entrepreneurs via conferences and workshops also help decode the hidden costs, thus leading to better financial planning (M7)
			Strong and specialized state institutions, NGOs and industrial associations help in increasing the trust levels of available information (I1)
			A centralized information facility with database on technologies and processes including their sources, prices, inputs, and environmental benefits, as well as information on related patents, market information, and business plans can go a long way in addressing the problem of lack of technical knowledge (B1) (Balachandra et al. 2010)
			Targeted information campaigns also serve to counter the misconception of RET being financially not viable (I6) (B1)
F4	Guidance of the search	This system function represents the selection process that is necessary to facilitate a convergence in development, involving, for example, policy targets, outcomes of technical or economic studies and expectations about technological options	Stimulating packages for enhanced technology transfer provide entrepreneurs with the right technology (M3)
			Removal of subsidies for fossil fuel and introductions of carbon taxes can tilt the scales towards renewable energy (M4) (Balachandra et al. 2010)
			Govt. institutions releasing recorded experiences of successful projects help improve technology reliability (T3), and also lower down the associated hidden costs (M7) (Reddy and Painuly 2004)
			Long-term legal frameworks which guarantee markets and preferential tariffs increase trust among investors (I2) (Balachandra et al. 2010)

Table 1 continued

Functions	Explanation	Event types associated (brackets indicate specific barrier(s) removed, refer to Table 3)
F5 Market formation	New technologies often cannot outperform established ones. In order to stimulate innovation it is necessary to facilitate the creation of (niche) markets, where new technologies have a possibility to grow	Liberalization of the energy sector by policy measures such as restructuring of the energy sector, opening up to introduce competition and removing other controls. Some examples of the specific policies are; creating separate entities for generation and distribution in the electricity sector, allowing private sector entry and diluting or removing controls on energy pricing, fuel use, fuel import, and capacity expansion, etc. (M1) (Painuly 2001)
		Niche market development lead to learning by doing and improve awareness of the technology (M2)
		Removal of restrictive trade policies/taxes for importing technology/equipment increases the access to technology (M3) (Painuly 2001)
		Introducing stricter environmental standards helps remove non-consideration of externalities (M4) (Bergek et al. 2008a)
		Specialized policy instruments for commercialisation stage prevent RET from falling into the 'valley of death' (Negro et al. 2010). An incentive scheme, which ensures the first time purchase of an RET, its continuous use, and ready replacement after its life time should be the preferred one. Since the full energy service is packaged, both the device price and energy price can be instrumented (I3) (Balachandra et al. 2010)
		Flexibility and decision making power to the field agencies and grass root level institutions decrease the bureaucratic hurdles (I5) (Jagadeesh 2000)
		To ensure that environmental plans are an integral part of the development plans, some of the govt. policies will have to be based on voluntary agreement scheme. The principle of 'technology negotiation' to adopt RET in the framework of voluntary agreements introduces an element of flexibility, which can make them easier to implement and help limit the risks of ineffectiveness of technology-forcing measures (I6) (Balachandra et al. 2010)
		Govt. and industry associations need to work together to form standards related to system components and technical standards that lead to strengthening of the overall reliability of the system (T1) (Jagadeesh 2000)
		Govt. can also take initiatives in partnership with entrepreneurs to provide complimentary infrastructure such as roads, connectivity to grid, and other such logistics (T5) (Painuly 2001)
		Also, govt. needs to develop an organized market for buying and selling biomass goods; some specific regulations/laws would go a long way in improving confidence among investors (M8)
F6 Resource mobilization	Financial, material, and human factors are necessary inputs for all innovation system developments, e.g. investments by venture capitalists or governmental support programmes	Govt. sponsored interest subsidies and loan guarantee schemes improve the access to capital (M5), while capital subsidies help in lowering the capital expenditure (M6) (Balachandra et al. 2010)
		To counter lack of technical knowledge, a capacity building programme for acquiring and upgrading technical and managerial skill set can be helpful (T2) (Balachandra et al. 2010)
		Govt. can facilitate tie-ups between Indian and foreign companies for improving the technological capacity of Indian firms (T2)
F7 Legitimization	The emergence of a new technology often leads to resistance from established actors. In order for an innovation system to develop, actors need to raise a political lobby that counteracts this inertia, and supports the new technology	Entrepreneurs can form industry associations/lobby groups and vouch for better legal frameworks and subsequent legitimization for their industrial sector (I4) (B1)

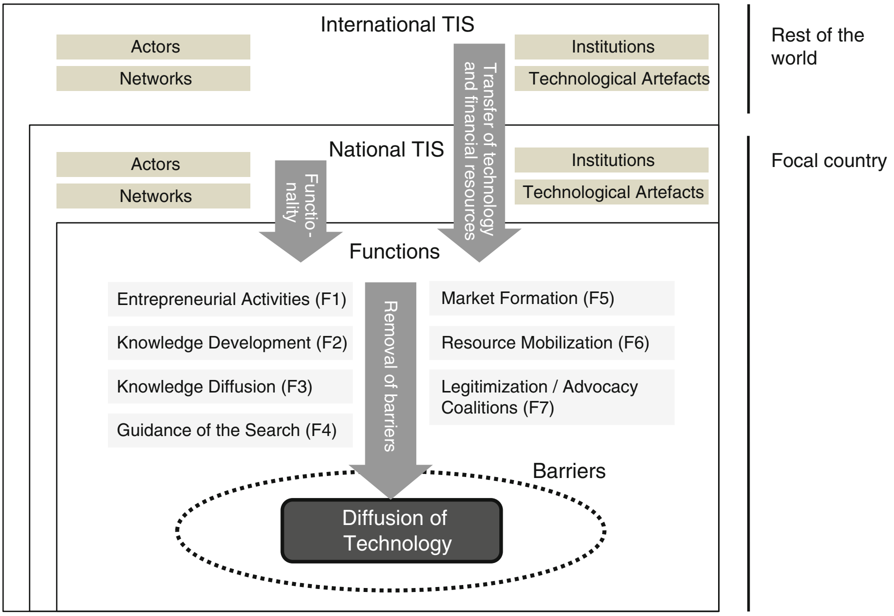

Fig. 1 Theoretical framework developed for the analysis: the ultimate goal of the developed theoretical model is to explain the diffusion (and its absence) of technology in the focal country, which is achieved by removal of barriers in the focal country. The ‘functions of innovation system’ are fulfilled either by the national TIS (directly) or the international TIS (indirectly, via transfer of technology and financial resources)

To this end, we propose a division of the TIS into a ‘national TIS’ comprising the actors, institutions, networks, and technological artefacts present in one focal country and an ‘international TIS’ referring to the elements of the TIS present in the rest of the world. The national TIS and the international TIS interact by means of international transfer of technology[5] and financial resources. Note that technology transfer is not referring to pure technological artefacts but includes “a broad set of processes covering the flows of know-how, experience and equipment” (IPCC 2000, p. 3) Due to these transfers, not only national but also international elements of the TIS can contribute to the functioning of the TIS in the focal country and thereby, partly help to remove the barriers which hinder the diffusion of the technology (compare Fig. 1).

In our framework, we bring the TIS and FIS literature closer to its roots, namely the literature on barriers to the diffusion of technology (Jacobsson and Johnson 2000) and add the concept of technology transfer, which plays a crucial role in climate change negotiations.[6] By doing so, we provide a framework which allows

[5] Technology and financial transfers can occur in many different forms, such as trade, licensing, joint ventures, foreign direct investment (FDI), international lending or grants (see e.g. Schneider et al. 2008).

[6] Technology transfer is prominently treated in the literature on climate change mitigation (e.g. Haites et al. 2012; Schneider et al. 2008; Seres et al. 2009) and acknowledged by innovation system scholars (compare e.g. Carlsson 2006; Lundvall 2009). While the FIS framework acknowledges that TIS cross geographical boundaries (Hekkert et al. 2007), this is hardly reflected in the empiric analyses. Technology transfer is largely ignored by FIS scholars to date.

for detailed and practical policy recommendations for both national and international policy makers.

Since most of the low carbon technologies are being developed in industrialized nations, while much of the potential for these technologies to make significant reductions in carbon emissions is in developing countries, successful transfer and absorption of these low carbon technologies in developing country economies is assumed to be of great importance (Ockwell et al. 2007). Thus, the proposed delineation of the global TIS into national and international components and the explicit consideration of technology transfer become even more pertinent for analyzing the diffusion of renewable energies in developing countries.

3 Methodology

We applied a qualitative case study approach to answer the research question and show the validity of our framework. Such approach is appropriate to study contemporary phenomena in complex contexts (Gibbert et al. 2008; Yin 2002). For all three steps—the barrier identification, the functionality of the TIS in removing the barriers and the role of the international TIS therein—that serve to address our research question we drew from two sources, literature and interviews in an iterative manner: the relevant facts identified in literature are checked and contrasted with the interview findings. New findings from the interviews are checked via literature and in the subsequent interviews. This iterative data triangulation assures a high validity of our findings. In the following, we shortly describe the literature analyzed and the interview procedure.

3.1 Literature

The first step, the identification of the barriers for the diffusion of biogas in India, is based on an extensive analysis of barrier-specific literature on three levels: (a) a general RET level, (b) a level specific to India and RET, and (c) a level specific to bio-energy in India. Painuly (2001) has given a framework for identification of barriers to diffusion of RET in general. He proposes that barriers can be explored and analyzed at several levels: Level I: a broad category of barriers; Level II: barriers within a category; Level III: elements of these barriers; and so on. To sustain the distinction among various barrier categories, Reddy and Painuly (2004) have simplified the list of barriers to lack of awareness and information, economic and financial constraints, technical risks, institutional and regulatory barriers, market barriers/failures, and behavioural. Working on similar lines we have structured barriers into four categories, namely, market and financial, institutional and regulatory, technical and behavioural and social barriers.

For the second and third steps, the functionality of the TIS in removing the barriers and the role of the international TIS therein, we used both academic as well as practical literature. The academic literature was mainly used to match the identified barriers with the seven functions theoretically. To this end, we compared the barriers with the various event types (Hekkert et al. 2007; Suurs and Hekkert 2009) allocated to different 'functions' in the FIS literature (see Table 1). A matrix, listing all barriers on one and all functions on the other axis, was developed to understand which barriers can be principally addressed by which functions. The practical literature was used to analyze the various event types (see Table 1) and thus the actual functionality of the TIS in India and how the international TIS contributes to this functioning[7] was arrived at. This literature included relevant information from government sources (e.g. MNRE 2006; MNRE 2011; MWH 2006a), magazine articles (e.g. Sooch 2009), conference presentations (e.g. Dhussa 2009; Shukla 2010a, b), project reports (e.g. Deodhar and Akker 2005), and news websites (e.g. Singh 2010).

3.2 Interview procedure

As stated above, we conducted interviews with relevant actors to triangulate our findings from the literature in an iterative manner.

3.2.1 Sample

We selected expert interviewees to arrive at a balanced sample of relevant actors, which in turn allows for a certain generalization of the status of the TIS of biomethanation in India. Table 2 shows the covered spectrum of the various types of actors active in the TIS. Interviewees included actors at different value chain positions and in different waste-streams based biomethanation projects (animal dung-based and municipal waste-based).

3.2.2 Data collection

For the interviews a semi-structured questionnaire format was chosen, which allows for new and unforeseen topics to be introduced by the interviewee.[8] The questionnaire included questions pertinent to each function, while questions concerning barriers and the international cooperation were asked explicitly. All interviews took place in November 2010 and were conducted personally by one of the authors via face-to-face communication. On an average each interview lasted about 90 min. Strong care was taken during the field visits to take advantage of unforeseen novel insights from the interviewees.[9]

[7] The entries in the matrix found in the results section stem from this literature as well as from the interviews.

[8] Two types of the questionnaire were used: one for investors/suppliers and the other for government officials/academicians/consultants. Both types of questionnaires can be found in the "Appendix".

[9] For example, during the interview with the potential investor/supplier, it was realized that the interviewees did not know at all about the latest applications of biogas such as bio-CNG; thus questions asked during the interview were transformed into a hypothetical setting.

Table 2 Overview of the interviews conducted

Main characteristic of the interviewees	Other characteristics	Number of interviews
Energy service company	Manager in a large and diversified organization involved in various waste management projects, manager of a new company focused on biomethanation	2
(Potential) investor	Manager of a large cow-shed with 2700 cows, manager of a large cow-shed with 3000 cows	2
Government official	Official at Haryana Renewable Development Authority, government expert for biomethanation projects	2
Academician	Professors in a state research institution	3
Consultant	Independent consultant on municipal waste-based biomethanation projects	1

3.2.3 Data analysis

The interview notes were transcribed by the researcher that had conducted the interviews. While the questions on the barriers and the role of international TIS were asked directly, the questions on the functions were set in open, semi-open and closed-ended formats to get to know about the various event types as listed in Table 1. These transcripted answers were assigned to the function categories by the same researcher. The final results were then reviewed by both authors and selected for their relevance.

4 Results

The results section is structured along the three steps that serve to answer the overarching research question. In Sect. 4.1, we shortly describe the barriers to the diffusion of large-size biogas plants in India based on our literature review. While in Sect. 4.2 we show how the functions of the current TIS impacted on these barriers, we present the findings on the role of the international TIS in Sect. 4.3.

4.1 Major barriers to the diffusion of large-size biogas plants in India

The major barriers to diffusion of large-size biogas plants in India are shown in Table 3. We structured all discovered[10] barriers along four categories, which we identified,[11] namely market and financial, institutional and regulatory, technical and behavioural and social barriers. These categories are also used for the “coding” of the barriers, which will be used in Sect. 4.2. The category containing most barriers is market and financial, whereas we only identified two behavioural and social

[10] Table 3 only mentions the interviews as source for barriers which were not identified previously in the literature. Barriers that were mentioned in the interviews that had been identified in the literature previously are not explicitly referenced by interviews.

[11] Note that these categories slightly differ from those previously identified by e.g. Painuly (2001). This mere question of definitions does not further impact on the results in the following sections.

Table 3 Barriers to diffusion of large-size biogas plants in India

Barrier category	Code	Barrier	Consequences	Source(s)
Market and financial	M1	Lack of market openness	A lack of participation by private sector might be caused	Painuly (2001)
	M2	Lack of awareness among market participants (customers, financers, etc.)	Uncertainty is increased, and hence costs. Supply side consisting of dairy owners, farmers, municipality, etc. is said to be less aware	Hansen et al. (1999; Jagadeesh (2000); Painuly (2001); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Interviews
	M3	Limited access to technology	Private entrepreneurs find it hard to contact technology providers, e.g. from developed nations	Painuly (2001); Interviews
	M4	Favour (such as subsidies) to conventional energy and non-consideration of externalities	The relative competitiveness of biomethanation technology is negatively affected	Painuly (2001); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Balachandra, Nathan et al. (2010)
	M5	Lack of access to capital and high capital cost	The economic viability is negatively affected. There is a lower number of entrepreneurs, reducing market efficiency	Jagadeesh (2000); Painuly (2001); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Balachandra et al. (2010)
	M6	CAPEX intensity of renewables	This acts as an entry barrier for entrepreneurs, especially for the smaller ones. There is a strong interaction with barrier M5	Painuly (2001); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Balachandra et al. (2010); Interviews
	M7	High hidden costs	Operation and management costs, and the costs associated with gathering, and analyzing information may be high	Jagadeesh (2000); Reddy and Painuly (2004); Interviews
	M8	Problematic buyer–supplier relationship	The feedstock for the project on a continuous basis is endangered	Interviews

Table 3 continued

Barrier category	Code	Barrier	Consequences	Source(s)
Institutional and regulatory	I1	Lack of trusted institutions to disseminate information	The availability of reliable information to the entrepreneurs and thus their confidence in the technology is low	Jagadeesh (2000); Painuly (2001); Interviews
	I2	Lack of long-term legal regulatory frameworks	This leads to less long-term investment from private sector	Hansen et al. (1999); Jagadeesh (2000); Painuly (2001); Reddy and Painuly (2004); Hekkert and Negro (2009); Interviews
	I3	Lack of policy instruments for commercialization	Technology may fall in the so-called 'valley of death', as diffusion is limited to demonstration stage only	Hekkert and Negro (2009); Interviews
	I4	Lack of involvement of stakeholders in decision making	Policy instruments are designed in an inappropriate and incoherent manner	Jagadeesh (2000); Painuly (2001); Interviews
	I5	High level of bureaucracy	Private participation is dis-incentivised	Jagadeesh (2000); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Interviews
	I6	Difficulty in mainstreaming environment into development plans	Consumer perception is limited to only the environmental component of the technology and economic viability remains unnoticed	Ravindranath and Balachandra (2009); Balachandra et al. (2010)

Table 3 continued

Barrier category	Code	Barrier	Consequences	Source(s)
Technical	T1	Lack of standards, codes and verification	Product quality and product acceptability is negatively affected	Hansen et al. (1999); Jagadeesh (2000); Painuly (2001)
	T2	Lack of technical knowledge in India	Technology indigenization leading to lower costs is affected negatively	Painuly (2001); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Balachandra et al. (2010); Interviews
	T3	Lack of reliable technology	The acceptance of the technology is lowered	Jagadeesh (2000); Painuly (2001); Reddy and Painuly (2004); Balachandra et al. (2010)
	T4	Lack of coordination among research groups, academic institutions and private industry	Laboratory success finds it difficult to be imitated at the plant level, consequently leading to lower research and technology levels in the country	Jagadeesh (2000); Ravindranath and Balachandra (2009); Interviews
	T5	Lack of complimentary infrastructure	Project feasibility often depends on complementary infrastructure, e.g. easy access to electricity grid can improve the success chances of a project	Painuly (2001); Balachandra et al. (2010)
Behavioural and social	B1	Lack of consumer acceptance of the product and high risk perception	Market size becomes small, leading to less interest from private sector	Painuly (2001); Reddy and Painuly (2004); Ravindranath and Balachandra (2009); Hekkert and Negro (2009); Interviews
	B2	Wrong profitability indicators	Payback period is simply taken as indicator for project selection, profitability indicators which incorporate the cost of capital (e.g. NPV) are neglected	Painuly (2001); Reddy and Painuly (2004)

barriers. At this juncture, it is important to notice that one single barrier can be enough to hinder the large-scale diffusion of a technology.

4.2 Impact of the functions of the technological innovation system on the barriers

A well-functioning TIS can remove all these barriers so that the technology diffuses to its potential. As stated above, removal of a barrier can be achieved by a combination of event types which are part of different 'functions'. Table 4 matches the functions with the barriers in a matrix. While one function is associated with the removal of several barriers, many barriers need to be removed by more than just one function. In Table 4, the first column contains the 'functions' as coded in Table 1, while the first row shows the barriers as coded in Table 3. The different cells are filled with either 'N' or 'S' or 'A' or left blank. A blank cell means that the events under the concerned function do not influence the removal of the corresponding barrier. If all event types corresponding to a specific 'function' for a specific barrier are present, then that cell has been labelled '*A*' i.e. All event types present. If only a few of the concerned event types are present, the cell is labelled '*S*' i.e. Some event types present, and if none of the event types are present corresponding to a specific 'function' for a specific barrier, that cell is labelled '*N*' i.e. No event types present. Fields containing an asterisk depict barriers which are addressed by a function (at least partially) provided by the international TIS.

As seen from Table 4, many event types associated with the 'functions of innovation system' are not present for each of the 'functions' and consequently most barriers to the diffusion of biomethanation technology have not been removed completely. In the following, we describe the details behind this matrix structured along the seven functions. For each function, we describe which event types have occurred as per Table 1 and then show which barriers still exist.

F1 Entrepreneurial activities Entrepreneurs are essential for a well-working TIS. They can be either new entrants or incumbent firms diversifying their business (Hekkert et al. 2007). Our interviews (all of them) pointed to a noticeable lack of entrepreneurial activity in the Indian biomethanation TIS. Moreover, the interviewees (academicians, investors, energy service company officials) pointed out the fact that there is very little coordination between private sector and the research institutions and there are no industrial associations as well. This lack of entrepreneurs retains several barriers. First, without technology providing entrepreneurs, technology cannot be accessed by potential investors (M3); second, as there are no associations, knowledge dissemination (I1), engagement of the private sector in the policy making process (I4) and common standard setting (T4) is hardly possible.

F2 Knowledge development This function lies at the heart of the TIS and encompasses 'learning by searching' and 'learning by doing' (Hekkert et al. 2007). In India a lot of work has been done on family size (2–4 m^3) biogas plants, however, the lack of networking with the private sector has resulted in a lack of up-scaling of biogas plants as reported in an interview (government official). As per the National Master Plan (MWH 2006a), there are quite a few number of organizations involved

Table 4 Matrix of the 'functions of innovation system' and the associated barriers

Barriers / Functions	Market and Economics								Institutional and Regulatory						Technical					Behavioral	
	M1	M2	M3	M4	M5	M6	M7	M8	I1	I2	I3	I4	I5	I6	T1	T2	T3	T4	T5	B1	B2
F1			N						N			N			N						
F2			S			N										S*	S*	N			
F3		S			S		S*		A					N						S	A
F4			N	S			N			S*							N				
F5	A	N	A	S				N		S	N		N	N	S				N		
F6					A	A		N								S*					
F7												N								N	

A => All event types present
S => Some event types present
N => No event types present
* => depicts barriers which are addressed by a function (at least partially) provided by the international TIS

in research on biomethanation in India. Most of these organizations have the capacity to take up lab/pilot scale work on biomethanation of liquid effluents; only two have the expertise and facilities to develop full-scale prototype plants for biomethanation of industrial wastewaters, while no specific expertise/facility is currently available in the country for undertaking waste-to-energy (WTE) R&D dealing with municipal solid waste (MSW) by biological or thermal processes. Pilot studies have been done for biogas enrichment process by removing CO_2, scrubbing of H_2S, compressing it into cylinders and using it for applications where CNG (compressed natural gas) is used, development of plug-flow digester and development of solid phase biogas plant, etc. (MWH 2006a) (T2, T3).

As far as the development and availability of biogas engines for producing electricity using biogas is concerned, the interviewees (energy service company officials) informed that there are locally made engines available for smaller capacities (<250 kW), whereas larger size engines are fully imported (M3). The interviewees (energy service company officials, government officials) lamented the fact that the procurement and maintenance of imported engines is quite expensive (M6).

F3 Knowledge diffusion This function refers to the exchange of information, mostly via networks in the TIS (Hekkert et al. 2007). Knowledge diffusion has been partially successful in the Indian biomethanation TIS. The number of workshops/conferences is relatively low and also they are not organized all over India (M2). As per the annual reports of the Union Ministry of New and Renewable Energy (MNRE) of India, 1–2 workshops and conferences are organized each year for promotion of the technology by the ministry. Other research institutions also organize 2–3 workshops each year (M7). Furthermore, MNRE publishes two bimonthly magazines related to renewable energy including biogas. Each state has a state renewable energy development agency to which entrepreneurs submit project proposals for subsidy consideration and every district in India has a district advisory committee for providing information regarding renewable energy policies of the government (MNRE 2011) (M2).

However, there is no centralized information facility where investors can get all kinds of information (I1, B1). The interviewees (energy service company officials, government officials) informed that there are very few energy service companies (ESCOs) and as of now, the information work expected from ESCOs is done to an extent by the independent consultants (M2). Also there are no specific programmes for spreading awareness amongst financers and banks take consultancy from outside for passing loans for such projects (M5, B2). Furthermore, there are no targeted information campaigns emphasizing the financial viability of such projects, thus maintaining the negative perception that such projects are only good for environment and not for earning profits (B1).

F4 Guidance of the search Limited resources call for the process of selection represented by this function (Hekkert et al. 2007). Our interviews (investors, energy service company officials) indicate that the general investors' feeling for biomethanation projects in India is of high risks and low rewards nature. The 11th Five Year Plan of the Indian Government has set targets for energy recovery from urban wastes (100 MWe from MSW, 30 MWe from biogas STPs, and 70 MWe from other urban wastes such as vegetable market waste, kitchen waste and cow-dung generated waste in urban areas) and energy recovery from industrial wastes (200 MWe) (MNRE 2006). R&D thrust areas include, *inter alia,* design and development of biogas engines, design and development of improved processes for drying of digested slurry and improving biogas quality (MNRE 2011). There is a comprehensive National Master Plan for development of waste-to-energy in India (*ibid.*). Also, the national biogas and manure management program was launched in 1981 (Shukla 2010a) (I2).

However, there is no separate legislative framework for WTE projects; these projects are regulated under the existing legal framework in the country. This framework consists of various acts, rules, policies and guidelines, resulting in increased bureaucratic hurdles for the entrepreneurs. There has been a gradual removal of subsidies on conventional fuel as well, but it has not really stirred the market for renewables as pointed out in one of the interviews (energy service company official) (M4). Also there are no specific packages for technology transfer (M3). Furthermore, the government has not released any kind of successful project experiences (T3, M7).

F5 Market formation For an emerging TIS market formation activities create the protective space and stimulation needed for establishing the market for the concerned technology (Bergek et al. 2008a; Hekkert et al. 2007). Provisions have been provided for open access to grid for RET power, preferential tariffs by state electricity regulators (tariffs are arrived at individually for each project in consultation with the project owner) (I2), introduction of renewable energy certificates (I6), and decontrolling of captive power generation (M1) (Shukla 2010b). Furthermore, the government has introduced various schemes for different plant sizes. For biogas plants of capacities 25–3000 m^3, the 'Biogas based Distributed/Grid power Generation Programme' is in place. Similarly, programmes for 'Energy Recovery from Urban Wastes' and 'Energy Recovery from Industrial Wastes' for higher capacity ranges have been employed. The government has also introduced a programme for 'Demonstration of Integrated Technology Package on Biogas Fertilizer Plants (BGFPs) of 200–1000 m^3 for Generation, Purification/Enrichment, Bottling and Piped Distribution of Biogas' (Shukla 2010a). Yet, the interviewees (academicians, energy service company officials) reported that outcomes of government programmes are hitherto unclear (I3).

A very high level of bureaucracy is seen as a big obstacle in bringing private sector investment in biomethanation (I5). One interviewee (investor) reported that a 100-kW project in the state of Haryana took around 15 months to get clearances from 16 state government departments. Our literature analysis shows that no niche markets have been identified by the government for special development (M2). Furthermore, there have been no efforts to integrate environment plans into the development plans of the government as environmental issues are still seen as an over-the-top burden. Stricter waste disposal standards have been imposed on the industry; however, the interviews (academicians) indicate that monitoring and verification aspect remains unreliable and corrupt to a large extent (M4). Complimentary infrastructure has also largely been ignored by the government (T5). There are no standards for the usage of biogas, or for the equipment used in such projects (T1).

F6 Resource mobilization For a TIS to evolve, a range of resources (financial, material, and human) needs to be mobilized (Carlsson and Stankiewicz 1995). To this end, the following has been done in India. The government has established Biogas Training and Development Centres (BTDCs) in different universities and Indian Institutes of Technology, which provide training, monitoring, evaluation, and preparation of technical booklets/guidelines/material support for quality implementation of biogas programme in addition to technology development. Also, regular workshops are held by MNRE and state level institutions for training of technical and management personnel in the field of biomethanation (Routh 2009) (T2). The government also provides capital subsidies that vary with the various schemes and the biogas plant sizes. Central financial assistance ranges from 20–50 % of the project cost. As per the government subsidy schemes, minimum 20 % of the project cost is to be borne by the investor/project owner. The government pays capital subsidies directly to the bank/financer after reviewing data of the plant performance (M5, M6) (Shukla, 2010a). According to most of the interviewees, financial closure of an economically sound project is a non-issue for the investors as obtaining credit from banks is not difficult.

However, interviewees (energy service company officials) reported that procuring waste on a continuous basis is an issue for many projects based on animal-dung as waste suppliers tend to raise prices strongly once the project becomes a success (M8).

F7 Legitimization Attaining legitimacy for a technology implies counteracting the resistance to change (Hekkert et al. 2007). Interviews (academicians) reveal that even though the biomethanation technology is considered to be mature in India as such, failures of many biomethanation plants, especially in the municipal waste sector, are relatively frequent. There are no formal industry associations in the WTE sector as it is still not considered as an industry (B1). The few players working in this area continuously try to interact individually with the officials at MNRE for better and suitable policies for this sector. Furthermore, one interviewee (government official) has pointed out that the diffusion of biomethanation in private sector can be partially attributed to the consultants looking after WTE projects (I4).

4.3 Provision of functions by the international TIS

In this section, we specifically analyze the contribution of the international biomethanation TIS to the functions within India, proceeding function by function. Theoretically, these contributions can vary from nil to very large.

F1 Entrepreneurial activities We could not identify any explicit influence of the international TIS on this function of the Indian biomethanation TIS.

F2 Knowledge development Multilateral agencies have been involved in initializing some knowledge development activities. In total, 16 demonstration projects were set up in India as part of the UNDP/GEF project—'Developing High-Rate Biomethanation Processes as Means to Reduce Greenhouse Gas Emission'. The objectives of the project were to develop requisite expertise and capabilities in national and state level institutes, R&D organizations and universities to assimilate and adapt technology, improve applied R&D skills, and to provide technical know-how and assistance in setting up plants using the biomethanation processes. The project was operationally closed in 2005 (Deodhar and Akker 2005) (T2, T3).

F3 Knowledge diffusion International TIS actors such as multilateral agencies and multinational companies (MNCs) are supporting the knowledge diffusion by providing awareness of that technology (M2) and giving feedback in the operation and financing of such plants (M7). As part of the UNDP/GEF project, a total of 46 conferences and workshops were organized with actors from different waste-generating sectors. A quarterly newsletter 'Bio-energy' news was also brought out (Deodhar and Akker 2005). MNCs, through their sales offices, are engaged in marketing activities, thus helping raise the awareness levels (M2).

F4 Guidance of the search Planning support is given by international institutions. For instance, the national master plan for waste-to-energy technologies was prepared as one of the objectives of UNDP/GEF project (Deodhar and Akker 2005) (I2).

F5 Market formation We could not identify any explicit influence of the international TIS on this function of the Indian biomethanation TIS.

F6 Resource mobilization Again, the efforts of the international TIS can be attributed mainly to the multilateral development agencies, which were involved in two major projects in India. First, the project "Developing High-Rate Biomethanation Processes as Means to Reduce Greenhouse Gas Emission" was funded by the Global Environment Facility (GEF), the Government of India and third-party investors (M5). It involved *inter alia* many training programmes for technicians/managers, and study tours for faculty from R&D institutions, government agencies and industry (Dhussa and Jain 2006). Second, the project "Removal of Barriers to Biomass Power Generation in India Phase I" is funded by GEF, Government of India, KfW (German government owned development bank) and private sector. Pilot models will be used to demonstrate how biomass power technology can be used to meet electricity needs in the rural areas. The project will help standardize financial packages to commercialize biomass power on a large scale (UNDP 2009) (M6). For almost all large-size biogas plants in India imported technology is used as biogas engines of a capacity of above 250 kW are still imported as reported by the energy service company officials (T2).

F7 Legitimization Also, for this function we could not identify any explicit influence of the international TIS.

5 Discussion and policy implications

This section is split into two parts: while we firstly discuss our results generally, we secondly derive policy recommendations on how to support the diffusion of large-size biogas plants in India.

5.1 Discussion of results

For the concrete case of biogas in India, our results indicate that of the many barriers identified, only few have been fully removed, explaining the hitherto low diffusion rate. While some barriers are still fully present, others have already been removed (at least partially) due to the working of one or several functions. No concrete pattern can be identified regarding the four categories we had defined for the barriers, i.e. it does not become obvious that certain categories are addressed in a better way than others. However, what becomes obvious if we read Table 4 from left to right is that certain functions can be relevant for the removal of many barriers (e.g. F5 being related to eleven barriers) or of few (e.g. F7 being related to two barriers, only). Furthermore, while some functions are hardly working and were thus not able to remove any of the related barriers (F1 and F5), others work better as they were able to remove some barriers well or at least partly. According to our findings, no function works very well currently, in that it would be able to remove all barriers related to it. Interestingly, a function can already work very well for the removal of a certain barrier but still not work so well to reduce others (see F3 and F5). This is assumingly related to the different heights of the barriers: while certain barriers can be removed relatively easily, i.e. partially working functions are enough to remove them), others need a very good functionality of the TIS to be removed.

Regarding the role of the international TIS, our analysis shows that so far the international TIS has only contributed to a few functions. However, those functions also happen to be the most developed in the Indian biomethanation TIS (compare Table 4), which points to the importance of the international TIS and its contribution to the functionality of the Indian TIS via technology transfer. For example, most of the large-size biogas plants are based on technology imported from Europe and U.S. It is in general mainly technology-related barriers that are affected and that have been (partly) removed: three of the barrier removal contributions from the international TIS are to be found in the technical barriers category, whereas just one barrier each in the market and economic as well as the institutional and regulatory categories are affected. This makes full sense as technology-related knowledge and resources can usually be more easily transferred than institutional factors. Barriers in the behavioural category are not affected by the international TIS, as these are fully location dependent. Hence, the functions addressing these barriers need to be provided fully by the national TIS. Generally speaking, functions from the international TIS are more relevant for the removal of barriers which are less rooted in national institutions and can be removed by more tangible resources. While the international TIS has provided some functions, there is assumingly more room for it to enhance the functionality of the system especially regarding the latter functions.

5.2 Policy implications

As shown, many barriers still exist. Therefore, national and international policies play an important role as they can support the functions in India by targeting either the national or the international TIS or their interface, i.e. cross-border networks. In order to support both national and international policy makers, we systematically deduce policy recommendations on how to strengthen the functions of the TIS to address the identified major barriers to the diffusion of biogas technology in India. In Table 5, we present these measures in order of the functions. For each function we distinguish national and international policy measures.[12] In total, we derive 25 recommendations, of which 17 are targeting the national TIS and therefore rather address national policy makers; and eight targeting the international TIS, hence addressing mainly international policy makers and organizations. In the most right column, we suggest political actors on a national and international level, which are responsible for the proposed measures. The role of the international bodies is discussed below.

While generally the analysis leads to more recommendations per function on the national TIS level, for F2, knowledge development, we derive more international recommendations. This knowledge relates mainly to the construction of biogas plants. Knowledge which stems from experience-based learning (or learning by using) needs to be provided rather by the national TIS. This is reflected in F3, knowledge diffusion, where the knowledge refers more to operation and maintenance knowledge, which is essential for biogas.

While Table 5 suggests many policy options, the question on how to realize and finance these measures goes beyond the purpose of our study. When considering the new international market mechanisms proposed under the Cancun Agreement (UNFCCC 2010), Nationally Appropriate Mitigation Actions (NAMAs) could be formulated by the Indian government which include the above measures. In this regard, our study shows how complex the requirements for national policy making can be for biogas alone. International policy making could also fall under the post-Kyoto mechanisms. The Cancun Agreement establishes a technology mechanism to facilitate technology development and transfer. Under this mechanism, there will be a technology executive committee to promote and facilitate, *inter alia*, collaboration on the development and transfer of technology for mitigation and adaptation between governments, the private sector, non-profit organizations and academic and research communities. There will also be a Climate Technology Centre and

[12] These measures correspond to those cells containing 'S' or 'N' in Table 4, where it is possible to improve the status via policy introduction/changes.

Table 5 Suggested policy measures

Function	TIS	Policy measures	Organization
F1 Entrepreneurial activities	National TIS	Provide incentives for international firms to set up local manufacturing, e.g. via tax incentives	National authorities (agricultural and energy)
		Support the foundation of a biogas industry association	
	International TIS	Provide a platform for SMEs to exchange information and interests across boarders	CTC&N
F2 Knowledge development	National TIS	Facilitate collaboration of the state research institutions and the private sector, to scale up local laboratory-scale technology	National authorities (research, education)
	International TIS	Provide collaboration mechanisms between Indian and international research institutions	CTC&N
		Finance large-scale demonstration projects	GCF (fast start)
F3 Knowledge diffusion	National TIS	Create centralized information facility ("one-stop-shop") containing all information required for developing and running biogas projects	National authorities (agricultural and energy)
		This facility should be used as platform for development of networks and exchange of experiences	
	International TIS	Create an international information facility on the Indian biogas potential and markets	CTC&N
			National development authorities
F4 Guidance of the search	National TIS	Create a separate legislative framework for WTE projects	National authorities (energy, environment and development)
		Introduce a specific package for facilitating technology transfer, including tax breaks, etc.	
		Record and release successful project experiences (facilitate learning by using)	
		Provide technology needs assessments	
	International TIS	Support technology needs assessments	CTC&N

Table 5 continued

Function	TIS	Policy measures	Organization
F5 Market formation	National TIS	Reduce bureaucratic hurdles; gradually phase-out fuel and fertilizer subsidies	National authorities (agricultural, energy, environmental and development)
		Introduce preferential tariffs for biogas energy	
		Identify niche markets and introduce support policies, such as conjugating biogas policy with national dairy development plan	
		Provide complimentary infrastructure, e.g. developing a CNG grid	
		Introduce standards for biogas usage	
	International TIS	Financially and technically support the reduction of subsidies and the introduction of feed-in tariffs	Development agencies, UNDP, UNEP
			CTC&N
			GCF (fast start)
F6 Resource mobilization	National TIS	Create an organized biomass market	National and regional authorities (environment, agriculture, economic)
		Regulate waste quality, streams and markets	
	International TIS	Financially and technically support biogas projects	CTC&N
			GCF (fast start)
F7 Legitimization	National TIS	Release successful project experiences	National and regional authorities (energy, agriculture)
	International TIS	Disseminate information on successful biogas cases outside of India	CTC&N

CTC&N Climate Technology Centre and Network, *GCF* Green Climate Fund

Network (CTC&N) that shall facilitate national, regional, sectoral and international technology networks, organizations and initiatives. Through collaboration of the private sector, public institutions, academia and research institutions, the development and transfer of existing and emerging environmentally sound technologies, as well as opportunities for North–South, South–South and triangular technology cooperation shall be stimulated. While these institutions were established in Cancun and further developed in Durban, the UN climate conference in Doha is expected to shed more light on how these institutions and mechanisms can work. Also the question on how to distribute financial and technological resources is still open. Regarding this question, our study shows how multifaceted also the international part of a policy mix can be. Besides multilateral agreements, bilateral support can also play an important role. Especially, source countries of technologies, such as the US, Germany or Japan, might have a major interest to support the functionality of innovation systems in foreign countries and thereby open new markets for domestic firms.

At this point, we want to highlight the role of the interface between the national and the international TIS. Mallett et al. (2009) have suggested that to facilitate engagement by international actors, clear articulation of the benefits (e.g. new market access, access to knowledge of local technological requirements) is required. Provision of such information could usefully be facilitated by investigations commissioned under the auspices of a multilateral body or by a source country. Furthermore, collaborative initiatives could include a specific element aimed at increasing knowledge and awareness of the domestic and global intellectual property system (Mallett et al. 2009).

6 Conclusions

Our analysis has shown that the technological innovation system for large-size biogas in India is functioning only to a limited extent. While several barriers have been removed (partially), no single function of the TIS is fully working. The contribution of the international TIS is important, yet limited: some functions could be further supported from the international TIS, others have to be strengthened nationally. This implies policy action on both the Indian and the international level, which are discussed in Sect. 5.1.

Our paper contributes to the debate on the diffusion of clean technology in two ways. First, we extend existing theory by introducing a spatial dimension into the TIS and FIS literature. We thereby address a shortcoming of that theoretical school which was very recently also identified by other authors and allow transfer of technology, know-how, financial and human resources to be an integral part of the innovation system literature. These transfers have been identified as crucial for the development of non-industrialized countries (for an overview, see Bozeman 2000). Also our research case on large-scale biomethanation in India shows that the transfer of technological and financial resources is critical to build a supportive environment for the diffusion of the technology. Splitting the TIS into an international and a national part (i.e. the focal country), helped to explicitly consider the role of these international transfers while keeping the empirics relatively simple (i.e. a purely Indian perspective). Thus, we consider our approach as one potential way to avoid the often found mismatch between TIS theory and the empirical analyses. Second, by applying the framework to the case of biogas in India allows us to derive policy recommendations for both, national and international policy makers on how to remove existing barriers by strengthening the functions of national and international parts of the TIS.

Our framework can generally be applied to other focal countries and other technologies in early stages of the diffusion process. Different country and technology combinations might be confronted with very different barriers and the functionality of the TIS might strongly depart from the one we have observed regarding biogas in India. Hence, future research should roll out similar kinds of studies in different countries and on different technologies to understand country and technology differences and how they can be addressed by policy makers. Furthermore, future research should be devoted to the question, how the resulting policy recommendations could be realized using the national and international institutions and their interplay. For instance, to which extent can they be part of a NAMA and how and to which extent should such NAMA be financed unilaterally or multilaterally.

Appendix

The two questionnaires used for the semi-structured interviews.

Questionnaire for investors, companies, and consultants

Q. Which were/are the most critical barriers that you faced/are facing in the project?

F1. Entrepreneurial activities

1. Are you part of any industrial association related to biomethanation?
   a. If no, then do you know about any such activities?
   b. If yes, then do you know about any other such activities?
2. Do you think other project owners share information/experiences with each other?
3. What is your perception about the scale of implementation of biomethanation in India?
4. Do you have any kind of cooperation with any university or research institution for your project?

F2. Knowledge development

5. How much do you know about Indian technologies in biomethanation?
   a. What are the advantages and disadvantages of Indian technologies?
   b. How do you get to know about foreign technologies?

F3. Knowledge diffusion

6. From where did you get the motivation to implement this project?
7. How many workshops/conferences have you attended related to biomethanation in the last three years?

F4. Guidance of the search

8. Did you visit any demonstration projects to see the working of this technology?

F5. Market formation

9. Are there any preferential tariffs for electricity?
10. How many energy service companies you know about?
11. How easy it is to source technology from outside India?
12. Do you know if there are any mandatory standards for equipment used in biomethanation projects in India?
13. Is selling electricity to grid/selling compressed biogas easy?

F6. Resources mobilization

14. Do you approve projects based on payback period?
15. How difficult or easy is the financial closure of the project?
16. Do the bank personnel you met with have knowledge about biomethanation projects, especially the technology used?
17. Do you get sufficient technical manpower to handle your project?

F7. Legitimization of the technology

18. Do you know about any lobby groups who advocate biomethanation besides government?

International Cooperation

Q. How can international transfer of loans/technology/know-how enhance the ease of development of a biomethanation plant in India?

Questionnaire for Govt. officials and Academicians

Q. Which are the most critical barriers in the diffusion of biomethanation plants in India?

F1. Entrepreneurial activities

1. Which industrial associations do you know about related to adoption of biomethanation?

2. Do you think project owners share information/experiences with each other?
3. What is your perception about the scale of implementation of biomethanation in India?
4. What is the level of cooperation between academia and private sector in this sector?

F2. Knowledge development

5. How much do you know about Indian technologies in biomethanation?
   a. What is the level of research in India?
   b. What are the advantages and disadvantages of Indian technologies?
   c. What are the pros and cons of foreign technologies

F3. Knowledge diffusion

6. Is enough being done to promote biomethanation in India?
7. How many workshops/conferences have you attended/know about related to biomethanation in the last three years?

F4. Guidance of the search

8. What kinds of incentives are there which promote diffusion of biomethanation in India?

F5. Market formation

9. How many energy service companies you know about?
10. How easy it is to source technology from outside India?
11. Do you know if there are any mandatory standards for equipment used in biomethanation projects in India?
12. What is the status of infrastructure complimentary to such projects in India?

F6. Resources mobilization

13. How difficult or easy is the financial closure of the project?
14. Is there sufficient technical manpower around to handle large-scale diffusion of this technology?

F7. Legitimization of the technology

15. Do you know about any lobby groups who advocate biomethanation besides government?

International Cooperation

A. How can international transfer of loans/technology/know-how enhance the diffusion of biomethanation plants in India?

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